Available online at www.sciencedirect.com
ScienceDirect
Journal of Magnetism and Magnetic Materials 310 (2007) 2599–2603
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

Power-law scaling behavior in Barkhausen avalanches of ferromagnetic thin films

S.-C. Shin[a,*], K.-S. Ryu[a], D.-H. Kim[b], S.-B. Choe[c], H. Akinaga[d]

[a]Department of Physics and Center for Nanospinics of Spintronic Materials, Korea Advanced Institute of Science and Technology, Daejeon 305-701, Republic of Korea
[b]Department of Physics, Chungbuk National University, Cheongju, Republic of Korea
[c]Department of Physics, Seoul National University, Seoul, Republic of Korea
[d]Nanotechnology Research Institute, National Institute of Advanced Industrial Science and Technology, 1-1-1 Higashi, Tsukuba, Ibaraki 305-8562, Japan

Available online 27 November 2006

Abstract

We report direct domain observations of Barkhausen avalanches at criticality in Co and MnAs thin films investigated by means of a magneto-optical microscope magnetometer, capable of time-resolved domain observation in real time. Through a statistical analysis of the fluctuating size of Barkhausen jump from numerous repetitive experiments for each sample, the distribution of Barkhausen jump size is found to exhibit a power-law scaling behavior with the critical exponent of ~1.33 in both systems. This value is consistent with the two-dimensional prediction of a theoretical model proposed by Cizeau et al. [Phys. Rev. Lett. 79 (1997) 4669].

PACS: 75.60.Ej; 05.40.−a; 75.60.Ch; 75.70.Ak

Keywords: Power-law scaling behavior; Barkhausen effect; Two-dimensional ferromagnetic thin films

1. Introduction

Magnetization reversal mechanisms in ferromagnetic thin films are the subject of great interest from both fundamental and technological aspects. Magnetization reversal mechanisms are different depending on applied field strength relative to the coercivity field. When an applied field is lower than the coercivity field, magnetization reversal takes place by thermal activation of both nucleation and domain wall-motion processes. An exponential behavior occurs in this regime [1,2]. When an applied field is larger than the coercivity field, magnetization reversal is mainly carried out by viscous domain-wall motion, where the domain wall velocity varies linearly with an applied field [3,4]. As the applied field is much larger than the coercivity field, magnetization reversal is carried out via spin precessional motion governed by the Landau–Lifshitz–Gilbert equation [5,6].

Recently, interest is growing on magnetization reversal when an applied field is around the coercivity field, which is called the critical regime because random avalanche behavior in magnetization reversal process usually occurs. In this regime magnetization reversal takes place with a sequence of discrete and jerky jumps which was first discovered by Barkhausen in 1919 [7]. The reason why the interest is revived in this classical and old subject is mainly motivated by a fundamental question whether there is any simple law governing this seemingly random avalanche events. It attracts a growing interest as a good example of a complex dynamical system showing scaling behavior. So far, most experimental studies have been carried out on bulk samples using a classical inductive technique [8–10], which is difficult to apply to thin film samples mainly due to the low signal intensity. For this reason, very few experiments have been done on two-dimensional (2D) ferromagnetic thin films. In this paper, we report direct domain observations of Barkhausen avalanches at criticality in Co and MnAs thin films and our finding that the distribution of Barkhausen jump size exhibits a power-law

*Corresponding author. Tel.: +82 42 869 2528; fax: +82 42 869 8100.
E-mail address: scshin@kaist.ac.kr (S.-C. Shin).

0304-8853/$ - see front matter
doi:10.1016/j.jmmm.2006.11.041

scaling behavior with the critical exponent of ~1.33 in both systems.

