Intermittency of Barkhausen avalanche in Co nanothin films

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We investigate the statistical distribution of separation time $\Delta T$ between the adjacent two Barkhausen jumps in Co films having the thickness ranging from 5 to 50 nm. By means of a magneto-optical microscope magnetometer, we determine the time-dependent magnetization curve and the separation time $\Delta T$ between two jump events during avalanche process from the directly observed time-resolved domain evolution patterns. Through a statistical analysis of $\Delta T$, we find that the distribution $P(\Delta T)$ seems to follow a power-law behavior with the same form within the error range, irrespective of the film thickness. © 2004 American Institute of Physics.

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Barkhausen avalanche in a ferromagnetic system is known to exhibit a scaling behavior over a wide range of spatial and temporal scale, during which the domain wall fluctuates nontrivially with intermittent avalanche-like bursts of magnetization jumps. Statistical analysis of such a fluctuation provides us a way to understand the scaling phenomenon. For example, it has been known that the distribution of the Barkhausen jump size follows a power-law behavior and that the distribution can be fitted with a single value of the slope on a log–log scale over several orders of magnitude, where the value of the slope allows us to determine the corresponding scaling exponent. In addition to the jump size distribution, the distribution of the duration of each jump has been also known to follow a power-law behavior, providing another corresponding scaling exponent. Interestingly, the statistical distributions of the fluctuating quantities such as jump size and jump duration are often described based on a universality, as the scaling behavior appears in the same way over wide varieties of physical systems ranging from the earthquake on a Richter scale, the vortex fluctuation in superconductors, and the emission of energy in microfractures. Thus, it has been believed that the scaling behavior characterized by the set of several scaling exponents does not sensitively depend on the microscopic details of the system but only depends on the global features of the system such as a dimension, symmetries, and an interactions range. There have been extensive theoretical efforts to explain the scaling behavior of the Barkhausen avalanche and its universality based on several concepts including the self-organized criticality and proximity to the classical criticality. However, the exact mechanism and the underlying physics of the scaling behavior in the Barkhausen avalanche are still unclear.

Numerous experimental studies have been devoted to investigate the Barkhausen avalanche mostly in bulk materials. Unfortunately, the scaling properties of the Barkhausen avalanche in thin film system have been very little known experimentally. Only recently, Puppin has carried out the Barkhausen avalanche experiment for Fe film and later, we have revealed the microscopic details of fluctuating domain wall during avalanche process in Co films. Recent experimental investigation of the Barkhausen avalanche in thin films is indebted to the novel method utilizing magneto-optical Kerr effect (MOKE) which is manifested by the change of polarization and/or intensity of the polarized light after the reflection from the surface of a magnetized medium and thus, the method is very appropriate to probe the magnetism of a thin film. Since the dimension is one of the main features which determines the scaling behavior, one might expect that the scaling behavior of thin films is described differently from that of bulk materials, which is recently reported by Puppin and Kim. However, in the previous two studies, scaling properties are examined only on a spatial scale, not on a temporal scale. It should be noted that the scaling behavior on a spatial scale is closely related to that on a temporal scale and they are not mutually independent. Therefore, experimental observation and statistical analysis of Barkhausen avalanche on a temporal scale as well as on a spatial scale can extend our understanding of the scaling phenomenon.

In this study, we report a statistical analysis of the intermittency of Barkhausen avalanche by measuring the distribution of the separation time $\Delta T$ between adjacent two Barkhausen jumps in Co films having the thickness ranging from 5 to 50 nm. The separation time is determined from a direct time-resolved domain observation by means of a technique using the magneto-optical microscope magnetometer which is basically consists of a polarizing optical microscope set to visualize an in-plane magnetic domain in real time via the magnetic contrast utilizing the longitudinal MOKE. The temporal resolution is about 30 ms and a series of 128 domain evolution patterns are captured sequentially during 4 s. Details of the experimental setup are described elsewhere. The Barkhausen avalanche is triggered by applying a constant magnetic field to an initially saturated sample. The strength of an applied field is kept to be constant near the coercive field to eliminate the influence caused by the difference in the field-sweeping rates. By means of

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this experimental setup, the intermittency of Barkhausen jumps are directly characterized and the separation time $\Delta T$ is determined from serial time-resolved domain images. A series of 1000 measurements have been repeatedly carried out at ten random positions of each sample to achieve a reliable statistics. We prepared several Co films having the thickness smaller than the typical domain-wall width of 50 nm$^{18}$ to avoid the magnetization change along the film thickness direction. Samples were prepared on glass substrates with area of 1 cm$^2$ by the dc-magnetron sputtering under 2 $\times$ 10$^{-7}$ Torr base pressure and 2 mTorr Ar sputtering pressure. A magnetic field of 300 Oe was applied in situ along a certain orientation in the film plane during the deposition to induce a magnetic anisotropy in this orientation, what was the same for all samples.

