Kinetic roughening of magnetic flux penetration in MgB2 thin films

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Abstract
Time-resolved magneto-optical studies are performed on MgB$_2$ thin film samples grown by in situ pulsed laser deposition and in situ reactive deposition technique. The latter reveal dendritic avalanche-free flux penetration. The kinetic roughening of magnetic flux penetration is studied for applied ac current. Dynamic scaling laws determined for both static field and ac current are consistent with the directed percolation depinning model, placing the vortex dynamics in MgB$_2$ in the same universality class as YBCO and Nb.

Keywords
Kinetic, roughening, magnetic, flux, penetration, MgB$_2$, thin, films

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MgB\(_2\) offers several advantages for superconducting applications over both the high-temperature superconducting cuprates and the more traditional Nb-based alloys. Despite its low critical temperature \(T_c=39\) K, less than one-third the record \(T_c=134\) K attained in mercury-based cuprates, MgB\(_2\) has larger coherence lengths, a lower anisotropy,\(^1\) transparency of the grain boundaries to current flow,\(^2\) light weight, and low cost. These characteristics make MgB\(_2\) a suitable and attractive candidate for applications such as power-transmission cables, transformers, motors, generators, current leads, and high-field magnets at temperatures above 20 K where NbTi and Nb\(_3\)Sn cannot be used. Furthermore, rapid single flux quantum logic MgB\(_2\)-based integrated circuits promise a higher operating temperature and a higher device speed than the present Nb-based technology.\(^3\) However, MgB\(_2\)-based applications are hindered by the problem of pronounced instabilities in the magnetic flux penetration, which endanger electronic devices and lead to energy dissipation. Instabilities in MgB\(_2\) appear as fingerlike structures, flux jumps, or dendritic patterns, which penetrate the material within nanoseconds.\(^4\) The instabilities are sensitive to both the internal structure of the superconducting film and to the external applied fields or currents. For instance, the dendritic instability disappears above threshold values of temperature,\(^5\) applied magnetic field,\(^6\) and also for sufficiently small sample dimensions,\(^7\) but experiments in MgB\(_2\) thin films showed that they can be triggered by short current pulses.\(^8\) A recent thermomagnetic model predicts that the sample related parameters such as pinning strength, thermal conductivity, thickness, and thermal exchange between the film and the substrate control the onset of the dendritic instability in MgB\(_2\) and in type-II superconductors.\(^7,9\) To what extent it is possible to control the flux instabilities triggered by rapidly varying fields and/or currents is an important and yet open question and a key issue for the successful realization of MgB\(_2\)-based commercial devices.

In this letter, we show how ac currents affect the flux penetration in MgB\(_2\) thin film samples. We first compare the flux behavior of MgB\(_2\) thin films grown by in situ pulsed laser deposition (PLD) technique\(^10\) and by a recently developed in situ reactive deposition\(^11\) (RD) technique. Surprisingly, we do not observe any dendritic instability for the RD samples. In addition, we study the kinetic roughening of the penetrating flux front employing the dynamic scaling concepts used in the studies of interface roughening of stochastic systems. We investigate two distinct cases: (i) a static magnetic field is applied to the sample and (ii) a static field plus an ac current are present simultaneously. We found that the scaling laws determined in both cases are consistent with the directed percolation depinning model, placing the vortex dynamics in MgB\(_2\) in the same universality class as YBCO and Nb. © 2007 American Institute of Physics.

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sample than the flux front. At a temperature above 9 K, the flux penetrates more homogeneously into the sample revealing an onset temperature for the dendritic flux avalanches in the PLD samples between 9 and 10 K. In the RD sample [Fig. 1(c)] instead, the flux also penetrates more homogeneously at \( T=5 \) K but deeper than the flux front of the PLD sample and forms fingerlike structures rather than avalanches. Figures 1(b) and 1(d) show two-dimensional (2D) maps of the current density distribution obtained from the calibrated MO images using bidimensional inversion of the Biot-Savart law. Shielding currents, induced by the applied field, flow along the positive \( B \) direction close to the edges of both PLD and RD samples, but loop around the flux branches of the dendritic pattern in the PLD sample [Fig. 1(b)]. This would obstruct the flow of an additional transport current in that region in the PLD samples but not in the RD one.

We studied the flux penetration in the RD sample, in the static case, when a static magnetic field is applied [Fig. 2(a)], and in the dynamic case, when a static field plus an ac current are applied simultaneously [Fig. 2(b)]. The corresponding flux front functions \( h(x) \) (red line) were extracted from the calibrated images as contour lines of the flux where the field intensity approaches zero. The fingerlike vortex penetration shows a self-affine structure that can be characterized via stochastic scaling laws following an approach successfully used in the study of YBCO (Ref. 15) and Nb (Ref. 16) thin films. For self-affine structures, the relevant scaling relation is given by

\[
h(x) \sim b^{-\alpha} h(bx),
\]

where the parameter \( \alpha \) is the self-affine exponent, used to quantitatively characterize the roughness of the system. The self-affine function \( h(x) \) rescales anisotropically and the factor \( b \) expands the system both horizontally, \( x \rightarrow bx \), and vertically, \( h \rightarrow bh \). The solution of Eq. (1) is a scaling law,

\[
\Delta(l) \sim l^\alpha,
\]

where \( \Delta(l) = |h(x_1) - h(x_2)| \) is the height difference between two points separated by \( l = |x_1 - x_2| \). We studied the spatial correlation of the flux front in MgB\(_2\) by analyzing the two point correlation function,

\[
C(l) = \langle [h(x + l) - h(x)]^2 \rangle_x,
\]

where \( \langle \cdots \rangle_x \) is the average over the sample length. The two point correlation function scales with the following relation:

\[
C(l) \sim l^\beta.
\]

The analysis of the correlation function for both the static [Fig. 3(a)] and the dynamic [Fig. 3(b)] cases reveals a power law behavior over \( \sim 2 \) decades, indicating universal self-organized criticality in the vortex system of MgB\(_2\). In the static case, an average roughness \( \alpha = 0.58 \pm 0.09 \) is obtained for different values of the applied field. The application of an ac transport current of only a few percent of the critical current \( I_0 \leq 0.5 \) A leads to a relaxation of the flux, which penetrates deeper into the sample Fig. 2(b). In this dynamic case, a distinct increase in the average exponent of the power law value \( \alpha = 0.77 \pm 0.12 \) reveals a roughening of the flux front. Both values are consistent within 10% uncertainty with the expectations of the directed percolation depinning (DPD) model that predicts a roughening value of \( \alpha = 0.63 \) for mainly pinned interfaces and \( \alpha = 0.75 \) for interfaces moving in the critical regime. In this scenario, the scaling laws directly reflect the competition between the vortex-vortex interaction and the vortex pinning by disordered and randomly distributed defects, leading to pinned or moving regimes depending...
results critical state show self-affine structure characterized by universal exponents. The exponents in the static case and in the dynamic case are different, revealing different scaling regimes both compatible with the DPD process. This result suggests that the flux penetration in MgB$_2$ thin film samples carries the fingerprints of self-organized criticality and belongs to the same universality class of YBCO and Nb. The dynamic scaling approach offers an effective way to study flux penetration in MgB$_2$ thin films and to understand to what extent sample properties can be tuned to obtain instability-tolerant MgB$_2$-based applications.
