Direct observation of Barkhausen effect in strip-patterned ferromagnetic Co/Pd multilayer films

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The one-dimensional Barkhausen effect was observed in lithographically defined magnetic strips of Co/Pd multilayer films. The magnetic domain expanded stepwise with a constant speed between pinning sites. Both the wall propagation and the pinning were characterized by the thermal activation process based on their exponential dependency on the strength of the applied magnetic field. The Barkhausen volume was determined to be 1.7×10^{-13} cm^3, which was several orders larger than the activation volume of the wall propagation, 6.5×10^{-18} cm^3. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2199978]

I. INTRODUCTION

The Barkhausen effect has been one of the intriguing classical issues in magnetism since it was discovered in 1919. In particular, recent studies of the self-organized criticality with a scaling behavior revived its intense attention.[1–3] It has been revealed that the universal features such as dimensionality and symmetry rather than microscopic details of a ferromagnetic system are dominant in the scaling behavior of the Barkhausen effect.[4] An investigation in a reduced dimension thus provides us better insight of this interesting century-old problem. However, most experimental studies have been so far devoted to rather bulk materials using a conventional inductive technique with pickup coils,[5] which is not applicable to a system having a reduced dimension such as thin films or patterned structures due to the low signal sensitivity. The magneto-optical Kerr effect (MOKE) provided a powerful experimental capability sensitive to thin films. By use of a MOKE microscope, magnetic domain nucleation, propagation, and pinning in structurally confined ferromagnetic systems have been thus extensively studied in recent years.[6–9] In this study, we report a real-time direct observation of the Barkhausen effect in quasi-one-dimensional magnetic strips of Co/Pd multilayer films.

II. EXPERIMENTAL PROCEDURE

For this study, quasi-one-dimensional strips were fabricated by photolithography on photoresist, followed by development and ion milling. The width of the strips was chosen to be 2 μm with a 4 μm periodicity. The structure was realized on Co/Pd multilayer films. The films were prepared on glass substrates by an *e*-beam evaporation under a base pressure of 2.0×10^{-7} torr at the ambient temperature. The multilayer structure was verified from the distinct peaks in the low-angle x-ray diffraction. The growth orientation was confirmed to be a [111] cubic orientation in high-angle x-ray diffraction studies. The multilayer structure was chosen to be (2 Å Co/11 Å Pd)$_{10}$, which exhibited a strong perpendicular magnetic anisotropy and showed wall-motion dominant domain dynamics.[10] The patterned structures showed basically the same magnetic properties compared with those of the unpatterned area of the samples. Figure 1 shows the morphological image measured by an atomic force microscope and the local magnetic hysteresis measured by a magneto-optical microscope magnetometer.[11]

Real-time magnetic domain evolution was observed by means of a MOKE microscope.[12] The microscope was capable of monitoring domain patterns in real time with a time resolution of 0.1 s and a spatial resolution of 0.4 μm. The image, composed of 200×160 pixels with a unit pixel size of 200×200 nm^2, was initially obtained in 256 gray levels

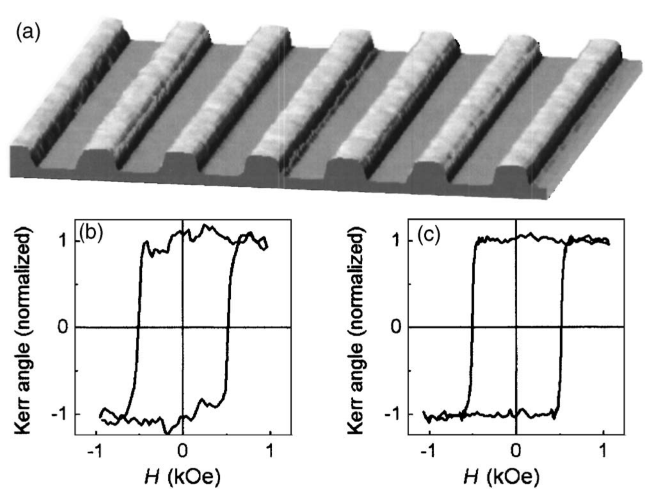

FIG. 1. (a) Topological image taken by an atomic force microscope. The width of the strips was 2 μm with a 4 μm periodicity. (b) Local magnetic hysteresis loop measured on the strip. (c) Magnetic hysteresis loop measured on the unpatterned area of the sample.

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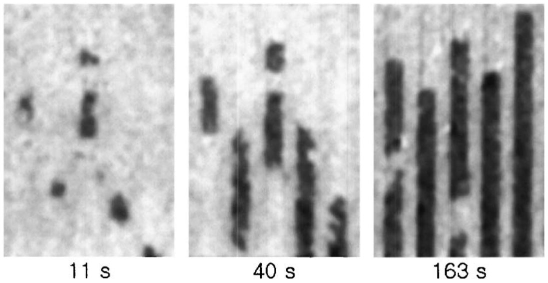

FIG. 2. Time-resolved domain images of periodic magnetic strips under a constant magnetic field. The reversed domains were formed in the beginning and then propagated along the strips in time.