The typical time-resolved domain evolution patterns and the scaling properties of the jump size distribution have been intensively investigated in our previous reports$^{13,16}$ where it has been revealed that discrete and sudden Barkhausen jumps with simple 180° domain walls exist throughout the avalanche process. In the present study, we will focus on the intermittency of the Barkhausen avalanche and its statistical distribution. The magnetization reversal curve with time is determined from the serial domain images, where we assumed that the net magnetic moment in the direction of an applied field is simply proportional to the reversed domain area. In Fig. 1(a), we plot the magnetization reversal curve determined from a typical domain-evolution pattern observed at $\times$200 magnification. Note that a stepwise feature is clearly witnessed, where each step in the curve is corresponding to the area swept by each jump. From the magnetization curve we can easily determine when each jump has occurred and what the elapsed time separating two successive jumps is, as demonstrated in the Fig. 1(a). All measurements for each sample are carried out during 4 s at $\times$200 magnification. As the experiments are repeatedly performed at the same area of the film, the magnetization reversal proceeds with quite different jumps every time as clearly shown in Fig. 1(b).

Through a statistical analysis of the fluctuating time interval $\Delta T$ between the two Barkhausen jump events from more than 1000 times repetitive experiments for each sample, the distribution of $\Delta T$ has been obtained. In determination of $\Delta T$, there should be a threshold value in jump size to identify the Barkhausen jump from the background noise. In our experimental configuration, the noise level is less than 1% at $\times$200 magnification. We only consider the Barkhausen jump event occurring with the measured jump size over than 1% of the observed area (400$\times$320 $\mu$m$^2$ at $\times$200 magnification). In many cases, the detailed domain evolution patterns are not so simple, as one domain wall advances in an avalanche-like way while another domain wall comes in our field of view and advances independently, which are counted together and not distinguished from each other in our present analysis of $\Delta T$ distribution. In all samples, the distribution of $\Delta T$ determined in this way is found to have a power-law form within the error, as demonstrated in Fig. 2. The power-law form of the distribution does not seem to vary with the slight change of threshold in counting jump events from 1% to 2%. Interestingly enough, one can notice that the four distribution curves from four kinds of samples having the different thickness (5, 10, 25, and 50 nm)

FIG. 1. (a) Typical example of time-dependent magnetization reversal curve obtained from a directly observed time-resolved domain evolution patterns. The definition of separation time $\Delta T$ is illustrated. (b) Magnetization curves repeatedly obtained at the same area with the same experimental conditions for ten repeats.

FIG. 2. Distributions of $\Delta T$ which separates two adjacent Barkhausen jump events. The distributions have been obtained from more than 1000 repeated observations for each sample.
seem to fall in a single universal curve within the measurement error. Unfortunately, the error is not negligible here and the experimental proving of the universal intermittency behavior of the Barkhausen avalanche is still an open problem. The relatively large error in the case of the distribution of separation time compared to the case of the distribution of jump size from Ref. 13 seems to be originated from the smaller temporal measurement region (0.2–4 s). However, the exact reason is not clear, since even from the same set of the time-resolved domain evolution patterns, the temporal fluctuation distribution has generally rough power-law form while the spatial fluctuation distribution has smoother power-law form.

In summary, we have investigated the Barkhausen avalanche at Co thin films on a temporal scale, where we have found the distribution $P(\Delta T)$ of the separation time $\Delta T$ between the two successive jump events seems to exhibit a power-law behavior for all samples having the different thickness ranging from 5 to 50 nm. The possibility of the universal scaling behavior of $P(\Delta T)$ is suggested. This result suggests the possibility of universal temporal scaling behavior of the distribution of the separation time between the two adjacent Barkhausen jumps in ferromagnetic thin films.

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