Time-resolved observation of Barkhausen avalanche in Co thin films using magneto-optical microscope magnetometer

Dong-Hyun Kim,[a] Sug-Bong Choe,[b] and Sung-Chul Shin
Department of Physics and Center for Nanospinics of Spintronic Materials, Korea Advanced Institute of Science and Technology, Taejon 305-701, Korea

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We develop an experimental technique for direct, full-field, time-resolved observation of the Barkhausen avalanche in a two-dimensional thin-film system, using a magneto-optical microscope magnetometer (MOMM). Real-time visualization capability of the MOMM enables us to microscopically observe all the details of the Barkhausen avalanche in Co thin films, which is not feasible using other indirect experimental techniques adopted so far. We find that there exist fluctuating flexible domain walls deformed by defects and that, interestingly enough, the domain wall exhibits still-detectable fluctuation even around a strong linear defect as well as a strong point-like defect, from which we conclude that a critical avalanche continues to exist even in strong pinning cases. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1557350]

A Barkhausen avalanche is generated by successive sudden magnetization jumps in a ferromagnetic system when an external magnetic field is applied.[1] It continues to be an essential issue with respect to our fundamental curiosity about magnetism, as well as of technological interest for noise characterization of upcoming spintronic devices,[2] since it is closely related to domain dynamics in magnetization reversal. Recently, interest in the Barkhausen avalanche has increased as it is a good example of a complex dynamical system exhibiting critical scaling behavior, where the characteristic length of the system does not exist and scale-free behavior appears.[3–7] One of the essential issues in understanding this phenomenon is to clarify if an exact reproducibility exists in the critical behavior, and if the critical system exhibits completely deterministic dynamics. Several models have been proposed to explain the Barkhausen avalanche, such as classical criticality,[8,9] self-organized criticality,[10,11] flexible-domain-wall model,[12,13] and rigid-domain-wall model,[7] each of which either expects or denies the possibility of the existence of an exact reproducibility. A few experimental studies have been devoted to investigate this.[14,15] However, none of them has clearly resolved this controversy, and thus, the underlying physics of the Barkhausen avalanche is still unclear.

Most experiments so far have been carried out using the classical inductive coil method,[4–7] in which the experimental information of a Barkhausen jump comes from the electromagnetic measurement at the pickup coil detecting the time derivative of the magnetic flux caused by a sudden magnetization reversal of the sample located in the middle of coil. The drawback of this method is that it cannot spatially resolve each Barkhausen jump in the avalanche. It is obvious that direct observation of the dynamic domain is essential to clarify the detailed mechanism of the Barkhausen avalanche. Here, it should be noted that it is difficult to figure out a precise domain configuration inside the sample when a system size is much larger than the exchange length, so that the sample has a multidomain structure. Thus, a thin-film system can be better than a bulk system for studying the Barkhausen avalanche since it effectively provides a two-dimensional system, in which we can ignore the magnetization change along the film thickness direction if the thickness is comparable to the width of the domain wall. Although versatile domain observation techniques have been extensively utilized in domain reversal dynamics study in recent years, to our knowledge, the direct observation of the Barkhausen avalanche in a thin-film system has not been reported as yet, although a few have studied three-dimensional bulk systems.[16,17] For direct observation of the Barkhausen avalanche in thin film, quantitative visualization capability, as well as enough sensitivity, should be satisfied, which has remained a scientific challenge to date.

In this study, we report a direct, time-resolved domain observation of a Barkhausen avalanche in Co thin films by means of a technique using a magneto-optical microscope magnetometer (MOMM), which directly visualizes microscopic behavior of the Barkhausen avalanche in thin film systems. The MOMM basically consists of a polarizing optical microscope set to visualize an in-plane magnetic domain via magnetic contrast, utilizing a longitudinal magneto-optical Kerr effect (MOKE).[18] The optical illumination path is tilted for the longitudinal MOKE to provide an incident

[a]Electronic mail: dirac@kaist.ac.kr
[b]Present address: Advanced Light Sources, Lawrence Berkeley National Laboratory, Berkeley, CA 94720.

angle of 20° from the film normal by shifting the position of the objective lens as well as adjusting the relevant optics. The Kerr intensity signal is detected by a digital intensified CCD with maximum gain of 10^6. The spatial resolution is 400 nm and the Kerr angle resolution is 0.1°. To store domain images, the system is equipped with a digital video processing board having an image grabbing rate of 30 frames/s in real time. The time-resolved domain images on a $400\times 320\ \mu m^2$ sample area are initially grabbed on a 256 gray scale, and then intensified by advanced image processing techniques, such as background subtraction, noise filtering, and black-and-white image extraction. The Barkhausen avalanche is triggered by applying a constant magnetic field to an initially saturated sample. The strength of an applied field is constant near the coercive field to eliminate the influence caused by the difference in the field-sweeping rates.[6] By means of this experimental setup, the Barkhausen jumps are directly visualized and characterized from serial, time-resolved domain images.

