2007

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Abstract

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Keywords

Kinetic, roughening, magnetic, flux, penetration, MgB2, thin, films

Disciplines

Engineering | Physical Sciences and Mathematics

Publication Details

Lucarelli, A, Hummert, S, Chaney, A, Lupke, G, Moeckly, B, Zhao, Y & Dou, SX (2007), Kinetic roughening of magnetic flux penetration in MgB2 thin films, Applied Physics Letters, 91(22), pp. 222505-1-222505-3.

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Kinetic roughening of magnetic flux penetration in MgB_2 thin films

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(Received 25 September 2007; accepted 30 October 2007; published online 30 November 2007)

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. © *2007 American Institute of Physics*.
[DOI: 10.1063/1.2815937]

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_3Sn 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 of YBCO and Nb.

Nanocrystalline MgB_2 films 400–600 nm thick were grown by PLD on single crystalline Al_2O_3–R substrates from a stoichiometric MgB_2 target using a two step *in situ* process.[12] The samples have typical dimensions of $2\times 6\ mm^2$, a critical current density of $J_c=2\times 10^6\ A/cm^2$ at 20 K and a $T_c=34$ K. RD epitaxial MgB_2 films of 500 nm thickness also were grown on single crystalline Al_2O_3–R substrates, using a single step *in situ* process.[11] The RD samples were cut to dimensions of $2\times 10\ mm^2$. These samples show a higher critical temperature $T_c=39$ K and also a higher critical current density $J_c=1\times 10^6\ A/cm^2$ at 36 K with respect to the PLD samples.[11] Furthermore, the RD technique produces broad homogeneous MgB_2 films on different substrates which are highly tolerant to moisture or water contact.

Samples are first zero-field cooled down to $T=5$ K, then a magnetic field B_a is applied perpendicular to the surface of the film and in the last step, we apply an ac current $I_a=I_0\sin(\omega t+\phi)$ with $\omega=400$ Hz to the sample. Time-resolved magneto-optical (MO) images are collected using a custom designed imaging setup based on a polarizing microscope and a pulsed laser light source synchronized with an ac current power source.[13]

Flux avalanches forming dendritic pattern start to nucleate at the edge of the PLD samples [Fig. 1(a)] for an applied field larger than 4 mT, and propagate much further inside the

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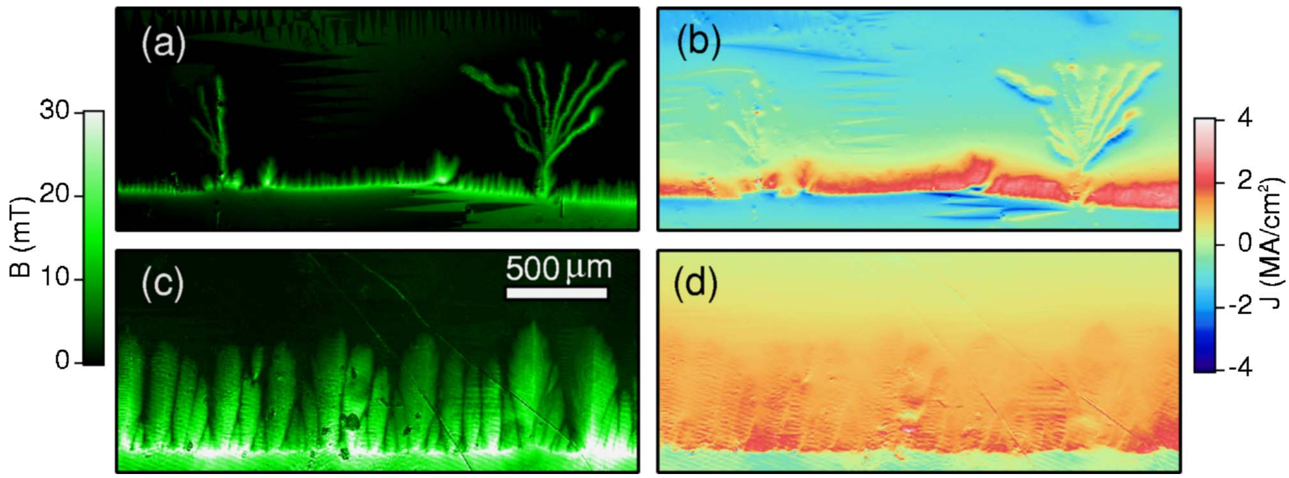

FIG. 1. (Color online) (a), (c) Magneto-optical images and (b), (d) current density 2D maps at T=5 K for an applied magnetic field of 10 mT of MgB_2 samples grown by PLD and RD, respectively.

