IOP Publishing Superconductor Science and Technology
Supercond. Sci. Technol. **31** (2018) 025005 (5pp) https://doi.org/10.1088/1361-6668/aa9f41

Dendritic flux instability in MgB_2 films above liquid hydrogen temperature

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Received 29 August 2017, revised 30 November 2017
Accepted for publication 5 December 2017
Published 27 December 2017

Abstract
Magnetic flux instability limits potential applications of superconductors such as MgB_2 in practical devices. Previous studies in MgB_2 films exposed to magnetic fields revealed the occurrence of dendritic flux avalanches at temperatures below $T \sim 10$ K. In the present work it is shown that films of MgB_2 exposed to a *fast-ramped* magnetic field display a dendritic flux instability at elevated temperatures, up to 23 K. Such instability can therefore cause malfunctioning of practical devices based on MgB_2 films even when operating at liquid hydrogen temperature.

Keywords: MgB_2, dendritic flux instability, magneto-optical imaging, liquid hydrogen, superconductivity

(Some figures may appear in colour only in the online journal)

MgB_2 is a promising material for superconducting applications such as electricity transmission cables, high-field magnets, energy storage devices, high power applications, and sensors [1–3]. Various characteristics ensure considerable attractiveness of this material, including its low cost, good mechanical properties, high critical current density, and relatively high critical temperature, $T_c \sim 39$ K. Nevertheless, dendritic flux avalanches resulting from the onset of a thermomagnetic instability in MgB_2 [4–8], strongly challenges the use of this material in practical applications. Avalanche events can critically impact the performance of the device by causing sudden changes in the material resistance and current flow. Clearly, thermomagnetic instability is not an intrinsic characteristic of the MgB_2 material. For instance, while most MgB_2 films display the instability, some exclusive ultrapure MgB_2 films did not exhibit dendritic avalanches [9, 10]. In addition, external parameters such as the magnetic field and the sample temperature may affect the stability. Therefore, all these factors should be considered in applying MgB_2 films in practical devices.

Previous studies of MgB_2 films have characterized the thermomagnetic instability in terms of a threshold magnetic field, B_{th}, for the onset of the avalanche activity. Those studies showed that as function of temperature, T, the threshold $B_{th}(T)$ increases up to $T \sim 10$ K, above which the instability stops nucleating [5–7]. This increases the interest for implementing MgB_2 devices using liquid hydrogen as coolant [11–13]. In the present work we show that MgB_2 films exposed to sufficiently rapid field variations can indeed result in nucleation and full development of thermomagnetic avalanches even above liquid hydrogen temperature.

An MgB_2 film was e-beam evaporated on an r-cut Al_2O_3 substrate by sequential deposition of magnesium and boron layers, and subsequent annealing [14, 15]. The film thickness was 300 nm and its superconducting transition temperature was $\sim$35 K. The lateral dimensions of the sample were 5×5 mm^2, suitable for measurements in both our custom-made magneto-optical imaging (MOI) system [16], and a 5 T Quantum Design MPMS magnetometer. The MOI system is capable of recording images at rates up to 70 000 frames per second, allowing exploration of flux dynamics in the superconducting films down to a time scale of 15 μs. In addition,

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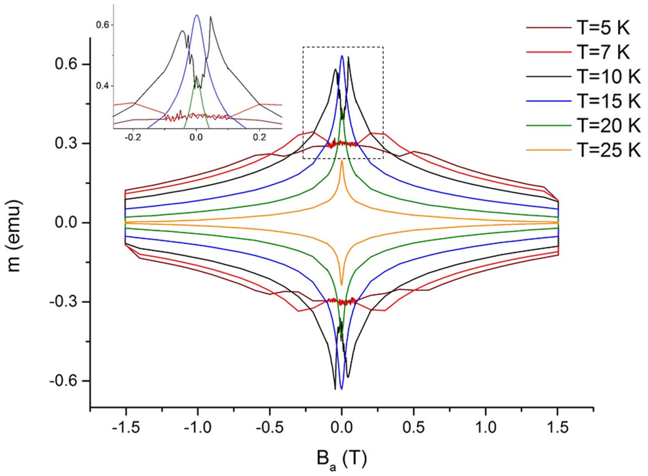

Figure 1. Magnetization curves of the MgB_2 film after initial zero-field-cooling of the sample to the indicated temperatures. The inset zooms in on the strong fluctuations taking place between 5 and 10 K in the field range of ± 0.1 T.

the system provides slow and high-field ramping rates, 2–20 mT s^{-1} and 0.1–3 kT s^{-1}, respectively, with a maximum applied field of 60 mT. The effective field ramping rate in the MPMS is 1–10 mT s^{-1}.

