Direct Observation of Barkhausen Avalanche in Co Thin Films

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We report direct full-field magneto-optical observations of Barkhausen avalanches in Co polycrystalline thin films at criticality. We provide experimental evidence for the validity of a phenomenological model of the Barkhausen avalanche originally proposed by Cizeau, Zapperi, Durin, and Stanley [Phys. Rev. Lett. **79**, 4669 (1997)], where the model describes a 180°-type flexible domain wall deformed by a localized defect with consideration of long-range dipolar interaction. The Barkhausen jump areas show a power-law scaling distribution with critical exponent $\tau \sim 1.33$ for all the samples having different thickness from 5 to 50 nm, which is in accord with the two-dimensional prediction of the model.

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It is recognized that the magnetization reverses with a sequence of discrete and jerky jumps, known as the Barkhausen effect [1]. Recently, interest in the Barkhausen effect has grown as it is a good example of dynamical critical behavior, evidenced by the experimental observation of a power-law distribution of the Barkhausen jump size [2–4]. The critical behavior observed in the Barkhausen effect is found to exist in a wide variety of other physical phenomena [5] such as bubble rearrangement in foams, dynamics of superconductor and superfluid, microfracture, and earthquakes.

Several models have been proposed to explain the Barkhausen criticality. Classical criticality, tunable by amplitude and distribution of disorder, was proposed within the context of a random-field Ising model [6]. On the other hand, self-organized criticality (SOC), achieved by self-organized evolution among barely stable states, was introduced [7] and then, applied to the Barkhausen effect [8]. With an appropriate model of long-range dipolar interaction known to be essential in these critical phenomena [3,9], Cizeau, Zapperi, Durin, and Stanley (CZDS) [4,10] proposed a phenomenological model of domain-wall dynamics in a disordered system, which could explain more general situations than the previous models [11], and later, the CZDS model was generalized into a dimensionless version [12]. These models predict the different values of the critical exponent [7,10,13]. Experimental values of the critical exponent are also diversely given [2–4,8] and do not show good linkage to the theoretical prediction. Thus, the underlying physics of Barkhausen criticality is still under debate.

So far, most experimental studies have been carried out on bulk samples using a classical inductive technique, 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 ferromagnetic thin films [14]. Nevertheless, experimental observation of the Barkhausen effect on thin films is crucial to extend our understanding of this critical phenomenon to two-dimensional systems, since the criticality is closely related with dimensionality [15]. The first reliable experiment based on a magneto-optical Kerr effect (MOKE) measurement was recently carried out for Fe thin films, where the critical exponent $\tau = 1.1$ was reported [16]. However the result for iron was quite different from the values predicted by the existing models [7,12,13]. Clarification of the reason for this disagreement and better understanding of the phenomenon require direct reversal observation of the Barkhausen avalanche. Unfortunately, the MOKE method like the classical inductive method probes only spatially averaged information in the process of sample magnetization and thus, neither method can reveal detailed domain configurations during Barkhausen avalanche. The development of a direct domain observation technique offering a better understanding of the Barkhausen effect as well as an accurate determination of the critical exponent has remained a scientific challenge to date.

In this Letter, we report a direct domain observation of Barkhausen avalanche at criticality in Co thin films by means of a magneto-optical microscope magnetometer (MOMM), capable of time-resolved domain observation [17]. The schematic of the apparatus is shown in Fig. 1. It basically consists of a polarizing optical microscope set to observe magnetic contrast via MOKE. The optical illumination path was tilted to provide an incident angle of 20° from the film normal by shifting the position of the objective lens as well as adjusting the relevant optics. Therefore, we could visualize in-plane magnetic domains utilizing longitudinal MOKE. The spatial resolution is 0.4 μm at $\times 1000$ magnification and the Kerr angle resolution is 0.1° in this setup. To store domain images, the system is equipped with advanced video processing having an image grabbing rate of 30 frames/s in real time. 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 coercive field to eliminate the influence caused by the