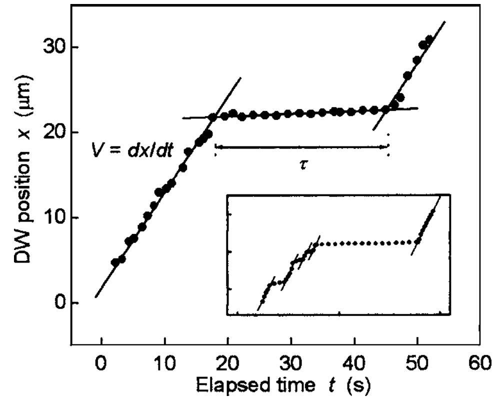

FIG. 4. The position of the domain wall front x with respect to the elapsed time t, measured from the images shown in Fig. 3. The linear fitting lines guide the wall propagation. The inset shows another stepwise process seen from other strips.

and then intensified by background subtraction, noise filtering, and black-and-white image extraction processes. The experiment was carried out by (1) initially saturating the sample with an applied magnetic field stronger than the saturation field normal to the film plane, (2) triggering the magnetization reversal by a reversed magnetic field slightly weaker than the coercive field, and then, (3) monitoring the time-resolved domain images. Series images in time, taken under a constant applied magnetic field, were analyzed to measure the wall propagation speed and the wall pinning time. The field dependence of these reversal parameters was examined with changing the strength of an applied field.

III. RESULTS AND DISCUSSION

The magnetization reversal of the magnetic strips was mainly carried out by the domain wall propagation along the magnetic strips, followed by the initial nucleation at several nucleation sites. Figure 2 shows time-resolved domain evolution patterns, where the elapsed time is denoted at the bottom of each frame. The unpatterned area of the sample originally showed a circular domain expansion from nucleation sites. But here the domain was confined in lithographically defined strips to show a linear expansion along the strips.

For a quantitative analysis we traced the wall front with time. Interestingly, the domain wall propagation exhibited a stepwise behavior with time. Figure 3 shows the domain images of a strip taken at several elapsed times with a constant time step. As seen in the figure, the domain was first created at a nucleation site designated by "A," followed by a propagation in both directions along the strip with time. The domain wall continued to propagate and then was pinned at a pinning site "B." After the lapse of time the domain wall was depinned and propagated again. The pinning took place at the same position reproducibly in a number of repeated observations irrespective of the strength of an applied magnetic field.

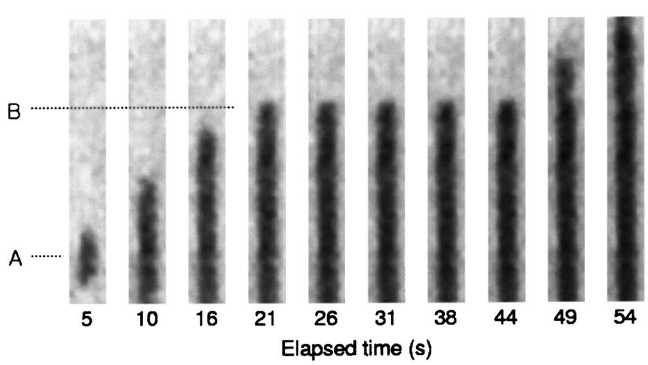

FIG. 3. Time-resolved domain images of a magnetic strip with a constant time step. The strength of the magnetic field was 355 Oe, smaller than the coercive field of 550 Oe. The domain wall propagation in a constant speed and the pinning are clearly seen from the figure.

It is worthwhile to distinguish the two types of defects between extrinsic pinning centers (macropins) and intrinsic ones (micropins).[13] The latter ones have been proposed within the context of a statistic treatment on critical phenomena,[14] whereas here we report the dynamic behavior of the former ones that clearly exhibit the individual Barkhausen jumps. The extrinsic pinning sites were possibly ascribed to structural defects inevitably introduced during the multilayer preparation process under a high vacuum environment and/or the patterning processes of photolithography and ion milling. An atomic force microscopy (AFM) study revealed a granular morphology of the films consisting of grains of 8–12 nm in diameter and the surface roughness of about ±2 nm.

The unpatterned area of the film showed the deflection of the wall front at pinning sites via detouring the wall propagation. Thus it is not easy to judge the characteristics between the depinning and the detouring. However, in our strips it is clear to see the effect solely from the depinning, excluding the detouring.

