Reentrant stability of superconducting films

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We propose a mechanism responsible for the abrupt vanishing of the dendritic flux instability found in many superconducting films when an increasing magnetic field is applied. The onset of flux avalanches and the subsequent reentrance of stability in NbN films was investigated using magneto-optical imaging, and the threshold fields were measured as functions of critical current density, $j_c$. The results are explained with excellent quantitative agreement by a thermomagnetic model published recently, Phys. Rev. B 73, 014512 (2006), showing that the reentrant stability is a direct consequence of a monotonously decreasing $j_c$ versus field.

In most superconductors a slow increase of external magnetic field is accompanied by a gradual penetration of magnetic vortices, which make their way into the sample through a random energy landscape created by structural irregularities. This results in formation of a critical state characterized by a critical gradient of the vortex density corresponding to the maximum lossless current in the superconductor. The critical state, however, is metastable and can be destroyed by flux jumps where large-scale redistribution of the vortices suddenly takes place. Such dramatic events, observed experimentally as abrupt drops in the magnetization, are due to a thermomagnetic instability where the local dissipation associated with vortex motion reduces the pinning, which in turn facilitate further motion. With this positive feedback a small perturbation can quickly evolve into a flux avalanche of sample spanning dimensions.

In recent years, space-resolved measurements, in particular using magneto-optical imaging (MOI), have revealed the detailed morphology of flux avalanches. Most work was carried out on superconducting thin films of MgB$_2$, Nb, Pb, Nb$_3$Sn, NbN, YBa$_2$Cu$_3$O$_y$, and YNi$_2$B$_2$C, where the images show that a typical flux avalanche in superconducting films has a branched dendritic structure with 50-100 micron wide branches. While each avalanche event has only local impact, they occur very frequently, i.e., with very small applied field intervals, and therefore manifest in magnetization versus field curves as a strong noisy component.

These magnetization curves display also two other generic features, namely the existence of a threshold field for the onset of avalanche activity, typically at a few millitesla, and an upper threshold field above which the superconductor regains full stability. In a recent Letter we reported a detailed study of the lower threshold, and explained key features of the instability onset. The important question why superconducting films suddenly become stable again at high fields remains open, and is the focus of the present work. We report here experiments carried out on films of superconducting NbN, and discuss the results within the theoretical framework of a recently proposed thermo-magnetic model. The reentrant stability is explained by accounting for the field dependence of the critical current density.

Superconducting films of NbN were prepared on single crystal (100) MgO substrates by pulsed laser ablation of a high purity Nb target in a controlled ultra high purity (99.9996) N$_2$ environment. A KrF excimer laser (248 nm) operated at 20 Hz was used for ablation with pulse energy density of 5 J/cm$^2$ on the target surface. Detailed procedures and structural characterization of the samples, which are superconducting below $T_c = 15$ K, is found in Ref. 21. The films have a thickness of $d = 280$ nm, and were lithographically patterned into a rectangular shape 2.4 mm wide and 4.8 mm long using reactive ion etching in a CHF$_3$ + O$_2$ plasma.

Flux penetration into the samples was investigated using a MOI method based on the Faraday effect in an in-plane magnetized bismuth-substituted ferrite garnet sensor film, that was placed on top of the NbN film. The sample was mounted on the cold finger of a continuous He-flow cryostat (Microstat, Oxford), which in turn was placed under the objective lens of a reflected light polarizing microscope (Leica). A variable magnetic field was applied perpendicular to the sample using a pair of resistive coils. The microscope was equipped with a mercury lamp, and by using crossed polarizers the resulting image brightness represents the local magnitude of the perpendicular flux density.