2. Experimental

Co thin films were prepared on glass substrates by dc magnetron sputtering technique with the film thickness ranged from 5 to 50 nm, which is smaller than a typical domain wall-width of Co. In-plane magnetic anisotropy was induced by applying a magnetic field during the sample preparation. MnAs films were epitaxially grown on GaAs substrates by MBE technique. Details of the sample preparation were described elsewhere [11]. The θ–2θ X-ray diffraction studies of the MnAs film reveal that two structural phases, α and β, are found to coexist at room temperature, where α phase has the hexagonal structure and β phase has the distorted hexagonal structure which is essentially orthorhombic. The epitaxial growth relation in the hexagonal index system is MnAs $[1\,1\,\bar{2}\,0]$ parallel to GaAs [1 1 0] in the plane and MnAs $[\bar{1}\,1\,0\,0]$ parallel to GaAs [0 0 1] out of the plane. The atomic force microscopic studies show that α and β phases are intercalated with stripe-like feature, where the stripes are along the MnAs [0 0 0 1] orientation.

For the Barkhausen criticality study of thin film systems, we have developed a novel instrument, namely magneto-optical microscope magnetometer (MOMM) as depicted in Fig. 1. The MOMM basically consists of a polarizing optical microscope equipped with an advanced video processing set of CCD and frame grabber. The incident beam path is tilted by 20° from the film normal to observe the magnetic contrast of an in-plane anisotropy sample utilizing longitudinal magneto-optical Kerr effect (MOKE). We could grab the domain images in real-time with a speed of 30 frames/s and a spatial resolution of 400 nm. Since the MOKE is surface-sensitive, the MOMM is ideal to monitor magnetization process in magnetic thin films. The Barkhausen avalanche was triggered by applying a constant magnetic field to an initially saturated sample. The strength of an applied field was about 99% of the coercivity field to eliminate the influence caused by the difference in the field-sweeping rate. Using the MOMM the Barkhausen avalanches were directly visualized in real time and characterized from serial time-resolved domain images.

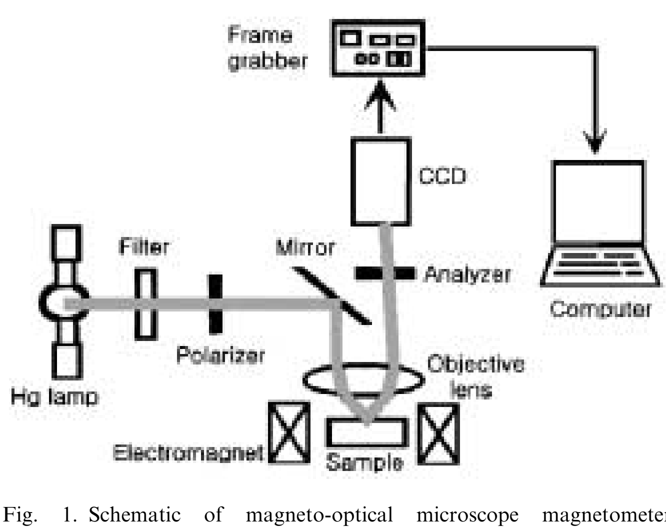

Fig. 1. Schematic of magneto-optical microscope magnetometer (MOMM) setup for the Barkhausen criticality study of magnetic thin films having in-plane anisotropy, from Ref. [12].

3. Results and discussion

3.1. Co thin films

In Fig. 2(a), we demonstrate a series of four representative domain-evolution patterns of 25-nm Co film observed on the exactly same area of the sample captured successively using the MOMM. Note that magnetization reverses with a sequence of discrete and jerky jumps rather than a continuous and smooth process. Therefore, one

