PHYSICAL REVIEW B **67**, 224510 (2003)

# Vortex avalanches in a Pb film with a square antidot array

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(Received 2 August 2002; revised manuscript received 18 February 2003; published 17 June 2003)

We have performed magnetization measurements on a Pb thin film perforated by a square array of antidots in a broad temperature range. For temperatures below 6 K, we observe magnetization jumps at low fields. In the film with the antidot lattice, the region in the field-temperature plane, where the jumps are observed, is substantially enlarged but the relative jump size is smaller compared to a reference film without any nanostructuring. Also, the width of the magnetization loops for the perforated film is much smaller than that for the plain film at very low temperatures. These results can be understood by taking into account the existence of a multiterrace critical state induced by the antidot array. The size distributions of the magnetization jumps do not follow the power-law decay expected in the case of self-organized criticality.

DOI: 10.1103/PhysRevB.67.224510 PACS number(s): 74.78.Db, 81.16.Nd, 74.25.Qt

## I. INTRODUCTION

Low-$T_c$ superconducting materials have been the subject of renewed and growing attention since the first patterning of regular pinning arrays in thin films, using lithographic techniques.[1] Until now, most of the studies of these ordered arrays were performed very close to the superconducting critical temperature $T_c$, where striking phenomena were observed, including the appearance of matching peaks in the $M(H)$ loops[2] or resistivity minima[3] when the number of applied flux quanta is a multiple of the number of antidots. The behavior of these structures at lower temperatures is much less known, since only a few studies were carried out at temperatures $T \ll T_c$. It is, however, important to investigate the properties of these superconducting samples in a much broader temperature range, since films with regular pinning arrays might be used in devices such as superconducting quantum interference devices, flux transformer transistors, etc.

Many years ago, vortex avalanches giving rise to jumps in the magnetization versus field $M(H)$ loop were observed in conventional low-$T_c$ superconductors at very low temperatures.[4] Several models have been proposed to explain the appearance of vortex jumps, including the possible existence of magnetothermal instabilities[5] or self-organized criticality.[6,7] Self-organized criticality is present in a large variety of phenomena such as sand avalanches, earthquakes, evolution of species, etc. In such a model, the size distribution of events follows a broad power-law decay with an exponent between 1 and 2.5.[8] The pinning potential in superconductors should affect the avalanche size distribution.[9] More precisely, in the case of antidots, it has been proposed that the introduction of periodic pinning arrays would induce a drastic modification of the size and the amount of avalanches,[10] favoring large scale avalanches and thus reducing the exponent of the power-law decay.

Quasiperiodic jumps in magnetization loops $M(H)$ have been observed recently in Nb thin films with a regular array of magnetic dots at very low temperatures.[11,12] The jumps have been related to a possible geometric barrier effect and a redistribution of flux as vortices overcome this barrier. The goal of this work is to investigate the appearance of these jumps in a simpler system of well characterized pinning centers. We have therefore used Pb films with a square array of square antidots and compared their superconducting properties systematically to those of a reference Pb film without any nanostructuring.

## II. EXPERIMENTAL DETAILS

The Pb films were electron-beam evaporated onto liquid-nitrogen-cooled $SiO_2$ substrates with a predefined resist-dot pattern. After lift-off, they were covered with a 50-nm-thick protective layer of amorphous Ge. The samples are 58-nm thick and have a surface of $3\times3$ mm$^2$ with a square array (period $d=1.5$ $\mu$m) of antidots (size $0.5\times0.5$ $\mu$m$^2$). The first matching field for this structure is $H_1=9.2$ Oe. For comparison, a reference Pb film without any nanostructuring, but with the same lateral dimensions, was evaporated under identical conditions. Magnetization measurements were performed using a vibrating sample magnetometer with the field applied perpendicular to the film surface and a temperature stability close to 20 mK. The sweep rate was varied from 5 Oe/min up to 100 Oe/min.

## III. RESULTS

Figure 1 shows the $M(H)$ loops between 3 K and 6.5 K for the reference film [Fig. 1(a)] and for the film with a periodic array of square antidots [Fig. 1(b)] recorded at a sweep rate of 100 Oe/min. The smallest loop corresponds to the highest temperature of 6.5 K. For the plain film, the $M(H)$ loops show a monotonic decrease of $M$ as $H$ increases for 4 K $\leq T \leq 6.5$ K. Magnetization jumps in the low-field range of $M(H)$ are only observed for very low temperature, i.e., below 4 K.

