Magnetic soft x-ray microscopy at 15 nm resolution probing nanoscale local magnetic hysteresis (invited)

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Recent progress in x-ray optics has pushed the lateral resolution of soft x-ray magnetic microscopy to below 15 nm. We have measured local magnetic hysteresis on a nanometer scale at the full-field x-ray microscope XM-1 at the Advanced Light Source in Berkeley, approaching fundamental length scales such as exchange lengths, Barkhausen lengths, and grain diameters. We have studied the evolution of magnetic domain patterns in a nanogranular CoCrPt film with a pronounced perpendicular magnetic anisotropy and revealed nanoscopic details associated with the granular film structure. From a quantitative analysis of the field-dependent magnetic domain patterns, we are able to generate local magnetic hysteresis map on a nanometer scale. Our findings indicate a significant variation of local coercive fields corresponding to the nanoscopic behavior of magnetic domains. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2167060]

I. INTRODUCTION

Imaging magnetic microstructures in low-dimensional systems with nanometer spatial and subnanosecond time resolution provides key information to both understand the fundamentals of magnetism and the rapid development in technologically relevant areas such as the increase in magnetic storage density[1] and the decrease in size in magnetic sensor and spintronic elements.[2] Studies of both magnetic static and dynamics properties are therefore of utmost interest. Changes of the magnetization state in most ferromagnetic systems are mediated by domain nucleation and domain-wall expansion.[3] With decreasing size of the magnetic devices fundamental length scales such as grain size Barkhausen length and exchange length are within reach and the local variation of magnetic properties on that length scale becomes relevant. Therefore, techniques capable to characterize local magnetic properties and their underlying magnetic microstructure are required. High-resolution magnetic soft x-ray microscopy is a promising imaging technique since it combines x-ray magnetic circular dichroism as element-specific large magnetic contrast mechanism with Fresnel zone plate optics providing currently a lateral resolution down to below 15 nm.[4] Utilizing the inherent pulsed time structure of synchrotron-radiation sources a stroboscopically pump-and-probe scheme allows us to study also fast magnetization phenomena on a subnanosecond time scale.[5]

Upon applying a varying external magnetic field, ferromagnetic systems exhibit a history dependence, resulting in a magnetic hysteresis loop[6] whose analysis can be used to determine important magnetic quantities such as coercivity, susceptibility, and overall reversal behavior. So far only few experimental attempts have been made to address the nanoscale local magnetic hysteresis behavior and its correlation with corresponding microscopic properties.[7–9]

Recently, measurements of local hysteresis loops in Co/Pd multilayer films have been reported utilizing the magneto-optical Kerr effect[7,8] (MOKE) in a polarized optical microscope, with a spatial resolution limited by the diffraction limit (>0.4 μm) of visible light. With a spin-polarized scanning tunneling microscope (SP-STM) nanoscale local hysteresis loops in Fe nanowires on stepped W(110) could be obtained and wall motion and creation annihilation of the domains have been observed.[9] Here, we report on magnetic soft x-ray microscopy measurements to probe local magnetic hysteresis loops at a high spatial resolution at 15 nm in a nanogranular CoCrPt sytem.

II. EXPERIMENTAL DETAILS

The results have been obtained at the high-resolution magnetic soft x-ray microscopy beam line 6.1.2 at the Ad-

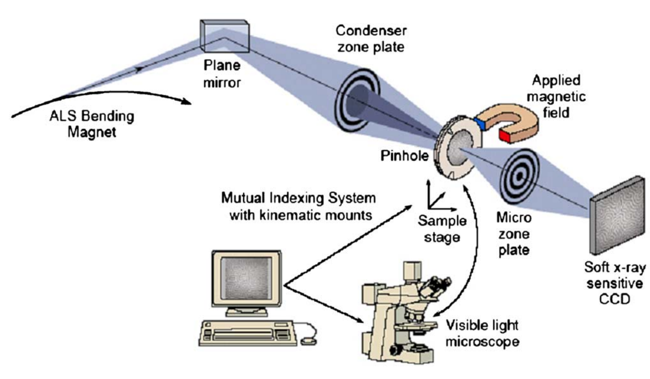

FIG. 1. Schematic diagram of the XM-1 setup (Ref. 10).