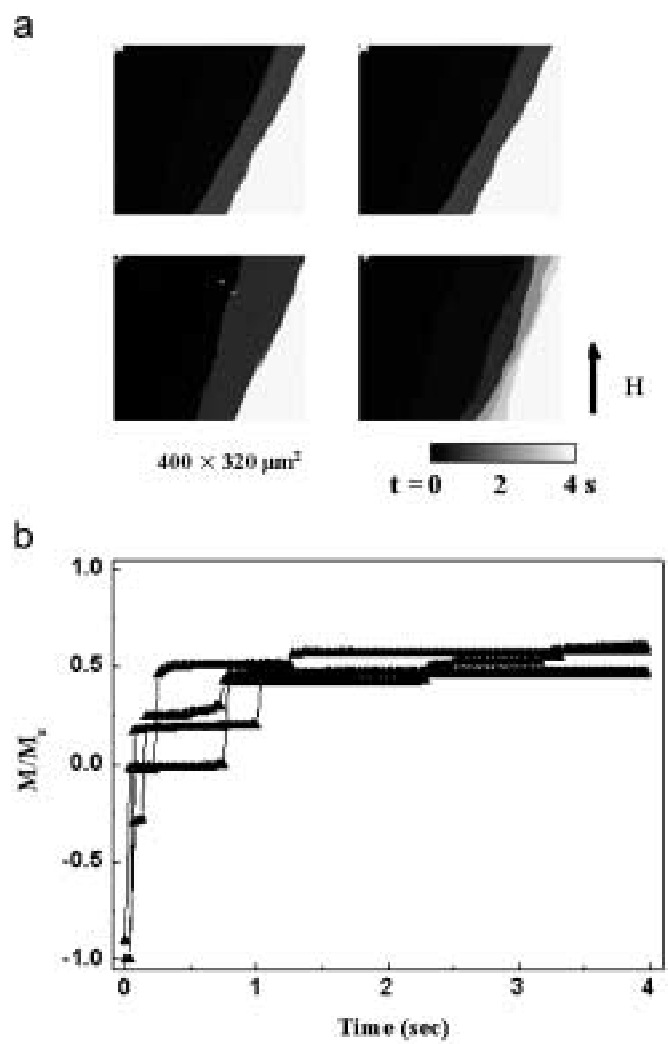

Fig. 2. (a) A series of four domain images showing Barkhausen avalanches of the domain structure captured successively on the exact same $400 \times 320\,\mu m^2$ area of a 25-nm Co film. The gray level from black to white represents the elapsed time from 0 to 4 s when magnetization reversal occurs. (b) Magnetization reversal curves obtained from the corresponding domain reversal patterns of (a).

could directly witness the Barkhausen avalanches in the evolution patterns. Moreover, domain evolution patterns among four pictures taken on the exactly same area of the sample seem to be random with respect to interval, size, and location of the jump. A direct visualization of the domain evolution by means of the MOMM enables us to witness the randomness of magnetization reversal process at Barkhausen criticality. Since the film thickness is smaller than the domain-wall width of Co, it is believed to observe 2D Co behavior of Barkhausen criticality. It is interesting to point out that a simple 180° flexible domain wall exists throughout the Barkhausen avalanche process. The observations on the other films with different thickness are not significantly different from those on the 25-nm sample, where the simple 180° flexible domain walls move with the similar Barkhausen avalanches.

In Fig. 2(b), we plot the magnetization reversal curves with time from the time-resolved domain image in Fig. 2(a), considering the fact that the net magnetic moment in the direction of an applied field is simply proportional to the reversed domain area. A stepwise feature in each curve is vividly witnessed, where each step is corresponding to the area swept by a sudden jump visualized in Fig. 2(a). The interesting characteristic of the curves in Fig. 2(b) is the presence of the steps whose time interval and amplitude are randomly fluctuate among the curves.

A fundamental question is whether a simple law exists which governs the randomness of the Barkhausen avalanches observed in Co thin films. To answer for this question numerous measurements are required for a statistical analysis. We have carried out more than 1000 repetitive experiments for each sample. In Fig. 3, we demonstrate the plots of the distribution P(s) vs. jump size s in the log-log scale for 5, 10, 25, and 50-nm Co films. As seen in the figure a power-law scaling distribution of the jump size is found to exist for all samples and fitted as $P(s) \sim s^{-\tau}$ with the critical exponent $\tau = 1.34 \pm 0.07$, 1.29 ± 0.06, 1.32 ± 0.03, and 1.30 ± 0.05 for 5, 10, 25, and 50-nm Co films, respectively. It should be mentioned that the value of the critical exponent is confirmed to be independent of the size of the sample area under examination as reported in Ref. [12].