In the case of the film with antidots, matching peaks in $M(H)$ are observed (not shown) down to $T=7.13$ K $=0.985T_c$, showing that the used antidots have a saturation number $n_s=1$ at this temperature.[13] At lower temperatures, the matching features smear out, thus transforming the $M(H)$ curve into a monotonically decreasing curve with $H$, as is also seen for $T=6.5$ K [Fig. 1(b), inner curve]. However, as $T$ decreases further, $T\leq6$ K, jumps in $M(H)$ appear

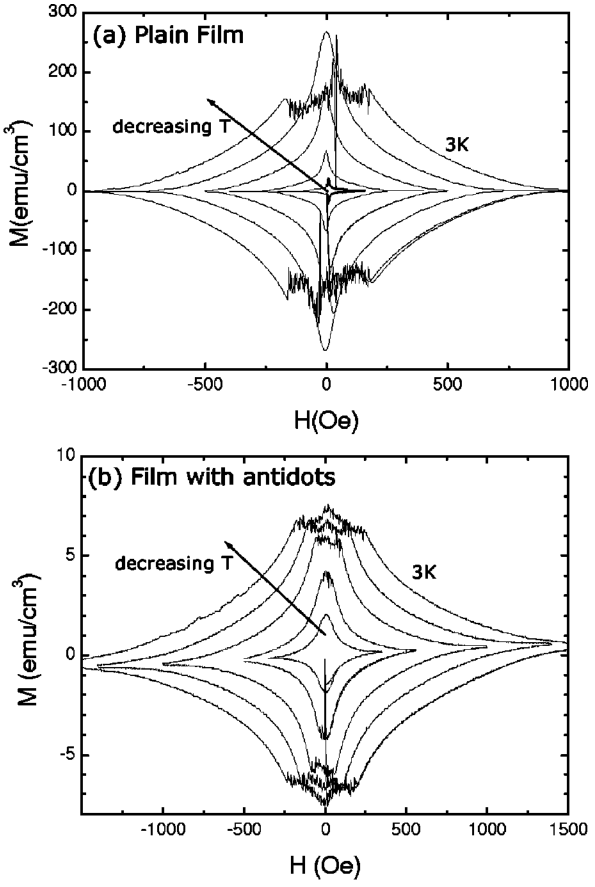

FIG. 1. $M(H)$ loops measured at 3 K, 4 K, 5 K, 6 K, and 6.5 K for (a) the plain film and for (b) the film with a square antidot array. The largest hysteresis loop corresponds to the lowest temperature of 3 K. The sweep rate is 100 Oe/min.

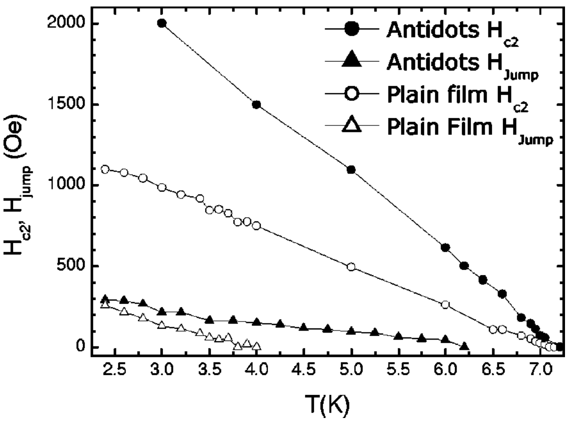

FIG. 2. Critical field $H_{c2}(T)$ and $H_{\mathrm{jump}}(T)$ determined from the $M(H)$ loops for the plain film (open symbols) and for the film with antidots (filled symbols). $H_{c2}$ is defined as the field at which the hysteresis is zero. $H_{\mathrm{jumps}}$ corresponds to the field $H$ up to which magnetization jumps are observed.

and persist down to the lowest used temperature.