Figure 4 shows the domain wall position with respect to the elapsed time from the images shown in Fig. 3. It is clear to see the stepwise behavior from the figure. This kind of the stepwise behavior was generally observed in other strips, as shown in the inset of the figure. The plateaus came from the trapping of the domain wall at pinning sites, and the length of the plateaus was determined by the time needed to overcome the pinning potential. The finite slop between the plateaus is ascribed to the regular domain wall propagation.

This stepwise behavior were analyzed by the Barkhausen effect. The Barkhausen effect was originally proposed to be composed of sudden rotations of the magnetization vector from one orientation to another in various small volumes, i.e., the Barkhausen volume. Based on the

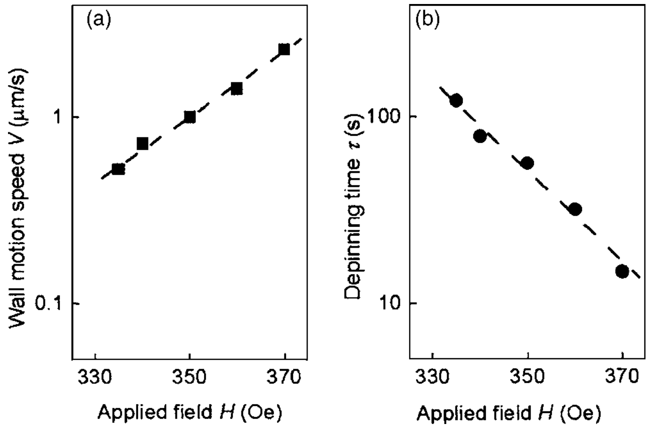

FIG. 5. (a) The magnetic field dependence of the wall propagation speed. The dashed line shows the best fit using Eq. (1). (b) The wall pinning time of the pinning site located at "B" in Fig. 3, with respect to the strength of an applied magnetic field. The dashed line shows the best fit using Eq. (2).

pinning site distribution in our sample, the Barkhausen volume was estimated to be about 1.7×10^{-13} cm^3 in average.

The domain wall propagation between the plateaus has a constant speed, as guided by the solid lines in the figure. The propagation speed was unique in all strips in a sample under a constant magnetic field but very sensitive to the strength of the magnetic field. From measurements with varying the strength of magnetic field, the wall propagation speed was exponentially dependent on the strength of the magnetic field, as shown in Fig. 5(a). The exponential dependency is ascribed to a thermal activation process.[15,16] In the process, the wall propagation speed V is given by an exponential function of an applied magnetic field H as

$$V = V_0 \exp\left[-\frac{M_S V_A}{k_B T}(H_C - H) \right], \tag{1}$$

where V_0 is the characteristic speed driven by the coercive field H_C, M_S is the saturation magnetization, V_A is the activation volume, k_B is the Boltzmann constant, and T is the temperature. By fitting, the activation magnetic moment $M_S V_A$ was determined to be $(1.7 \pm 0.1) \times 10^{-15}$ emu. Using the value of M_S determined from the magnetometric measurement, the activation volume V_A was estimated as $(6.5 \pm 0.2) \times 10^{-18}$ cm^3. Please note that the thermal activation volume was several orders smaller than the Barkhausen volume.

It is interesting to note that the wall pinning time also showed the exponential dependence on the field strength. Figure 5(b) shows the pinning time, measured at the pinning site located at B in Fig. 3, with respect to the field strength. An exponential dependency is clearly seen in the figure, as guided by a dotted line of the best fit. From the exponential dependency, one could analyze the pinning process within the context of a thermal activation process, as given by

$$\tau = \tau_0 \exp\left[\frac{M_S V_A}{k_B T}(H_C - H) \right], \tag{2}$$

where τ_0 is the characteristic switching time under the coercive field. From the fitting, the activation magnetic moment was estimated as $(2.3 \pm 0.2) \times 10^{-15}$ emu, which was distinguishably larger than that of the regular wall propagation. The existence of the plateau could be thus explained since the longer time was needed to switch the pinning site due to the larger activation magnetic moment. The larger magnetic moment may come from a larger activation volume or a larger saturation magnetization, but it is not easy to clarify here due to the lack of experimental technique to measure the local magnetic moment at the pinning site.

IV. CONCLUSION

In this study, the Barkhausen effect in magnetic domain dynamics was directly observed by the use of a magneto-optical microscope. The wall propagation showed a stepwise behavior along quasi one-dimensional magnetic strips lithographically defined on Co/Pd multilayer films. The stepwise behavior was decomposed into the regular wall propagation and the pinning processes. Both processes could be analyzed within the context of the thermal activation process. The activation magnetic moment of the pinning process was distinguishably larger than the regular wall propagation process.

ACKNOWLEDGMENTS

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