The most interesting feature of the Barkhausen criticality of 2D Co films is the fact that the critical exponent is invariant with the film thickness within the experimental error as shown in Fig. 4. This universality of the critical exponent with respect to the film thickness is quite striking. One may naturally expect that the number of defects in a film increases in proportion to the film thickness, since all samples were prepared with the same sample preparation conditions except the film thickness. Therefore, our experimental result implies an invariance of the critical exponent irrespective of the number of defects in the 2D Co thin films, which is consistent with the recent theoretical studies predicting that the variation of the number of defects does not affect the critical exponent [13,14].

3.2. MnAs thin films

The torque and vibrating-sample magnetometer (VSM) measurements reveal that the MnAs film has an in-plane uniaxial magnetic anisotropy with an easy axis along the

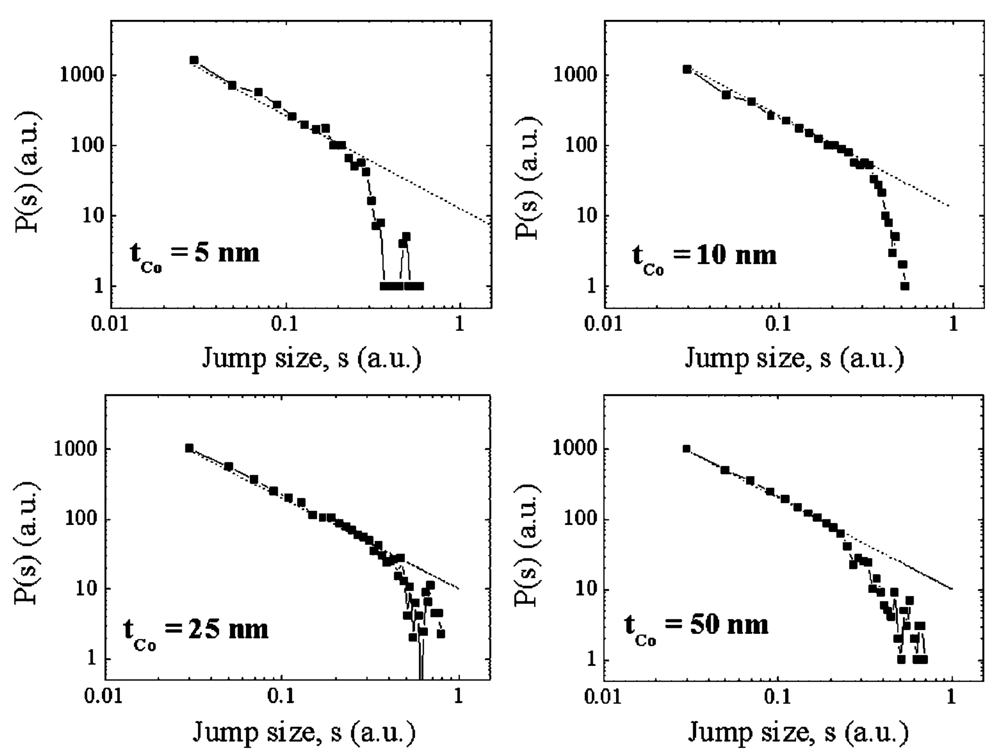

Fig. 3. Distributions of the Barkhausen jump size in 5, 10, 25, and 50-nm Co films.