The film was characterized magnetically at 'conventional' slow rates, measuring its magnetization as a function of temperature and applied perpendicular field, B_a, using the MPMS magnetometer. Figure 1 shows the magnetization-versus-field loops measured between -1.5 T and 1.5 T at temperatures from 5 to 25 K. The width of the loops, being proportional to the critical current density, J_c, is expected to become wider as the temperature decreases. This is indeed the case for the higher temperature loops. However, below 10 K the behavior changes, as strong fluctuations together with dramatic reduction of the central peak are apparent in the magnetization curves. Similar results for the temperature dependence of the magnetization in MgB_2 films were reported previously [5, 9]. Note that in all these magnetic measurements the field is ramped at relatively slow rates, typically 1–10 mT s^{-1}.

A more detailed view of the magnetic behavior below 10 K is shown in the MOI pictures of figure 2. They were recorded after zero-field-cooling (ZFC) the sample to 7 K before an external field, B_a, was ramped up from zero to 60 mT at the 'slow' rate of 2 mT s^{-1}. The images in panels (a) and (b) capture the local induction at the fields of $B_a = 5$ mT and 20 mT, respectively, and show the frozen traces of the dendritic flux avalanches, similar to those found in other MgB_2 films [4–8]. These numerous avalanche events are responsible for the noise-like features present at low fields in the magnetization curves of figure 1.

To characterize the stability of the film in terms of the threshold field, B_{th}, i.e., the field applied when the first dendrite appears, a series of MO images were recorded after ZFC the sample to different temperatures, and then applying a perpendicular field at the rate 2 mT s^{-1}. The measured temperature dependence of B_{th} is displayed in figure 3, and resembles data reported previously for MgB_2 films [5–7].

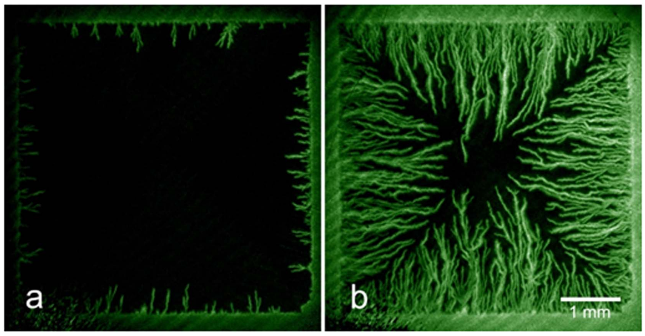

Figure 2. Magneto-optical images of the MgB_2 film after zero-field-cooling to 7 K and applying a gradually increasing field at a rate of 2 mT s^{-1}. The images in (a) and (b) show the flux penetration when the applied field reached 5 mT and 20 mT, respectively.

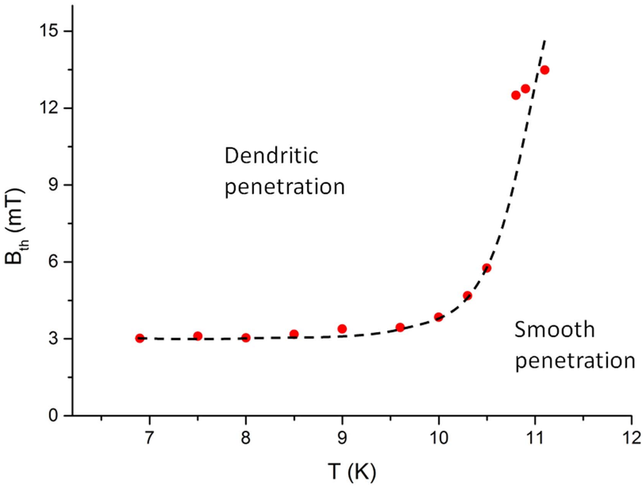

Figure 3. The threshold field, B_{th}, of the MgB_2 film as a function of sample temperature when a perpendicular field was ramped up at the rate of 2 mT s^{-1}. The dotted line is a guide to the eye. The film is stable at the conditions below this line.