We have analyzed the field ranges in which the magnetization jumps occur in the film with antidots and in the plain reference film. The results are given in an $(H,T)$ diagram in Fig. 2, where the circles represent the critical fields, and the triangles indicate the fields $H_{\mathrm{jump}}$ up to which the magnetic instabilities are observed. As expected in the case of thin films in a perpendicular magnetic field, the critical field shows a linear $H_{c2}(T)$ dependence[14], and is much larger for the film with antidots[15] (filled circles) than for the reference film (open circles). It is clearly seen that the area of the phase diagram at which jumps are observed is considerably larger for the film with antidots (filled triangles) than for the reference film (open triangles). We also note that at very low temperatures, $H_{\mathrm{jump}}$ for the film with antidots is close to 300 Oe, a value which is almost 30 times larger than the first matching field.

Figure 3 shows the low-field part of the $M(H)$ loops obtained at 3 K, this time measured with a sweep rate ten times smaller than the data presented in Fig. 1, i.e., 10 Oe/min. The size of the magnetization jumps relative to the undisturbed part of the $M(H)$ loop (for example, at 250 Oe) is considerably smaller in the film with the antidot array compared to the reference film. Moreover, the presence of the antidots reduces the jump width, i.e., the number of observed jumps is increased. Note also that at the considered temperature, the magnetization value is at least ten times larger for the plain film than for the film with antidots. This difference in magnetization is observed only at low temperatures, and the ratio $M_{\mathrm{p\ film}}/M_{\mathrm{antid}}$ decreases as $T$ increases. At temperatures close to $T_c$, the magnetization is much larger for the film with antidots, as usually observed.[16] A similar dependence of the

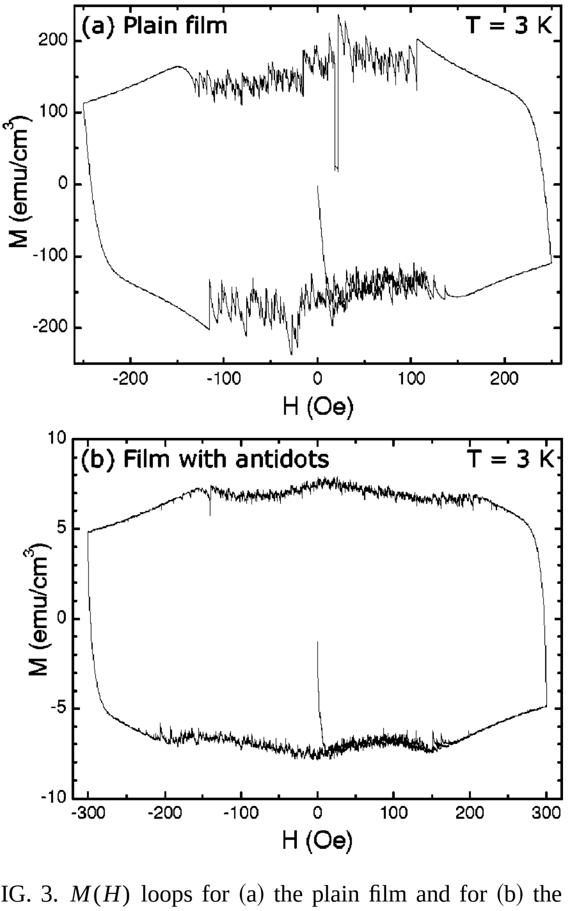

FIG. 3. $M(H)$ loops for (a) the plain film and for (b) the film with antidots, measured at 3 K with a sweep rate of 10 Oe/min.