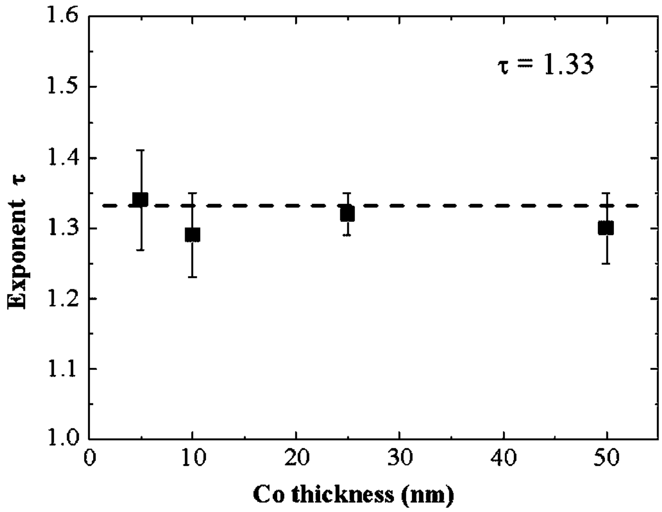

Fig. 4. The critical exponent vs. the Co film thickness.

MnAs $[1\,1\,\bar{2}\,0]$ orientation and a hard axis along the MnAs [0 0 0 1] orientation in the film plane. The Barkhausen criticality study was carried out by applying a magnetic field along the easy axis of the MnAs $[1\,1\,\bar{2}\,0]$ orientation. In Fig. 5, we demonstrate (a) a series of four domain evolution patterns captured on the exact same $80 \times 64\,\mu m^2$ area of a 50-nm MnAs film, together with (b) the magnetization reversal curve obtained from the corresponding domain evolution patterns. The gray level from black to white indicates the elapsed time during 4 s when the magnetization reversal occurs. One vividly sees Barkhausen avalanches in magnetization reversal process, where the discrete and jerky jumps occur. From Fig. 5, we notice that domain evolution process of this system seems to be random with respect to interval, size, and location of the jump as seen in the Co films.

It should be mentioned that domain evolution behavior of the MnAs film is quite contrasting compared to the Co film from two aspects. One aspect is saw-tooth patterned domain propagation with the saw-tooth angle of about 55°. The other aspect is the fact that the domain wall is not parallel to the magnetization direction. If the magnetization directions of two domains meet head-on, their separating domain wall could develop a zigzag shape to reduce the magnetic charge density, which is frequently observed in low magnetization materials. The detailed saw-tooth shape is decided from a minimization of the total magnetic energy consisted of the magnetostatic energy, the anisotropy energy, and the domain-wall energy. When an angle between the magnetization direction and the easy axis is small due to the strong in-plain anisotropy of the film as revealed in our film, the saw-tooth angle 2ϕ is approximately expressed as $2\phi = \pi(AK_{\perp})^{1/2}/8M_S^2D$, where A is the exchange stiffness, $K_{\perp}$ is an anisotropy constant in the normal-to-film plane, M_S is the saturation magnetization, and 2D is the sample thickness [11]. Using the experimental data of the MnAs film, the saw-tooth angle 2ϕ is estimated to be 56.8°, which is well matched to the observed value within an experimental error.