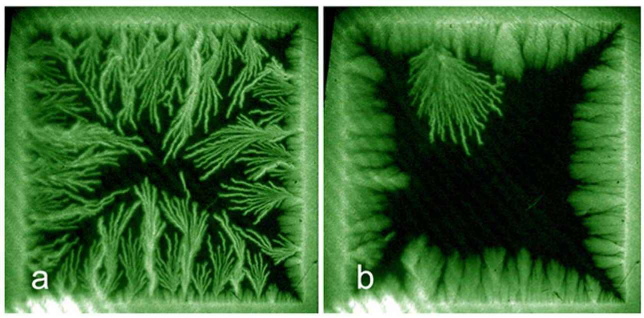

Figure 4. Flux penetration in the MgB_2 film exposed to magnetic field of 20 mT applied by using ramp rates of (a) 2700 T s^{-1}, and (b) 48 T s^{-1}. In both cases the sample was initially cooled to 12.5 K in zero magnetic field.

Consider now the behavior observed when exposing the same film to much faster ramp rates. Figure 4 shows magneto-optical images recorded in two consecutive experiments. In both, the film was first zero-field-cooled to 12.5 K, a

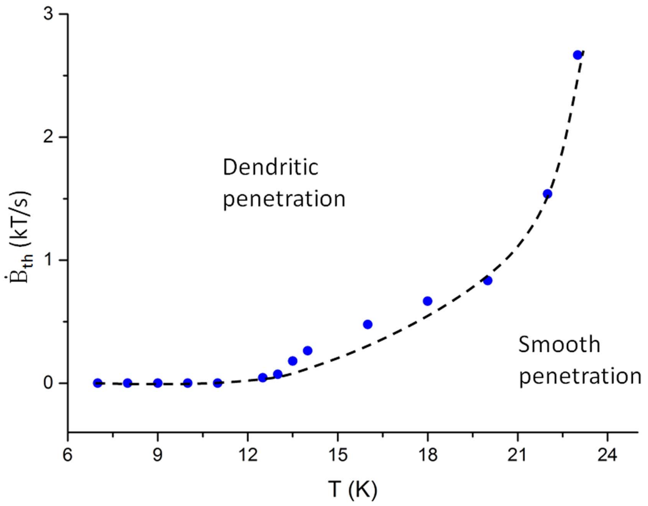

Figure 5. Temperature dependence of the threshold ramp rate, $\dot{B}_{th}$, of the MgB_2 film. The dotted line is guide to the eye. The film is stable below this line.

temperature where the 2 mT s^{-1} ramp rate created only smooth regular flux penetration. The applied field was then increased to 20 mT at the high rates of 2700 T s^{-1} (left panel) and 48 T s^{-1} (right panel). Evidently, both these field variations triggered avalanche activity. Moreover, one clearly sees that the higher the ramp rate, the more numerous are the avalanche events.

Based on such experiments we find that for a given temperature there exists a field ramp rate above which the MgB_2 film becomes thermomagnetically unstable. To determine this threshold value as a function of temperature, the sample was repeatedly zero-field-cooled to a target temperature, and then an external field of $B_a = 20$ mT was applied at different ramp rates. This B_a value was chosen because it results in a quasistatic flux penetration extending a sizable 70% into the sample at the temperature of $T_c/2$.

For each target temperature, the smallest field ramp rate generating avalanches was defined as the threshold value $\dot{B}_{th}$. As the temperature increased it was found that also the threshold ramp rate increased. Eventually, at 23 K the system reached its maximal rate capability for 20 mT ($\dot{B}_{th} = 2.7$ kT s^{-1}). Presented in figure 5 is a graph of the measured ramp rate threshold plotted as function of temperature.

