Direct observation of individual Barkhausen avalanches in nucleation-mediated magnetization reversal processes

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We report the scaling behavior of Barkhausen avalanches [H. Barkhausen, Z. Phys. 20, 401 (1919).] along the hysteresis loop of a CoCrPt alloy film with perpendicular magnetic anisotropy for every field step of 200 Oe. Individual Barkhausen avalanches are directly observed via soft x-ray microscopy with a spatial resolution of 15 nm. The Barkhausen avalanches exhibit a power-law scaling behavior, where the scaling exponent of the power-law distribution drastically changes from 1 ± 0.04 to 1.47 ± 0.03 as the applied field approaches the coercivity of the CoCrPt film. We infer that this is due to the coupling of adjacent domains. © 2009 American Institute of Physics. [doi:10.1063/1.3256188]

For almost a century, it has been known that the field-driven magnetization reversal in ferromagnetic materials occurs via a series of discrete and sudden magnetization changes, known as Barkhausen avalanches.1 Recent studies on Barkhausen avalanches in two-dimensional (2D) and three-dimensional ferromagnetic materials have revealed a power-law scaling behavior with applied field as observed in a wide variety of physical phenomena with other driving forces such as the metal-insulator transition, earthquakes, vortices in superconductors, or charge density waves.9 Barkhausen avalanches thus play a crucial role in the hysteretic behavior of the magnetization reversal process, which is not only a fundamental scientific topic but also a key technological issue e.g., in magnetic recording.10–13 Therefore, systematic studies on the statistical behavior of Barkhausen avalanches via small field steps along the hysteresis loop are very important. Particularly, studies of 2D ferromagnetic films with out-of-plane or perpendicular magnetic anisotropy (PMA) are of great interest since the magnetization reversal in those systems is accompanied by the nucleation of magnetic domains and subsequent domain wall motion.3,14

So far, most experimental studies on Barkhausen avalanches have been carried out on materials with pronounced in-plane anisotropy; these have revealed a domain-wall-mediated magnetization reversal process. Such systems involve large Barkhausen jump sizes which can be easily detected by a classical inductive method or a magneto-optical Kerr effect technique.4,6 Most experimental studies have focused on the critical field region around the coercive field or the ensemble-averaged statistical behavior of Barkhausen avalanches throughout an entire hysteresis loop.5,6,15 Few experiments have been done on Barkhausen avalanches in nucleation-mediated magnetization reversal processes, mainly due to the low sensitivity and limited spatial resolution of the available measurement techniques. The direct observation of Barkhausen avalanches at small field steps along hysteresis loops in nucleation-mediated magnetization reversal process, together with a thorough statistical analysis, has thus remained a scientific challenge to date. In this letter, we report the findings on the statistical behavior of Barkhausen avalanches for each field step along the hysteresis loop of a CoCrPt alloy film investigated by full-field magnetic transmission soft x-ray microscopy with a spatial resolution of 15 nm.16 These films exhibit a pronounced PMA and are, therefore, considered as promising candidates for high-density perpendicular magnetic recording media.17,18

High resolution images of the magnetic domain configuration were recorded at the soft x-ray microscopy beamline 6.1.2 at the Advanced Light Source in Berkeley, CA. A detailed description of the experimental setup can be found elsewhere.16 Magnetic contrast is achieved by the elementspecific effect of x-ray magnetic circular dichroism (XMCD). The key optical elements are Fresnel zone plates (FZPs). A condenser zone plate together with a pinhole close to the specimen serves as an inline radiation monochromator. Thus one can select a specific photon energy range, e.g., 777 ± 0.5 eV, which corresponds to the Co L1 absorption edge. Left and right circularly polarized x-rays are selected by moving an aperture either in the upper or lower half of the x-ray cone of the bending magnet source. Thus, circularly polarized x-rays of a specific wavelength illuminate the ferromagnetic specimen, giving rise finally in a difference image to XMCD. A second FZP, the so called microzone plate is located downstream of the sample and acts as an objective lens, projecting the x-ray image onto a backside-illuminated charge coupled device detector with 2048 × 2048 pixels.

50-nm thick (Co0.83Cr0.17)87Pt13 alloy films were prepared on a 40-nm thick Ti buffer layer using dc magnetron cosputtering of CoCr alloy and Pt targets at a base pressure of <8 × 10−7 Torr and with a sputtering Ar pressure of 3 mTorr at ambient temperature. The magnetic easy axis of the film was determined using a torque magnetometer and was observed to be normal to the film plane. The macroscopic magnetic properties were characterized by vibrating sample magnetometry (VSM).
domains was triggered. Figure 1 shows magnetic domain evolution of Barkhausen avalanches was studied by the following procedure. First, the sample was saturated by applying a strong positive magnetic field. Then, the applied field was reduced so that the spontaneous nucleation of magnetic domains was triggered. Figure 1 shows magnetic domain configurations of the CoCrPt film taken at different field strengths of +600, +400, +200, 0, and −200 Oe, together with the macroscopic M-H curve obtained via VSM measurement.