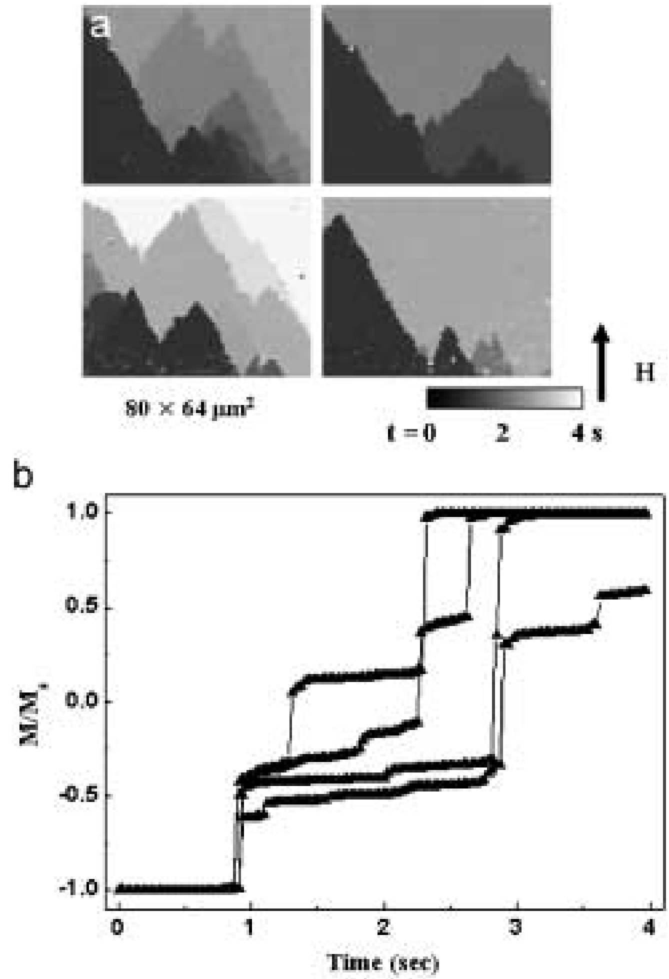

Fig. 5. (a) A series of four domain images showing Barkhausen avalanches of the domain structure captured successively on the exact same $80 \times 64\,\mu m^2$ area of a 50-nm MnAs film. The gray level from black to white represents the elapsed time from 0 to 4 s when magnetization reversal occurs. (b) Magnetization reversal curves obtained from the corresponding domain reversal patterns of (a).

A fundamental question is whether the power-law also governs the randomness of saw-tooth patterned domain propagation. For a statistical analysis, we have carried out more than 1000 repetitive experiments of domain evolution behavior. In Fig. 6, we show the distribution of the Barkhausen jump size s in the log–log scale for the 50-nm MnAs film. We again obtain a power law-scaling behavior with the critical exponent $\tau = 1.32 \pm 0.06$, which is independent of the size of the sample area investigated. Since the film thickness is smaller than the domain wall-width of 80 nm in this system [15], we believe that the experimental result is ascribed to a 2D behavior of MnAs system.

3.3. Comparison with the existing theories

Since the critical exponent is a key parameter in the description of the power-law scaling phenomenon, it is worthwhile to compare the experimental value of τ with the theoretical prediction. Before comparing the experimental

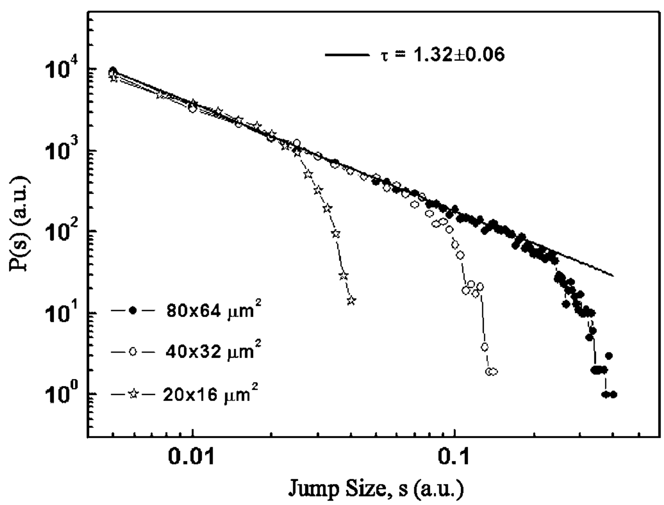

Fig. 6. Distributions of the Barkhausen jump size in the 50-nm MnAs film.

and theoretical values it is necessary to carefully examine the assumptions of the model as well as to clearly define the experimental configuration. Since we could directly visualize the details of Barkhausen avalanches, we can compare our experimental results with the existing theories and thus, judge which theoretical model is suitable to explain our experimental results.