We have prepared Co films having a thickness range of 25 to 50 nm, comparable to the typical domain-wall width of Co films.[19] Samples were prepared on glass substrates by dc magnetron sputtering under 2×10^{-7} Torr base pressure and 2-mTorr Ar sputtering pressure. An *in situ* magnetic field of 300 Oe was applied along a certain orientation in the film plane during deposition to induce magnetic anisotropy in this orientation, which was confirmed from the square in-plane Kerr hysteresis loops along this orientation.

In Fig. 1(a), we demonstrate a time-resolved domain evolution patterns of 25-nm Co film observed successively by means of the MOMM, where one can directly witness Barkhausen avalanches. The observation is carried out at the central region of $400\times 320\ \mu m^2$, where the total sample size is 1 cm^2. Domain evolution patterns in each picture of Fig. 1(a) clearly exhibit discrete and sudden jumps in the magnetization reversal process. Simple 180° domain walls exist throughout the reversal process, which is expected from the uniaxial anisotropy induced during the sample preparation. The magnetization reversal curve with time is determined from the serial domain images, where we assume that the net magnetic moment in the direction of an applied field is simply proportional to the reversed domain area. In Fig. 1(b), we plot the magnetization reversal curves corresponding to the domain-evolution patterns in Fig. 1(a). Note that a stepwise feature is vividly witnessed, in which each step in the curve is corresponding to the area swept by a sudden jump visualized in Fig. 1(a). As the experiments are repeatedly performed at the same area of the film, magnetization reversal proceeds with quite different jumps every time, by which one can relate these jumps to the Barkhausen avalanches. The observations on the 50-nm film are not significantly different from those on the 25-nm film, where the simple 180° domain walls move with the similar Barkhausen avalanches.

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

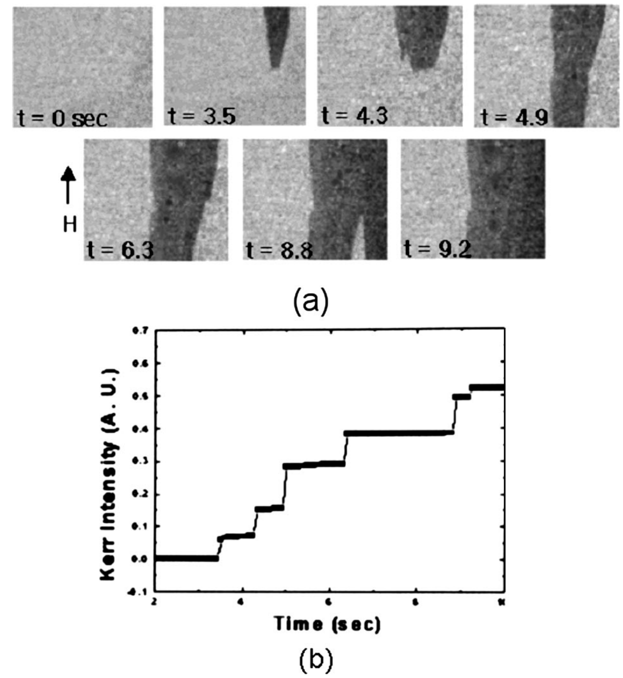

FIG. 1. (a) Real-time domain-evolution patterns of $400\times 320\ \mu m^2$. An initially downward field is applied to saturate the sample and a constant upward field around the coercive field is then applied, as denoted by the solid arrow to trigger Barkhausen avalanches. Black domains represent the reversed domains having an upward magnetization direction. The elapsed time is shown at the bottom of each figure. (b) Magnetization reversal curve corresponding to domain-evolution images of (a).

jump, while the pinned part is fixed at the same position for a relatively long time. This is quite expected because of the role of disorders as the pinning sites. It is very interesting to determine whether the domain-wall fluctuation continues to appear even when a strong pinning site exists in the observed area. Time-resolved images of domain walls around the strong point-like pinning site were repeatedly obtained at the same area as illustrated in Fig. 2, where the position of point-like pinning site is indicated by the dashed arrow. As clearly seen in Fig. 2, 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 without an exact reproducibility. Moreover, careful examination of the figure reveals that, even near the strong point pinning, the avalanche does not exhibit an exact reproducibility. Note that in a certain case, as illustrated at the left bottom image of Fig. 2, the avalanche of the Barkhausen jump just passes without any stopping at the pinning site. Therefore, we cannot find any clue to the existence of a pinning site in this case. For clear and strong point-like pinning sites in many other regions, we can always find that the avalanche is not exactly reproducible, which means that avalanche is not completely deterministic in the point-pinning cases.