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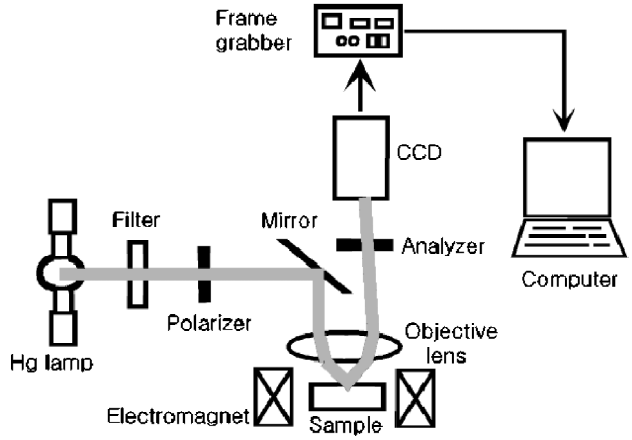

FIG. 1. Schematic of magneto-optical microscope magnetometer (MOMM) setup. The relevant optics is adjusted to provide an incident illumination angle of 20° from the film normal.

difference in the field-sweeping rates [4]. The Barkhausen jumps were *directly visualized* and characterized from serial time-resolved domain images. We prepared several Co films having thickness smaller than the typical domain-wall width of 50 nm [18] to avoid the magnetization change along the film thickness direction.

In Fig. 2(a) we demonstrate a series of six representative domain-evolution patterns of 25-nm Co film observed successively by means of the MOMM, where one can directly witness the Barkhausen avalanche. Here, the colors from red to blue indicate the elapsed time during 4 sec according to the color palette at the bottom of the figure. Domain-evolution patterns in each picture clearly exhibit discrete and jerky jumps in the magnetization reversal process. Moreover, as the experiments are repeatedly performed at the same area of the film, magnetization reversal proceeds with quite different jumps every time: the occurrence of these jumps seems to be random with respect to interval, size, and location. A visualization of the domain evolution by means of the MOMM enables us to directly witness the randomness of location, in addition to the randomness of interval and size of the jumps as clearly demonstrated in Fig. 2(a). Obviously, one could relate these jumps to the Barkhausen avalanches. Note that a simple 180° domain wall exists throughout the avalanche process. This is expected from the uniaxial anisotropy induced during the sample preparation process. The observations on other samples having different thickness are not significantly different from those on the 25-nm film, where the simple 180° domain walls move with the similar Barkhausen avalanches.

We have determined the magnetization reversal curve 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. In Fig. 2(b), we plot the magnetization reversal curves corresponding to the six domain-evolution patterns in Fig. 2(a), where a stepwise feature is vividly witnessed. Each step in the curve is corresponding to the area swept by a sudden jump clearly visualized in Fig. 2(a). The interesting characteristic of the curves in Fig. 2(b) is the presence of steps whose time interval and amplitude randomly fluctuate among the curves.

Through a statistical analysis of the fluctuating size of the Barkhausen jump from more than 1000 times repetitive experiments for each sample, the distribution of the Barkhausen jump size was obtained. We define the jump size s to be the area when it has two end points outside the image, since most of the Barkhausen jumps spread much outside the visualized region as illustrated in Fig. 2. Our definition of s is justified by the observation of the universal critical exponent irrespective of size of the field of view via the change of magnification from $\times 50$ to $\times 1000$, as clearly demonstrated in Fig. 3. The distribution is found to exhibit power-law behavior and fitted as $P(s) \sim s^{-\tau}$ with 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, as plotted in Fig. 3.

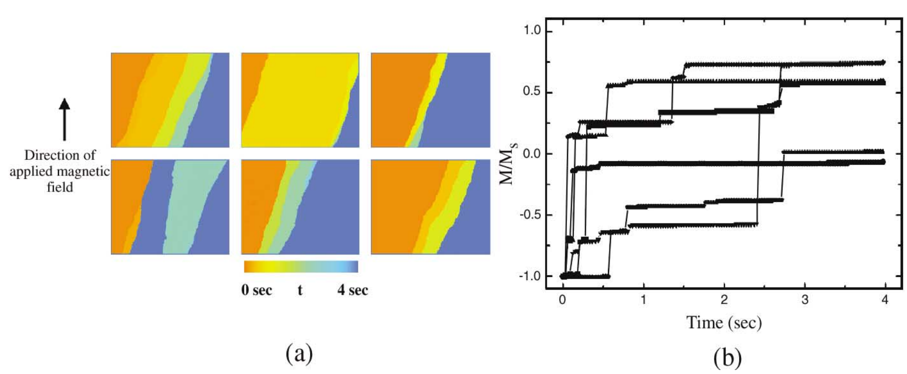

FIG. 2 (color). (a) A series of six domain images showing the avalanches of the domain structure captured successively on the same $400 \times 320\ \mu m^2$ area of a 25-nm Co film. The color code represents the elapsed time from 0 to 4 sec when magnetization reversal occurs. The sample was saturated downward first, and then a constant field was applied upward, denoted by the solid arrow, during observation. (b) Magnetization reversal curves obtained from the corresponding domain patterns of (a).