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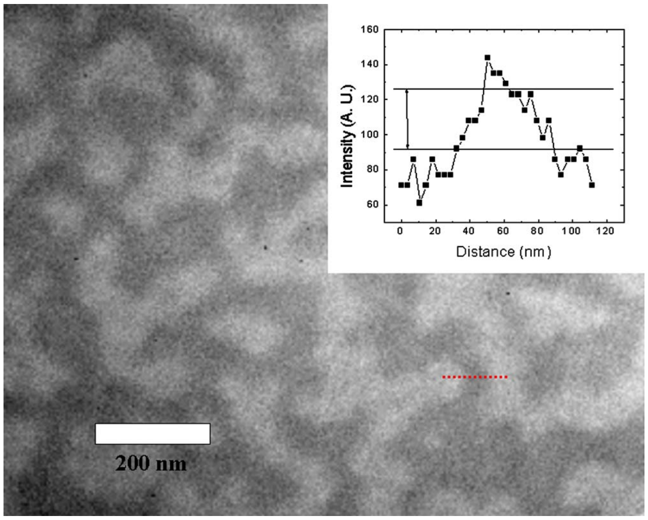

FIG. 2. Typical magnetic domain image of CoCrPt over $1.1\times 0.9\ \mu m^2$ at $H=0$. Line intensity profile of the dotted vertical line in the image is shown in the inset.

vanced Light Source in Berkeley, CA. Its schematical setup is illustrated in Fig. 1. A detailed description of the experimental setup used for imaging static and dynamic magnetic structures is described elsewhere.[5,10,11] Since the refractive index of x rays is close to 1, conventional lenses cannot be used for imaging soft x rays. However, Fresnel zone plates, i.e., circular gratings with a radial increasing line density, are now well established as x-ray optical elements. Both condensers and objectives can be fabricated by applying nanotechnological lithographic tools. The outermost zone width in the objective lens determines largely the obtainable spatial resolution, and recently the sub-15 nm resolution has been achieved.[4,12] The condenser zone plate (CZP) together with a pinhole close to the specimen acts as a linear monochromator due to the wavelength dependence of the focal length of the CZP. The microzone plate (MZP) projects a full-field image nto a 2048×2048 pixel array of a CCD. Magnetic contrast is given by x-ray magnetic circular dichroism (XMCD) and proportional to the projection of the magnetization onto the photon propagation direction. Circularly polarized x rays are obtained by viewing the off-orbit emitted x rays from the bending magnet source.

$(Co_{83}Cr_{17})_{87}Pt_{13}$ alloy films with 50 nm thickness were prepared on a 40-nm-thick Ti buffer layer using dc magnetron cosputtering of a CoCr alloy target with Pt chips at a base pressure better than 10^{-7} Torr and a sputtering Ar pressure of 3 mTorr. A 200-nm-thick Si_3N_4 membrane was used as a substrate in order to allow high transmission of soft x ray to guarantee an enough intensity for imaging within few seconds per image frame. The magnetic anisotropy and the saturation magnetization are $1.58\times 10^6\ \mathrm{ergs/cm^3}$ and $362\ \mathrm{emu/cm^3}$, respectively. The average grain size of the sample determined from analyzing transmission electron microscope images using particle-analysis software was about 35 nm.[11]

The images have been recorded at the Co L_3 edge (777 eV) with varying external magnetic field pointing perpendicular to the sample plane with a maximum field strength of ±4.6 kOe. The illumination time required per image is typically a few tens of seconds. Since the observed magnetic contrast is directly proportional to the local Co magnetic moment in a quantitative analysis of the recorded images of 300×240 pixels ($\sim 1.1\times 0.86\ \mu m^2$ at 2×2 pixel binning), we can determine the *local magnetization* as a function of external field, i.e., the local magnetic hysteresis loop. To demonstrate the power of high-resolution full-field imaging it is worth noting that with a grid of 5×5 pixels, 2880 local hysteresis loops on a nanoscale are simultaneously measured, where a unit pixel area corresponds to a $3.6\times 3.6\ \mathrm{nm}^2$ of the film surface at 2×2 pixel binning.