In Fig. 3, we provide another interesting example of critical fluctuation of a Barkhausen avalanche in the case of a linear defect. From the time-resolved images illustrated in Fig. 3, we may expect that there exists a nearly horizontal linear defect, since all the domain evolution patterns indicate a common stop of evolution along a linear line at the same location, indicated by dotted line. Unfortunately, we cannot

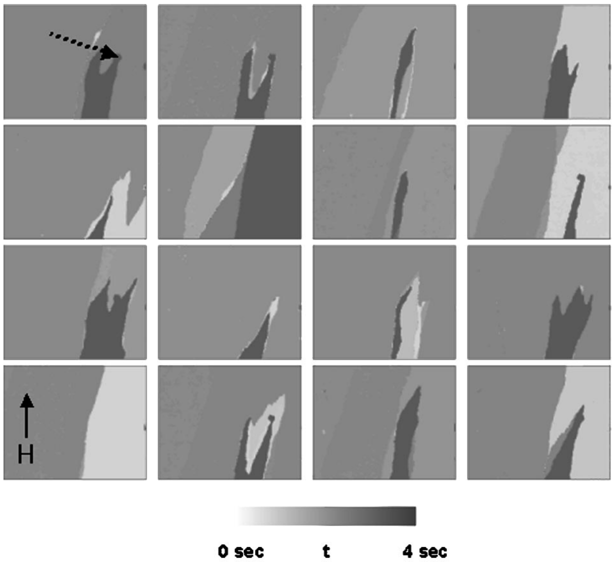

FIG. 2. A series of domain-evolution images captured repeatedly on the same $400\times320\ \mu m^2$ area with the same experimental conditions. The grey code represents elapsed time from 0 to 4 s when magnetization occurs, as shown at the bottom of the figure. The pinning site is indicated by the dotted arrow at the upper left image. The field is applied upwardly, as denoted by solid arrow.

identify the linear defect in an optical image of the sample. In general, most of defects are not identified by an optical image, mainly due to the resolution limit of optical microscopy. However, this very reproducible event at the line of the same location implies that something is clearly acting as a linear barrier, preventing the domain wall from passing through it. Interestingly enough, even in this extreme situation in which the strong linear defect is expected to exist, the detailed propagation of domain wall shows a significant fluctuation with the constraint introduced by the linear defect. The Barkhausen jump occurs still in a random critical way, still keeping the system at the criticality.

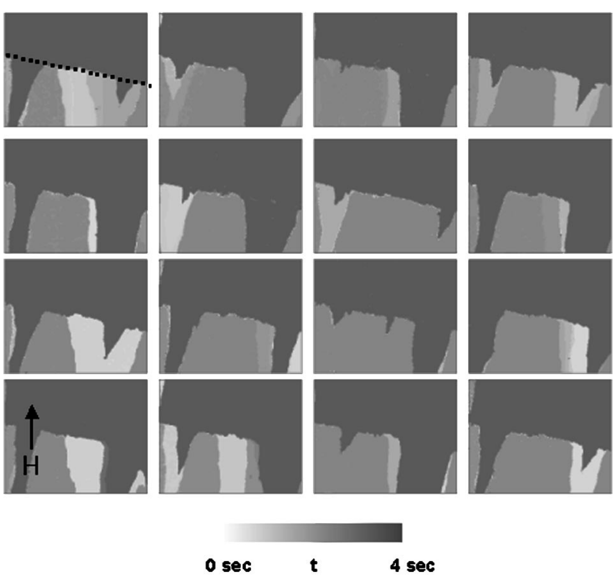

FIG. 3. A series of domain-evolution images captured repeatedly. The grey code represents elapsed time. The dotted line at the upper left image indicates the estimated location of the linear defect. The field is applied upwardly.

From our direct observation, we can microscopically justify that there still exists detectable fluctuation in the detailed domain evolution of Co thin films even in strong pinning cases, whether pinning is provided by the shape of the point or line, when the system continues to be at criticality. This provides clear experimental evidence that exact reproducibility is not satisfied in the Barkhausen avalanche as expected from the flexible-domain-wall model[6,12,13] and self-organized criticality,[10] where the domain-wall fluctuation originated from complex dynamical origin plays a key role in determination of critical random feature, whereas the classical criticality[8,9] predicts exact reproducibility. We clearly resolve the controversy with respect to the question as to whether the critical system exhibits an exact reproducible avalanche or not.[14,15] To quantitatively analyze the critical behavior, it is required to find the distribution of the size and the duration of the Barkhausen jump, which is beyond the scope of this paper and will be published elsewhere.[20]

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