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[13] using bidimensional inversion of the Biot-Savart law.[14] Shielding currents, induced by the applied field, flow along the positive x 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[17]

$$h(x) \sim b^{-\alpha} h(bx), \quad (1)$$

where the parameter α 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, $h \rightarrow b^{\alpha} h$. The solution of Eq. (1) is a scaling law,

$$\Delta(l) \sim l^{\alpha}, \quad (2)$$

where $\Delta(l) \equiv |h(x_1) - h(x_2)|$ is the height difference between two points separated by $l \equiv |x_1 - x_2|$.[17,18] We studied the spatial correlation of the flux front in MgB_2 by analyzing the two point correlation function,

$$C(l) \equiv \sqrt{\langle [h(x+l) - h(x)]^2 \rangle_x}, \quad (3)$$

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

$$C(l) \sim l^{\alpha}. \quad (4)$$

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 ~2 decades, indicating universal self-organized criticality in the vortex system of MgB_2. In the static case, an average roughness α=0.58±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 $I_0 \leqslant 0.5$ 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 α=0.77±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 α=0.63 for mainly pinned interfaces and α=0.75 for interfaces moving in the critical regime.[16–18] 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

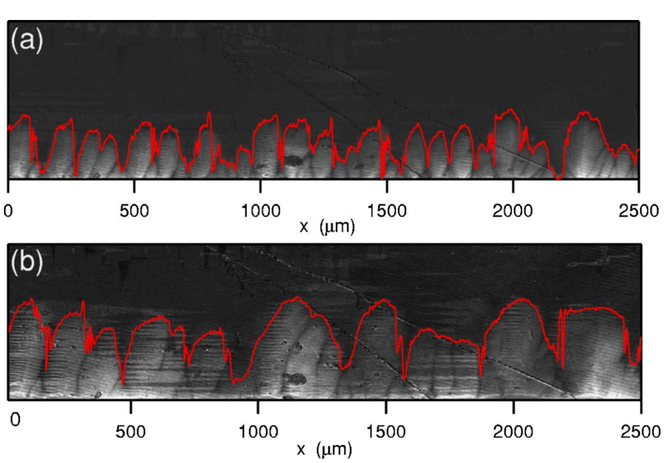

FIG. 2. (Color online) MO images and flux fronts (red line) of the RD sample with a static field of B=10 mT (a) and with additional ac transport current (b).

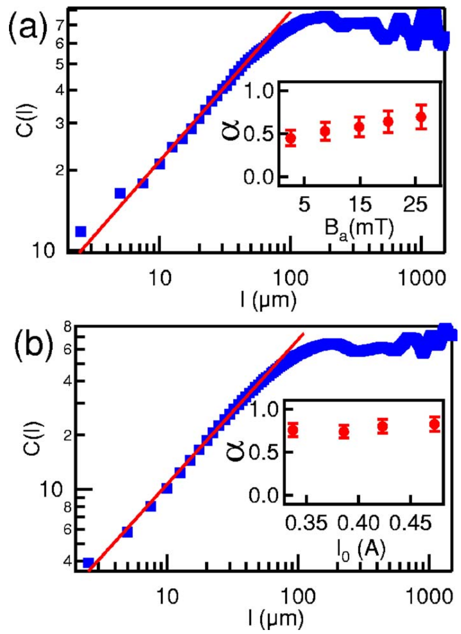

FIG. 3. (Color online) Correlation function for the static application of a magnetic field B_a=20 mT (a) and with an applied ac current I_0=0.4 A (b) The insets show the roughness coefficient α calculated for different values of the applied field (a) and current (b).

on the intensity of the driving Lorentz force due to the applied ac current. According to the critical-state model, the depinning of the vortices generally happens when the local value of the applied current is higher than J_c. In our measurements, we keep the temperature constant at T=5 K, but we cannot exclude rapid local variations in the temperature that would effectively lower the local pinning potential and reduce J_c. However, the temperature rise would result in a smoother flux front and in a lower roughness exponent α.

In summary, we observed a marked difference in the penetration of magnetic flux in superconducting MgB_2 thin films grown by PLD and by RD techniques. We studied the kinetic roughening of penetrating flux front in RD samples using the dynamic scaling concepts of interface roughening in stochastic systems for an applied static field and for a static field plus ac current. We found that in both cases, the resulting 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.

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