X-ray microscopy images of the magnetic domain structure in the CoCrPt alloy film were recorded at the Co L3 (777 eV) absorption edge with the external magnetic field oriented normal to the sample plane. To distinguish magnetic contrast from structural contrast, e.g., due to defects, inhomogeneities, etc., each image was normalized to a saturated image taken under sufficiently strong external magnetic field. The evolution of Barkhausen avalanches was studied by the following procedure. First, the sample was saturated by applying a strong positive magnetic field. Then, the applied field was reduced so that the spontaneous nucleation of magnetic domains was triggered. Figure 1 shows magnetic domain configurations of the CoCrPt film taken at different field strengths of +600, +400, +200, 0, and −200 Oe, together with the macroscopic M-H curve obtained via VSM. The typical nucleation-mediated magnetization reversal process is clearly visible. New domains are randomly appearing at many nucleation sites between +600 and +400 Oe, which is designated as field step I. It is found that the average size of newly nucleated domains is ≈40 nm, following a Gaussian distribution. Considering that the grain size in the film is also expected to follow a Gaussian distribution with an average size under 30 nm, the nucleation-mediated reversal process in this system is believed to be carried out by switching individual grains which are segregated by a higher Cr composition at grain boundaries. As the applied magnetic field changes from +400 to +200 Oe (field step II), the small nucleated domains grow with an irregular shape, while new domains are formed at other nucleation sites. With the applied field approaching 0 from +200 Oe (field step III), the magnetic domains grow mainly by elongation of already existing domains, as shown in Figs. 1(c) and 1(d). In field step IV, i.e., from 0 to −200 Oe, neighboring magnetic domains begin to connect with each other as the magnetic domain density increases, as seen in Fig. 1(e). In this regime, magnetization reversal mostly proceeds by domain wall propagation rather than domain nucleation.

It is important to note from Fig. 1 that the reversal of magnetic domains takes place via a sequence of Barkhausen avalanches at each field step. To visualize the Barkhausen avalanches in each field step, we have subtracted the domain configuration image taken at the final field of the step from that at the initial field of the step. The results are displayed in Fig. 2(a), showing the distributions of Barkhausen avalanches which existed in the four field steps. The color codes of blue, green, yellow, and red correspond to the field steps I, II, III, and IV, respectively. One can clearly distinguish discrete Barkhausen avalanches randomly distributed in the film. Most interestingly, the size and shape of Barkhausen avalanches noticeably changes with the variation of the field step. In the field step I, small-size Barkhausen avalanches with a jagged shape are observed. In contrast, as the field increment approaches the step IV, mostly large and elongated avalanches appear. These results reflect the different reversal mechanisms in the Barkhausen avalanche process, namely domain nucleation in the step I versus domain wall propagation in the step IV. Obviously, the different size and shape of Barkhausen avalanches observed for each field step is due to a rather complex magnetization reversal process along the hysteresis loop in the CoCrPt alloy film. We have witnessed randomness in the size and shape distributions of Barkhausen avalanches in repeated measurement cycles, as representatively demonstrated in Fig. 2(b), which shows the same region of the sample during two separate hysteresis measurement cycles. We believe that this random nature can be attributed to a thermal effect which dominates the magnetization reversal process, rather than, e.g., defect or grain boundary induced processes.

In this context, the most fundamental question is what kind of statistics governs the randomness of Barkhausen avalanches. To answer this question, we have systematically investigated the Barkhausen avalanches in each field step. The magnetic domain configurations were repeatedly imaged and analyzed in several dozen successive hysteretic cycles on the exactly identical sample areas. The size of individual avalanches was determined by counting the pixels using particle-analysis software. More than 700 Barkhausen avalanche sizes were accurately determined for each field step. From the statistical analysis of the probability of a given size, we have found that the average size of Barkhausen avalanches increases significantly from the field step I to IV. In Fig. 3, the distributions of Barkhausen avalanche sizes for

![Figure 1](image1.png)

**FIG. 1.** (Color online) Typical magnetic domain configurations of the CoCr0.83Pt0.17 alloy film recorded at the Co L3 x-ray absorption edge (777 eV) with applied magnetic fields of (a)+600, (b)+400, (c)+200, (d)/, and (e)−200 Oe. (f) M vs H hysteresis loop obtained via VSM measurement.

![Figure 2](image2.png)

**FIG. 2.** (Color online) (a) Distributions of Barkhausen avalanches observed in the field steps I, II, III, and IV. (b) Two repetitive cyclic measurements in the exactly identical area of the sample.
the four field steps are plotted on a log-log scale. Superimposed images of two domain configurations taken at the initial and final fields of each step.

The most remarkable feature in Fig. 3 is the fact that the scaling exponent, which is the key parameter for a description of complex avalanche phenomena, drastically changes in going from field step III to field step IV. The scaling exponents in field steps I, II, and III are measured to be 1.02 ± 0.02, 0.96 ± 0.04, and 0.98 ± 0.03, respectively, which are identical within experimental error. In contrast, the scaling exponent in field step IV is found to be 1.47 ± 0.03. Hence, the critical scaling behavior of Barkhausen avalanches undergoes a sudden change from the usual behavior around the coercive field. We believe this sudden change is caused by the coupling among neighboring magnetic domains due to the high density of domains around this field.

As can be clearly seen in the insert of Fig. 3(d) a number of Barkhausen avalanches are generated by combinations of adjacent domains (marked by circles). This situation is only observed near the coercive field. Domain coupling through interaction between neighboring domain walls in field step IV is expected to modify the Barkhausen avalanche process, resulting in the observed change of the scaling behavior. This transition of the statistical behavior of Barkhausen avalanches in a specific region near the coercive field is thus indicative of a complex phenomenon in the magnetization reversal process of real 2D ferromagnetic systems.

In summary, we have investigated the statistical nature of Barkhausen avalanches along the magnetic hysteresis loop of a CoCrPt alloy film with PMA by direct observation of magnetic domains using high resolution magnetic soft x-ray microscopy. We find a simple power-law scaling behavior of Barkhausen jump domain sizes for fields decreasing toward the coercive field. Surprisingly, the critical scaling exponent changes abruptly at an applied field around the coercivity of the sample, which is most likely due to the coupling of adjacent domains.

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