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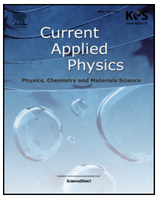

Stochastic nature of magnetic processes studied by full-field soft X-ray microscopy

Mi-Young Im[a,b,c,*]

[a] Center for X-ray Optics, Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA
[b] Department of Emerging Materials Science, Daegu Gyeongju Institute of Science and Technology, Daegu 42988, South Korea
[c] School of Materials Science and Engineering, Ulsan National Institute of Science and Technology (UNIST), Ulsan 44919, South Korea

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ABSTRACT

In nanomagnetism, one of the crucial scientific questions is whether magnetic behaviors are deterministic or stochastic on a nanoscale. Apart from the exciting physical issue, this question is also of paramount highest relevance for using magnetic materials in a wealth of technological applications such as magnetic storage and sensor devices. In the past, the research on the stochasticity of a magnetic process has been mainly done by macroscopic measurements, which only offer ensemble-averaged information. To give more accurate answer for the question and to fully understand related underlying physics, the direct observation of statistical behaviors in magnetic structures and magnetic phenomena utilizing advanced characterization techniques is highly required. One of the ideal tools for such study is a full-field soft X-ray microscope since it enables imaging of magnetic structures on the large field of view within a few seconds. Here we review the stochastic behaviors of various magnetic processes including magnetization reversal process in thin films, magnetic domain wall motions in nanowires, and magnetic vortex formations in nanodisks studied by full-field soft X-ray microscopy. The origin triggering the stochastic nature witnessed in each magnetic process and the way to control the intrinsic nature are also discussed.

1. Introduction

With the high potential of magnetic nanomaterials for applications in advanced nanotechnologies such as high-density recording media, data storage devices, and magnetic sensors [1–7], one of the fundamental and crucial issues is whether a magnetic process is deterministically behaved. This issue is directly linked to the question for the reproducibility of the magnetic process, which is a basic factor for achieving a high and accurate performance in magnetic nanodevices. In years ago, due to limitation in conventional magnetic microscopy techniques providing high spatial resolutions, the stochasticity and/or reproducibility of magnetic processes have been mostly studied by indirect probes such as macroscopic hysteresis loops [8–10]. Therefore, accurate analysis for stochastic and deterministic natures of magnetic processes happened on a nanoscale and comprehensive understanding the related physical principles have not been successfully addressed.

Since characterization techniques offering high spatial resolutions such as X-ray microscopes have been advanced, the stochastic issue has been tackled based on the direct observation of statistical behaviors of magnetic structures and magnetic phenomena on a nanoscale. A representative advanced imaging technique utilizing X-ray sources, which has been actively employed in such research, is a magnetic transmission soft X-ray microscope (MTXM) at Advanced Light Source (XM-1, ALS) [11,12]. This microscope enables direct imaging in-plane and out-of-plane magnetic components with a lateral resolution down to 20 nm provided by state-of-the-art X-ray optics called Fresnel zone plates [12]. In addition, XM-1 is in a full-field mode and thus allows observing magnetic structures on a large of field of view (~10 µm) within a few seconds, which is strongly beneficial for the investigation of statistical behavior of magnetic processes and therefore their stochastic natures.

In this article, previous works on stochastic natures of various magnetic processes such as domain nucleation and reversal process in ultrathin CoCrPt alloy films [13,14], the domain-wall motions in $Ni_{80}Fe_{20}$ notched nanowires [15,16], and the creation of vortex structure in $Ni_{80}Fe_{20}$ nanodisks [17–19] studied by soft X-ray microscopy are reviewed. A primary factor affecting the stochasticity in each magnetic process and the approach how to control the intrinsic character, stochastic nature are further discussed.

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[*] Corresponding author. Center for X-ray Optics, Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA.
E-mail address: mim@lbl.gov.

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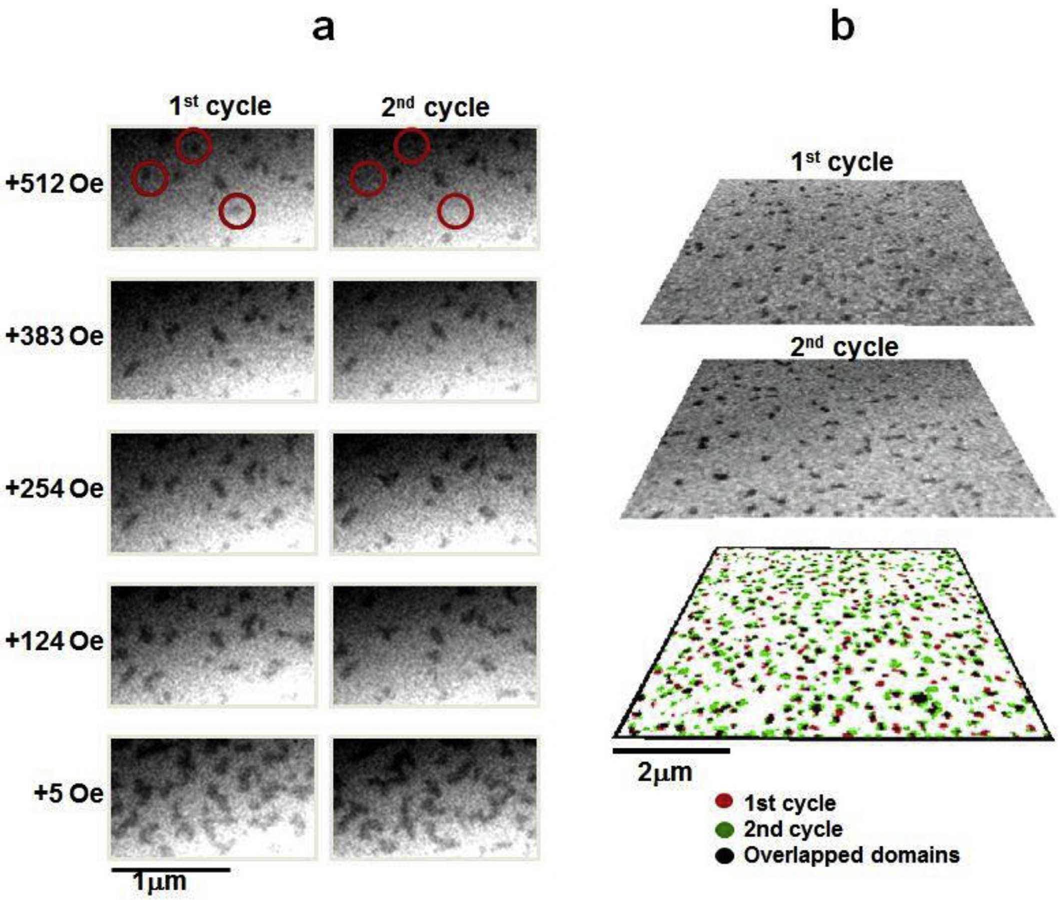