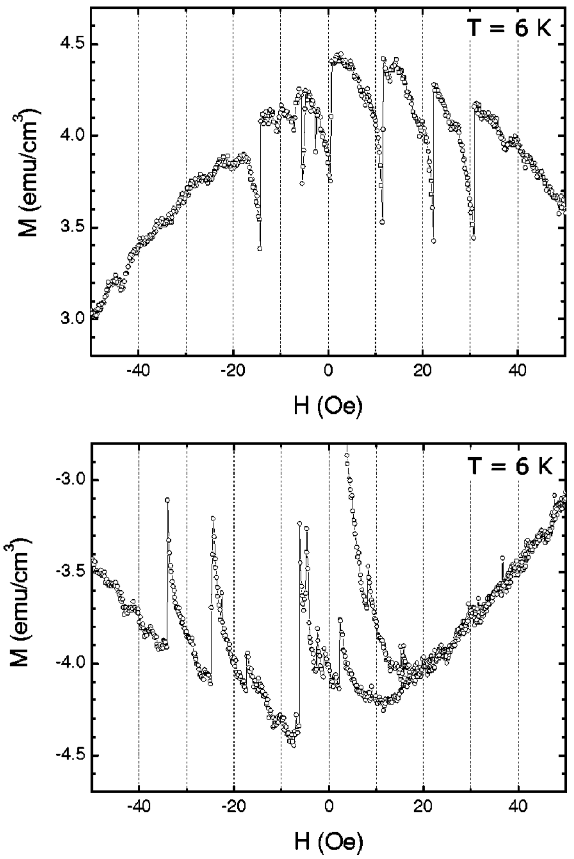

FIG. 4. Enlargement of the (lower panel) increasing and (upper panel) decreasing branches of the $M(H)$ loop of the film with the antidot array taken at 6 K with a sweep rate of 10 G/min.

magnetization value on temperature was also reported by Terentiev *et al.*[11] for the case of a Nb film with an array of Ni dots. At 3 K, no precise structure emerged from the magnetization jumps, but at 6 K, they seem to appear in a quasiperiodic manner. Figure 4 shows an enlargement of the increasing (lower panel) and decreasing (upper panel) branches of the $M(H)$ loop at 6 K, recorded with a sweep rate of 10 G/min. The magnetization jumps are observed at exactly the same fields as those in the curve taken at a higher sweep rate (100 G/min) [Fig. 1(b)], indicating that the appearance of the jumps is independent of the sweep rate. At the considered temperature, the avalanches are separated by a field interval close to the first matching field of 9.2 Oe. Each time a jump in $M(H)$ has occurred, the magnetization recovers with a slope that is exactly the same as the virgin magnetization slope recorded at very low fields [see Fig. 4(b)], in agreement with the data[11,12] for superconducting Nb films with an array of Ni dots.

Finally, a precise analysis of the jump size distributions is shown in Fig. 5 for 3 K, 4 K, 5 K, and 6 K. The size distribution does not appear to depend strongly on temperature. All distributions are less than a decade wide and the jump size is roughly $\sim 0.23$ emu/cm$^3$. Only at 6 K, the distribution is not peaked around 0.23 emu/cm$^3$ (note, however, that the statistics is very bad at 6 K, since only a few jumps are observed).

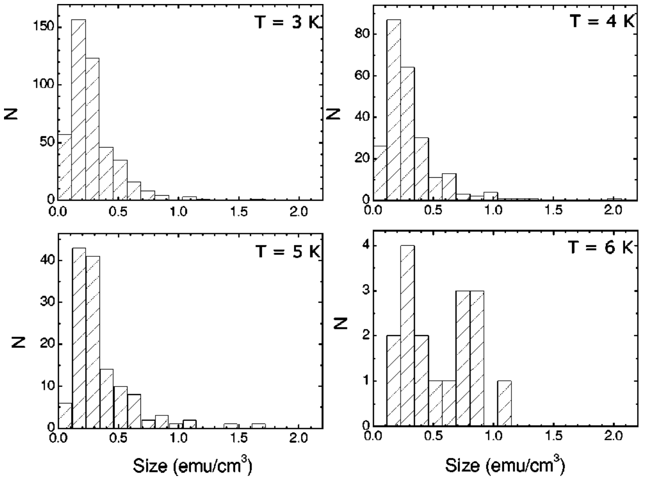

FIG. 5. Size distributions $N(size)$ of the jumps measured in the film with antidots for 3 K, 4 K, 5 K and 6 K.

## IV. DISCUSSION

Different models have been proposed to analyze the appearance and size of vortex jumps in low- and high-$T_c$ materials. A possible scenario first suggested for low-$T_c$ superconductors is that of magnetothermal instabilities,[5] which were also evidenced in high-$T_c$ materials such as $YBa_2Cu_3O_7$, in which quasiperiodic oscillations of magnetization were found simultaneously with the oscillations of the sample temperature. In this model, the size and number of oscillations strongly depend on the sweep rate of the magnetic field.[5] In the experiments described here on nanostructured Pb films, different sweep rates were used, ranging from 5 G/min to 100 G/min, but no difference in the magnetization jumps was found. Due to that, we think that in our case magnetothermal instabilities are not responsible for the appearance of the observed flux jumps.