Several theories have been proposed to explain the power-law scaling behavior of Barkhausen avalanches. The theory of self-organized criticality predicts that dissipative dynamical systems tend to organize themselves into a critical state where chain reactions of all sizes in time and space propagate through the system with the power-law correlations. The critical exponent in the size distribution is predicted 0.98 for a 2D system [16]. In the random-field Ising model proposed by Sethna et al. a random field is added at each site of the Ising model, where the random field is assumed to have a Gaussian distribution. The total local field at each spin is given by the summation of the exchange field, random field, and applied external field. Then, the critical properties can be solved within the mean field theory. This model predicts the critical exponent of 1.5 for a 2D system [14]. These two models could not explain our experimental results of Co and MnAs thin films. Our experimental results on the Barkhausen criticality of Co as well as MnAs thin films confirm the validity of the CZDS model [9,17] and its generalized version [18], where it is assumed that the flexible 180°-type (d−1)-dimensional domain wall moves with Barkhausen jumps. This model predicts the critical exponent τ of 4/3 for a 2D system, which is consistent with the experimental results of Co and MnAs films.

4. Summary

We have directly observed the Barkhausen avalanches in two-dimensional Co and MnAs films in real time using a time-resolved magneto-optical microscope magnetometer. It is found that the distribution of the Barkhausen jump size follows the power-law scaling behavior with the critical exponent of ~1.33 in both systems, which is in accordance with the theoretical prediction considering a 180°-type flexible domain wall.

Acknowledgements

This work was supported by Ministry of Science and Technology of Korea through the Cavendish-KAIST Research Cooperation Project, Korea Science and Engineering Foundation through the Basic Research Program, and Korea Research Foundation Grant funded by the Korean Government(MOEHRD)(KRF-2005-042-D00165).

References

[1] A. Kirilyuk, J. Ferré, V. Grolier, J.P. Jamet, D. Renard, J. Magn. Magn. Mater. 171 (1997) 45.
[2] S.-B. Choe, S.-C. Shin, Phys. Rev. Lett. 86 (2001) 532.
[3] R.P. Cowburn, J. Ferré, S.J. Gray, J.A.C. Bland, Appl. Phys. Lett. 74 (1999) 1018.
[4] K.-S. Ryu, K.-D. Lee, S.-B. Choe, S.-C. Shin, J. Appl. Phys. 95 (2004) 7306.
[5] W.K. Hiebert, A. Stankiewicz, M.R. Freeman, Phys. Rev. Lett. 79 (1997) 1134.
[6] Y. Acremann, C.H. Back, M. Buess, O. Portmann, A. Vaterlaus, D. Pescia, H. Melchior, Science 290 (2000) 492.
[7] H. Barkhausen, Z. Phys. 20 (1919) 401.
[8] J.S. Urbach, R.C. Madison, J.T. Markert, Phys. Rev. Lett. 75 (1995) 276.
[9] S. Zapperi, P. Cizeau, G. Durin, H.E. Stanley, Phys. Rev. B 58 (1998) 6353.
[10] G. Durin, S. Zapperi, Phys. Rev. Lett. 84 (2000) 4705.
[11] K.-S. Ryu, D.-H. Kim, S.-C. Shin, H. Akinaga, Phys. Rev. B 71 (2005) 155308.
[12] D.-H. Kim, S.-B. Choe, S.-C. Shin, Phys. Rev. Lett. 90 (2003) 087203.
[13] J.P. Sethna, K.A. Dahmen, C.R. Myers, Nature (London) 410 (2001) 242.
[14] O. Perković, K. Dahmen, J.P. Sethna, Phys. Rev. Lett. 75 (1995) 4528.
[15] F. Schippan, G. Behme, L. Däwertiz, K.H. Ploog, B. Dennis, K.-U. Neumann, K.R.A. Ziebeck, J. Appl. Phys. 88 (2000) 2766.
[16] P. Bak, C. Tang, K. Wiesenfeld, Phys. Rev. Lett. 59 (1987) 381.
[17] P. Cizeau, S. Zapperi, G. Durin, H.E. Stanley, Phys. Rev. Lett. 79 (1997) 4669.
[18] A. Vázquez, O. Sotolongo-Costa, Phys. Rev. Lett. 84 (2000) 1316.