Shown in Fig. 1 is a set of images recorded during a slow ramping up of the applied magnetic field, $H$, after...
FIG. 1: Magneto-optical images of a NbN film (only left half of the sample area is shown) at 4 K in increasing applied field. The left edge of the sample, seen as a vertical line of enhanced brightness, is 2.4 mm long. The images were contrast enhanced individually.

the sample was initially zero-field cooled to \( T = 4 \) K. In image (a), taken at \( H = 8 \) Oe, there is only a shallow penetration, with a flux front that moved gradually inwards as the field increased. This smooth mode of penetration ended abruptly when reaching \( H = 12 \) Oe, where a flux avalanche suddenly occurred. The avalanche area is seen in Fig. 1 taken at 12 Oe as the branching structure rooted on the lower sample edge. As the applied field increased further, more and more avalanches took place, creating a complex pattern of flux dendrites covering most of the sample area, see Fig. 1 at \( H = 400 \) Oe and 425 Oe, and the critical state mode of flux penetration was restored. The bright fan-like features in the lower part of the images are due to tiny film defects, and are not related to the flux instability.

FIG. 2: Schematic plot illustrating the existence of two threshold fields for the dendritic instability. The two main curves represent the threshold field \( H^\text{th} \) versus \( j_c \) according to Eqs. (1) and (2), and a typical monotonous field dependence of the critical current density. The intersection of the two curves defines the two thresholds \( H^\text{th}_1 \) and \( H^\text{th}_2 \) for the onset and vanishing of the instability.

This experiment gives direct evidence that there exists an upper threshold field for the dendritic instability, in agreement with earlier measurements on various superconducting films.\[3, 12, 15, 16\] Before presenting more results, we give first a qualitative argument for why reentrant stability can follow from the thermo-magnetic model proposed in Ref. \[20\]. The theory predicts that a superconducting thin strip of half-width \( w \) becomes unstable when the flux penetration depth exceeds

\[
\ell^* = \frac{\pi}{2} \sqrt{\frac{\kappa T^*}{j_c E}} \left( 1 - \frac{2h_0 T^*}{n d j_c E} \right)^{-1},
\]

provided that \( \ell^* < w \). Here, \( j_c \) is the critical current density, \( T^* \equiv - (\partial \ln j_c / \partial T)^{-1} \), \( E \) is the electric field, \( \kappa \) is the thermal conductivity, and \( h_0 \) is the coefficient of heat transfer from the superconducting film 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 instability onset field can be obtained from \( \ell^* \) using the Bean model relation between the penetration depth and applied field,\[26\]

\[
H^\text{th} = \frac{j_c d}{\pi} \arccosh \left( \frac{w}{w - \ell^*} \right).
\]

It follows from Eqs. (1) and (2) that the threshold field depends strongly on the critical current density, more specifically according to the graph marked \( H^\text{th}(j_c) \) in Fig. 2. For intermediate \( j_c \) the threshold field is nearly constant, and increases slowly as \( j_c \) becomes larger giving eventually a sublinear asymptotic dependence, \( H^\text{th} \sim j_c^{3/4} \). More importantly, when \( j_c \) decreases the threshold
field will diverge at some finite $j_c$, corresponding to $\ell^*(j_c)$ approaching $w$. Taking now into account that the critical current density most commonly decreases with the field, typically as the $j_c(B)$ curve in Fig. [2] it follows that the field range with unstable behavior can indeed have both a lower and upper limit, $H_{1}^{th}$ and $H_{2}^{th}$, as indicated in the figure. Evidently, it is essential in this picture how fast $j_c$ is decreasing with the field. E.g., in the Bean model (constant $j_c$), or with a $j_c$ having only weak field dependence, the conditions for having an upper threshold will never be met. Note also that if $j_c$ is sufficiently small, e.g., because of a larger temperature, the thermomagnetic avalanches will not occur at any magnetic field.

To obtain quantitative support for this explanation we performed MOI of flux penetration after first cooling the sample to 4 K in various constant magnetic fields, $H_{fc}$. This allowed measurement of the field dependence of both $j_c$ and the two instability threshold fields. Cooling fields up to 300 Oe were applied, and MOI did not detect any contrast, which implies that the full flux density $H_{fc}$ was frozen into the sample. To measure $j_c$ a small additional field was subsequently applied, creating a critical state type of penetration of the new flux. [27] From the depth of the penetration front in the middle section of the rectangular sample the $j_c$ was determined, [26] and Fig. [3] shows its dependence on the cooling field. A nearly exponential decay was found, with $j_c$ decreasing from $7.6 \times 10^{10}$ Am$^{-2}$ at zero field to almost one half at $H_{fc} = 300$ Oe. This agrees well with the results obtained earlier from ac susceptibility measurements [21] on the same type of films.