To understand the origin of flux jumps, precise knowledge of the distribution of $B$ in the sample would be required. In type-II superconductors, the magnetic flux penetrates the sample in the form of vortices, a quantized amount of magnetic flux. The evolution of the magnetic induction in the sample has been modeled by Bean,[17] where a linear decrease of $B$ versus $x$, the distance from the surface sample, was proposed [Fig. 6(a)]. In a self-organized criticality model, there exists a critical slope of $B(x)$ above which the "sandpile" becomes unstable and avalanches can be triggered. As the slope of $B(x)$ increases when temperature decreases, the fact that avalanches are observed only at very low tempera-

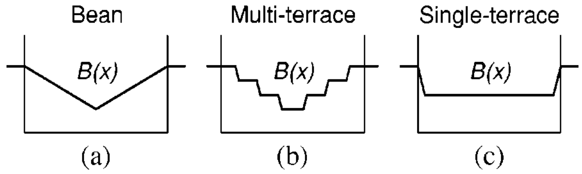

FIG. 6. Schematic presentation of the evolution of the induction $B$ versus the distance $x$ from the sample edge in the case of (a) the Bean critical state, (b) the multiterrace model (Ref. 18), and (c) the single-terrace model (Ref. 19).

tures in reference nonperforated films can easily be understood. In the case of a film with antidots, the Bean critical state model can no longer be applied since the material is perforated and therefore not homogeneous.

It was proposed by Cooley and Grishin that in this case it should be replaced by "the terraced critical state"[18] [Fig. 6(b)]. Instead of a linear decrease of $B$ versus $x$, terraces of constant $B$ (i.e., zero critical current) appear, separated by sharp borders (with high critical current). At temperatures close to $T_c$, a single-terrace critical state can be realized, as was proposed by Moshchalkov *et al.*[19] The existence of a multiterrace critical state should induce strong peaks or jumps in the $M(H)$ loops corresponding to the appearance (or disappearance) of a terrace.[18] Peaks of $M(H)$ have indeed been observed in $M(H)$ loops measured very close to $T_c$,[19] where the multiterrace state is transformed into a single-terrace state. We propose that, as the temperature decreases, the multiterrace state is preserved, but as the mean slope of $B(x)$ increases, the movement of terraces induces *jumps* rather than peaks in the $M(H)$ loops.

Although numerical simulations[20] have been performed in fields up to $28H_1$, we cannot use these data to interpret our results related to the appearance of vortex avalanches. We think that the small magnetization value obtained in the film with antidots at low temperatures should then be linked to the existence of ordered flux terraces. In the multiterrace state model, regions of very large critical current coexist with areas in which critical current density is zero, the flux terraces.[18] The global current density and the magnetization measurements will therefore be average values, much smaller than the large current at the border of the terraces.

An estimate of the terrace length $A_N$ can be calculated from the magnetization measurements:[18] $A_N \approx d j_e / j$, with $d$ the period of the antidot array, $j$ the mean current density, and $j_e$ the current density at the terrace edge. Considering that the critical current at the edges of the terraces is certainly larger than the critical current in a plain film, i.e., $j_p \geqslant j_{\mathrm{p\,film}}$, we obtain a lower limit for the terrace size, $A_N \geqslant d j_{\mathrm{p\,film}} / j$. Assuming that the ratio of the magnetization of the plain film $M_{\mathrm{p\,film}}$ and of the film with antidots $M_{\mathrm{antid}}$ is equal to the ratio of their respective critical current densities, i.e. $j_{\mathrm{p\,film}} / j_{\mathrm{antid}} = M_{\mathrm{p\,film}} / M_{\mathrm{antid}}$, this formula reads $A_N \geqslant d M_{\mathrm{p\,film}} / M_{\mathrm{antid}}$. Using the low field values of $M$ at 3 K ($M_{\mathrm{p\,film}} / M_{\mathrm{antid}} = 25$), we obtain a lower limit for the terrace length of $A_N = 0.038$ mm. The number of terraces in the 3-mm-wide sample, therefore, amounts to at most ~80. A conclusive way to determine the precise length of the terraces and of pinned domains would be to perform direct local magnetization measurements, for example, with a scanning Hall-probe microscope.[21]