We witness that the distribution $P(t)$ of the separating time t between two Barkhausen jumps also follows a power law for all samples.

The most striking feature of Fig. 3 is the fact that the τ values are in the same universality class (~ 1.33) for all samples within the measurement error despite the difference in the film thickness. We may expect that the 50-nm film has about a 10 times larger number of defects compared with the 5-nm film, since all samples were prepared with the same preparation conditions except the thickness. Our experimental result implies an invariance of the critical exponent τ irrespective of the number of defects in the Co thin films, within a thickness range smaller than the domain-wall width. This result is consistent with the recent theoretical studies predicting that the variation of the number of defects does not affect the critical exponent, but only changes the cutoff where the distribution deviates from the power-law scaling [5,13]. In Fig. 3, note that the cutoff of the power-law scaling exists in all samples. The origin of the cutoff is still controversial: the variation of disorder distribution [5,13], the demagnetization effect [2,4], or the finite size effect [7,8] has been suggested to explain the origin. In the present work, as clearly seen in Fig. 3, with varying magnification of observation for the 25-nm Co sample, it is revealed that there exists a cutoff at each magnification, which implies that cutoff in our result is originated from the finite size effect of the field of view of the microscope.

A visualization capability of the MOMM enables us to directly investigate the motion of the domain wall in the Barkhausen criticality. The repeated observation of the motion of the domain wall reveals that there exist some pinning segments around which domain walls are very flexible. The flexible part of the domain wall moves forward via a Barkhausen jump while the pinned part is

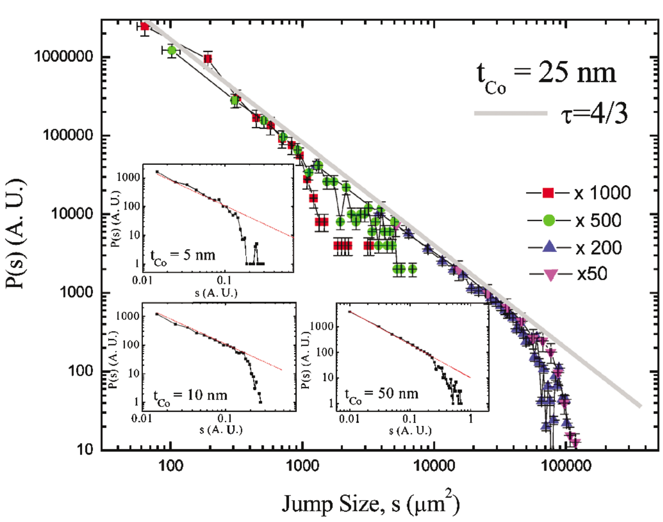

FIG. 3 (color). Distributions of the Barkhausen jump size in 25 and 50-nm Co samples. Distributions in 5, 10, and 50-nm Co samples are shown in the insets. Fitting curve with $\tau = 1.33$ is denoted at each graph.

fixed at the same position for a long time. This is quite expected because of the role of disorders as the pinning sites. The common pinned segment can be simply detected by superimposing each domain-wall image as exhibited in Fig. 4(a). Interestingly enough, the red and blue lines representing the domain walls observed at the same sample area in successive measurements seem to be very different at a glance, but they have common segments of domain wall whose positions are denoted by the arrows. This common segment does not exactly reappear as we repeat our experiment. If there is significant spatial correlation between disorders and thus, the random pinning potentials due to disorders are not localized, one should expect corresponding reproducibility in the Barkhausen avalanche [19,20], contrary to our observation. Therefore, we can conclude that the disorders are spatially uncorrelated or only short-range correlated in our system.