Fig. 1. (a) Magnetic domain configurations of $(Co_{0.83}Cr_{0.17})_{87}Pt_{13}$ alloy film taken at applied magnetic fields of +512, +383, +254, +124, +5 Oe in the descending branch of the major hysteresis loop and (b) the overlapped domain configuration image taken at an applied magnetic field of +400 Oe.

2. Magnetization reversal process in thin films

Nanogranular thin films with perpendicular magnetic anisotropy have been considered as promising candidates for high-density magnetic recording media [20–22]. Repeatable local domain nucleation and reliable magnetic reversal process are key aspects for developing magnetic-based recording technologies [23–26].

In perpendicularly magnetized CoCrPt alloy films, the repeatability of domain nucleation and magnetic reversal process was investigated. Magnetic images in CoCrPt were recorded at the Co L_3 (778 eV) X-ray absorption edge. Fig. 1 (a) shows magnetic domain configurations observed on the identical sample area of $(Co_{0.83}Cr_{0.17})_{87}Pt_{13}$ alloy film during two consecutive hysteretic cycles. The sample was fully saturated by +3 kOe and then the reverse fields of +512, +383, +254, +124, +5 Oe. One clearly sees that the domain nucleation sites observed in two successive cycles are not identical. The nucleation process of domains is rather stochastic than deterministic in $(Co_{0.83}Cr_{0.17})_{87}Pt_{13}$ film even with its nanogranular microstructure containing numerous grain boundaries acting as pinning sites. This is more clearly visualized in Fig. 2 (b) where two MTXM images for domain configurations taken at +400 Oe within two consecutive measurements are overlapped.

The same type of experiment was conducted for Barkhausen avalanches [27,28], which are discrete and sudden jumps occurred during the field-driven magnetization reversal. Fig. 2 illustrates representative magnetic configurations recorded at the applied magnetic fields of +400, +200, 0, −200 Oe in two consecutive cycles in $(Co_{0.83}Cr_{0.17})_{87}Pt_{13}$ (a) and the distributions of Barkhausen avalanches in each field step, I, II, or III where the color codes of green, yellow, and red correspond to the field steps I, II, and III, respectively (b). To visualize the Barkhausen avalanches in each field step, the domain configuration image taken at the initial field of the step was subtracted from that at the final field of the step. It is clearly visible in Fig. 2 (b) that discrete Barkhausen avalanches randomly distributed over the film. The size and shape of Barkhausen avalanches are quite different in the three field steps. In the field step I, small-size Barkhausen avalanches are witnessed while large and elongated avalanches appear as the field approaches the step III, which implies that the mechanism in the Barkhausen avalanches changes accordingly with the variation of the magnetization reversal process from domain nucleation in the step I to domain wall propagation in the step III. More importantly, the distributions of Barkhausen avalanche considerably transforms in repeated hysteresis cycles as observed in the domain nucleation and magnetization reversal processes [14].

As a reason for the stochastic nature observed in the nucleation and reversal processes of domains in CoCrPt films, thermal fluctuation effect was considered. The random behavior of Barkhausen avalanches in the films was also interpreted to be attributed to a thermal effect which dominates the magnetization reversal process rather than, e.g., defect or grain boundary induced processes. To confirm the effect of thermal fluctuation, nanomagnetic simulations for the magnetization reversal process of CoCrPt alloy films utilizing the stochastic Landau–Lifshitz–Gilbert equation was performed at T = 0 and 300 K [29]. In this equation, the thermal effect is reflected by considering a fluctuating magnetic field, which is caused by fluctuations of the magnetic moment orientation due to interaction of the magnetic moment with conducting electrons, phonons, nuclear spins, etc. The variance of thermal fluctuation is defined by $V_{ar}=2\alpha\, k_BT/(1+\alpha^2)\gamma\mu_0\, M_sV$, which is derived from Brown's Fokker-Planck equation [30]. Here, the γ and α are a gyromagnetic ratio and a damping parameter and the V is the island volume. In the simulations, the granular microstructure of