As can be seen in Fig. 3, at low temperatures, the jumps have a magnitude close to 30% of $M(200\ \mathrm{Oe})$ for the plain film and of only 5%–8% for the film with antidots. This shows that due to the presence of antidots, vortex jumps occur more locally, consistent with the model that $B$ is strongly inhomogeneous in the sample. To summarize the evolution of jumps as a function of temperature, in the case of a plain film, jumps appear only at very low temperatures when the $B(x)$ slope is steep enough to induce vortex avalanches. For the film with antidots, the definition of a critical slope is more tedious since one can define a local and a mean slope in the multiterrace critical state.[18] Since the magnetization value $M$ is very small in the case of antidots, the *mean* slope is also very small. The relevant parameter which triggers the avalanches is therefore the *local* slope in between terraces, which should be very large in a large temperature range.[18] This explains why avalanches can be triggered even at higher temperatures in the film with antidots and why they appear only locally. Closer to $T_c$, the multiterrace state is turned into a single-terrace state which induces peaks rather than jumps in $M(H)$.[19] One point which remains unclear is the disappearance of jumps and peaks in the $M(H)$ loops of the film with antidots in the intermediate temperature range [see, for example, the smooth dependence of $M$ versus $H$ at 6.5 K in Fig. 1(b)]. A possible explanation might be that for these intermediate temperatures, the local slope is not large enough to trigger the avalanches.

Our results are similar to those found in Nb films with an array of Ni dots.[11] Indeed, both studies show magnetization jumps in the $M(H)$ loops of films with a periodic pinning array, at temperatures at which the reference unpatterned film has a (relatively) smooth $M(H)$ dependence. For a certain range of temperatures, the jumps appear to be quasiperiodic, with a period that can be related to the first matching field. Remarkably, in both works, the recovery of the magnetization after a vortex avalanche has occurred has a slope that is equal to the virgin slope of the $M(H)$ loop, which is in agreement with the prediction of Cooley *et al.* for a terraced critical state.[18]

It is, however, interesting to also point out some differences between the behavior of the two systems. In the case of the Nb film with magnetic dots, the magnetization jumps that are observed at low temperatures are always quasiperiodic. For the Pb film with antidots, a similar quasiperiodicity appears only at intermediate temperatures ($T \approx 6$ K). Also, the field range at which the vortex jump are observed is more limited in the case of antidots (up to $\sim 30H_1$ at $T = 0.34T_c$) than for the system with magnetic dots [up to $\sim 100H_1$ at $T = 0.34T_c$ (Ref. 12)]. These differences could be due to the different balance between the intrinsic pinning of the film (higher for Nb than for Pb) and the pinning strength of the antidots or magnetic dots. Finally, in the Pb film with antidots, only *one* period was found in the magnetization jumps, corresponding approximately to $H_1$, while Terentiev *et al.* reported periods of $H_1$, $H_2 = 2H_1$, and of $H_3$. It is possible that the number of periods appearing in the magnetization jumps is linked to the saturation number $n_s$ of the pinning centers, as suggested in Ref. 12. In any case, more experiments on films with a periodic pinning array would be required to reveal the nature of the vortex avalanches.

It should be noted that the characteristic exponents expected in the case of self-organized criticality have not been observed here. Indeed, from Fig. 5, it is difficult to define a power law for the size distribution, especially on such a narrow size interval, close to only one decade. Several experimental studies have demonstrated recently that such power-law decays were not observed even when local magnetic measurements were performed.[22] The most convincing result on self-organized criticality was obtained when the system was left unchanged and evolves only as a function of time.[8] In the present experiments, the applied field is ramped up at a relatively large sweep rate which might prevent the system from reaching a self-organized state. More important, contrary to the calculation of Cruz *et al.*,[10] the presence of strong periodic pinning does not increase the number of bigger avalanches but reduces their size as jumps occur more locally.

## V. CONCLUSION

Our magnetization data have demonstrated the presence of jumps appearing in the low-field part of the $M(H)$ loop of a Pb film with a regular array of antidots. Compared to a reference film without antidots, the jumps are present up to higher temperatures and magnetic fields. The size of the jumps, however, is strongly reduced by the antidots. The observed results can be explained in the framework of the multiterrace critical state model in which regions with very high current density exist only locally in the sample. The vortex avalanches are confined in space due to the presence of the terraces and therefore the magnetization jumps are much smaller than those in the plain film. As previously observed in global and local magnetization measurements by other groups, the size distributions of jumps do not show a convincing power-law decay associated with self-organized criticality.

## ACKNOWLEDGMENTS

This work has been supported by the Belgian IUAP and Flemish GOA and FWO Programs. S. Hébert and L. Van Look acknowledge the support from the Research Council of the Katholieke Universiteit Leuven.

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