It is very interesting to note that the critical features continue to appear even when there exists a strong pinning site in the observed area. Images of domain walls around the strong pinning site were repeatedly obtained at the same area and then, they were superimposed. The resultant image is illustrated in Fig. 4(b), where the position of the strong pointlike pinning site is indicated by the solid arrow and the different color represents each repeated experiment. The pinning site in Fig. 4(b) was also observed in a pure optical image, while most of the pinning sites could not be identified by optical image probably due to the resolution limit of the optical microscope. As nicely demonstrated in Fig. 4(b), the domain wall is still flexible in this case. The flexible and dangling part of the domain wall intersecting this pinning site jumps to the other state as indicated by the dotted arrow. Note that although the overall domain evolution is mainly governed by this strong pinning site, there still exists detectable fluctuation in the detailed domain evolution.

To quantitatively understand the role of disorders in the process of the Barkhausen avalanche, we superimpose domain-wall images 100 times repeatedly measured at the same area and then represent the number of finding of wall as the color code. Thus, it is possible to generate the distribution map of disorders as illustrated in Fig. 4(c). It is very interesting to note that there *clearly exists* a more probable domain-wall region (red) indicating the role of disorders in the process of Barkhausen avalanche, even though we could not find the clear pinning site at a glance. Our direct observation and quantitative analysis provide a significant insight to the Barkhausen criticality that the random fluctuation and the reproducible pinning are counterbalanced in both cases of strong and weak pinning cases.

Since the critical exponent is a key parameter in the description of this phenomenon, we need to compare the value of τ with theoretical prediction. The prediction of τ for a two-dimensional system is diversely given as 1.5 for classical plain-old criticality [13], $\sim$1.0 for SOC [7,21], and 4/3 for the generalized CZDS model [10,12].

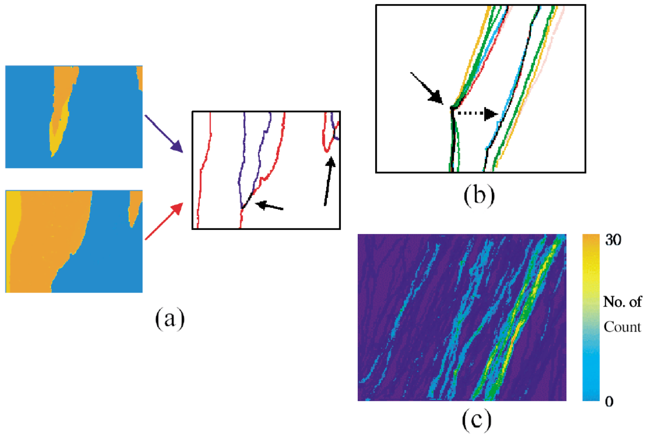

FIG. 4 (color). (a) Superimposed domain walls from two repeated experiments represented by red and blue wall lines. The common pinned segments are pointed by the solid arrows. (b) Superimposed domain walls from seven repeated experiments in the case of a strong pointlike pinning site whose position is denoted by a solid arrow. The progress of the domain wall for each experiment is shown by a dotted arrow. (c) Probability map to find a domain wall at a certain position of the observed area where no clear optical defect has been detected. The color code represents probability determined from 100 repeated observations at the same area.

Moreover, it is well known that a difference may exist even among experimentally obtained critical exponents due to a different magnetization reversal mechanism, different domain type, or different driving-field rate [4,11]. Therefore, before comparing the experimental and theoretical values it is necessary to carefully examine the assumptions of the models as well as to clearly define the experimental configurations by direct domain observation and driving-field rate control. Here, it should be pointed out that the experiment in our study was carried out with direct domain observation around the occurrence of the Barkhausen jump at a vanishing regime of the sweeping field rate. Only under this well-identified experimental condition, the comparison of the critical exponent τ between experimental and theoretical values is meaningful. We want to emphasize that all our experimental results directly confirm the validity of the CZDS model [4,10] and its generalized version [12], where it was assumed that the flexible 180°-type $(d-1)$-dimensional domain wall moves with Barkhausen jumps as deformed by localized defects. Considering this fact, we conclude that the prediction from this model (1.33) for a two-dimensional system is consistent with our experimental result ($\sim$1.33) for Co thin films. We propose this model, which successfully describes three-dimensional soft-magnetic bulk systems [4,10], can be extended to two-dimensional thin films.

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