The present results show that the ramping rate of the applied perpendicular magnetic field is a key parameter determining the nucleation of thermomagnetic avalanches in films of MgB_2. From previous work on the avalanche activity in MgB_2 films, one got the impression that a fixed temperature (~10 K) divides states where dendritic avalanches would nucleate, and states that were thermomagnetically stable when perpendicular magnetic fields were applied. Here we have shown that the stability diagram has another dimension, namely, the ramp rate, $\dot{B}_{th}$, of the perpendicular field experienced by the superconducting film. By systematically varying the ramp rate we have here shown that dendritic avalanches can occur in MgB_2 films at temperatures up to 23 K. Presumably, the 23 K temperature limit is only restricted by the maximal field ramp rate of our experimental equipment.

The observed monotonic increase of the threshold ramp rate with temperature is similar to that reported for YBCO [17], and it agrees also qualitatively with theoretical predictions [18, 19]. These theories propose that the dendritic instability is controlled by the magnetic flux diffusion coupled to the thermal diffusion in the sample. At high temperatures, as the sample becomes more susceptible to flux entry, faster application of the external field is required to obtain sufficient heat and trigger the instability [17].

Different stability diagrams are clearly expected for different film's material and also for films of the same material but with different parameters such as the film thickness [20, 21], its lateral dimensions [6] and substrate [22]. In addition, it has been demonstrated that metal layer on top of the superconductor help to avoid instability occurrence [23–25], however it may not be efficient in screening magnetic flux changes at fast rates. Obviously, natural and artificial defects may also affect the stable diagram [26]. In applying MgB_2 in practical devices it is desirable to maximize the stability region by considering all these parameters.

There is at present a significant interest in devices based on MgB_2 used in an environment cooled by liquid hydrogen at 20 K [11–13]. This interest has motivated investigation of the stability limits in transient situations. Our results are the first to establish that regular MgB_2 films may be unstable above liquid hydrogen temperature. While our work focuses on field transients, Bobyl *et al* [27] studied the effect of transient currents, also showing that the threshold temperature could be pushed up (to ~19 K), although in that work it required a sample in the critical state. It should also be mentioned that a recent theoretical work [28] emphasizes the enhancement of the thermomagnetic instability by AC magnetic fields. Also note that some ultrapure MgB_2 films, grown with the hybrid physical-chemical vapor deposition method [9, 10], do not produce dendrites, even at our very fast ramp rates [17, 29]. As suggested in our recent study [17], the flux flow resistivity, ρ_F, is the key parameter in the stability of the film against avalanches. As the ultrapure films have much lower ρ_F, they are more stable. Thus, the stability of a sample is not an intrinsic characteristic and must be studied for each sample separately. This fact encourages further investigation into material parameters and conditions determining dendritic instability in MgB_2 films.

In summary, in this work we have used MOI to determine the temperature dependence of the thresholds in applied perpendicular magnetic field, B_a, and its ramp rate, $\dot{B}_a$, delineating boundaries between thermomagnetic stability and instability of a superconducting MgB_2 film. The two thresholds were found to have strong similarities by (i) showing very little variation with temperature up to 9.5 K and 11 K for B_a and $\dot{B}_a$, respectively. And (ii), above these temperatures the thresholds in B_a and $\dot{B}_a$ both display a dramatic increase. Of particular importance is the finding that films of MgB_2 can become unstable at temperatures as high as 23 K provided that the field ramp rate is sufficiently large, i.e., 2.7 kT s^{-1} or more. This implies that the range of external conditions where dramatic avalanche activity occurs in MgB_2 is much wider than previously known. In particular, it means that MgB_2 films can become unstable even above the hydrogen liquid–gas transition temperature.

It is also important to point out that the boundary between the stable and unstable states is not an intrinsic material characteristic. In fact, we expect it to depend on various parameters such as the flux flow resistivity of the film, the lateral size of the film, its geometrical shape, the film thickness and its substrate. All these factors should be taken into account in the design of future devices based on MgB_2 films exposed to rapid changes in the magnetic field.

Acknowledgments

The authors thank Dr Claudia Stahl, Max-Planck Institute for Intelligent Systems, Stuttgart, for the preparetion of the MgB_2 film, and Assoc. Professor Jørn Inge Vestgården, University of Oslo, for important discussions. We also acknowledge a financial support from the Israel Science Foundation (ISF-164/12) and the Norwegian Research Council.

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