The threshold fields were determined by slowly ramping up the additional field after an initial field-cooling. The values of the total applied field when the first and last flux dendrite appeared were recorded for various $H_{fc}$, giving the result shown in Fig. [4] The onset field increases almost linearly, and with some upward curvature, whereas the upper threshold field remains essentially constant until the two thresholds eventually merge into one when $H_{fc} = 300$ Oe. For larger cooling fields, i.e., for smaller $j_c$’s, the instability was found to be fully suppressed.

To demonstrate that these data are in excellent agreement with the scenario depicted in Fig. [2] we note first that the applied field which induces shielding currents in the sample, and triggers the first avalanche, is $\Delta H = H_{1}^{th} - H_{fc}$. Thus, in the presence of a cooling field, the curve representing the $H^{th}(j_c)$ in Fig. [2] should be shifted upwards by the amount $H_{fc}$, while the $j_c(B)$ curve remains as is. Then, as $H_{fc}$ becomes larger the distance between the two intersection points of the curves becomes gradually smaller, and at some cooling field the two thresholds become one, just like in the experiments. To show the agreement quantitatively, the data for the lower threshold field are replotted in Fig. [5] as $\Delta H$ versus $j_c$. The full curve is a theoretical curve obtained from Eqs. [1] and [2], using two fitting parameters, $\kappa T^*/E = 343.75$ W/V and $h_0 T^*/n E = 687.5$ kW/V (which can mean, e.g., $\kappa = 5$ W/Km, $h_0 = 110$ kW/Km, $n = 11$, $E = 0.16$ V/m, $T^* = 11$ K).

In contrast to $H_{1}^{th}$, the upper threshold field $H_{2}^{th}$ was found to be essentially independent of $H_{fc}$. Even this behavior is fully consistent with our explanation illustrated by Fig. [2]. Near the intersection point determining $H_{2}^{th}$, the diverging $H^{th}(j_c)$ curve has a very steep slope. Hence, a vertical shift of $H^{th}(j_c)$ accounting for a non-zero cooling field $H_{fc}$ hardly changes the value of $H_{2}^{th}$. The robustness of the upper threshold field by being independent of the initial conditions, is actually a remarkable and unexpected result. Indeed, the flux distribution after cooling the sample in $H_{fc}$ and then ramping the field up to $H_{2}^{th}$ dramatically depends on the value of $H_{fc}$. In the zero-field cooled experiment shown in Fig. [1] one finds...
dozens of overlapping dendrites, while for \( H_{fc} = 300 \) Oe the flux distribution remains of a critical-state type until a single dendritic structure is formed at \( H_{th}^{j_c} \). Note that the exact dendritic pattern is every time different even if one repeats the experiment under the same conditions. Thus, despite the wide variety of flux distributions, the dendritic activity in all these cases vanishes at the same threshold field \( H_{th}^{j_c} \approx 350 \) Oe. Note also that the \( H_{th}^{j_c} \) curve in Fig. 4 was calculated assuming an initial critical-state flux distribution, and therefore the observed invariance of \( H_{th}^{j_c} \) suggests that the theoretical prediction is valid for a much broader set of initial magnetic states.

The present thermomagnetic scenario, and in particular the \( H_{th}^{j_c} \) dependence shown in Fig. 4 has very recently received even further support from MOI studies of MgB\(_2\) films grown on vicinal substrates giving a slight anisotropy in the critical current.\[23\] The observed dramatic anisotropy in the direction of dendritic avalanches was fully explained by the very steep slope of the \( H_{th}^{j_c} \) curve.

In conclusion, the dendritic flux instability, which is a serious threat to superconducting devices based on thin films, was investigated to understand mechanisms that allow the films to recover stability. We explained reentrant stability in the framework of a thermo-magnetic model,\[20\] and demonstrated by a quantitative agreement of the theory with experimental results, that it stems from the field dependence of the critical current.

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to suppress the instability. [23, 24]