III. RESULTS

Typical raw images of magnetic domains in the $(Co_{83}Cr_{17})_{87}Pt_{13}$ alloy film are illustrated in Fig. 2. Previous

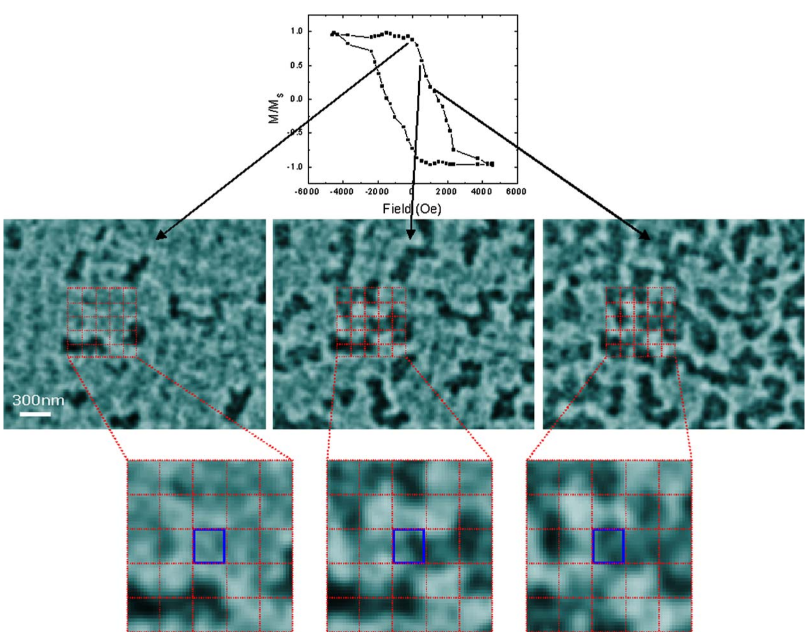

FIG. 3. Hysteresis loop (top) determined by analyzing the intensity of the total observation area (300×240 pixels). Field-dependent magnetic domain patterns (middle) during the field cycle are illustrated, where the 75×75 pixel region is denoted as divided by 5×5 grids. Each grid has 15×15 pixels ($\sim 100\times 100\ \mathrm{nm}^2$).

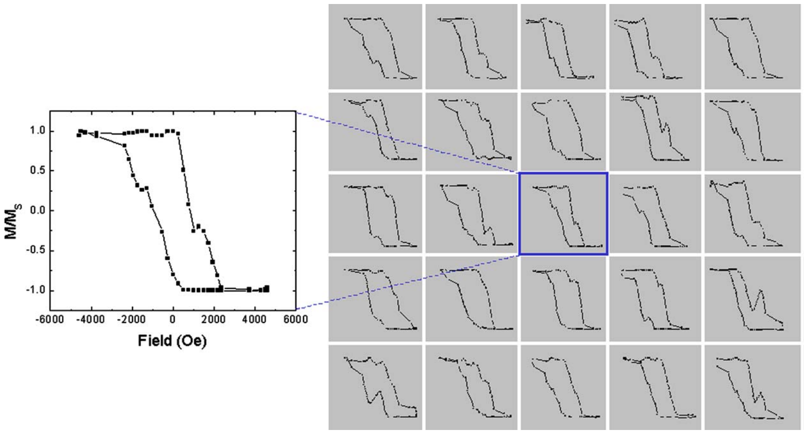

FIG. 4. Local hysteresis loop (left) for center grid and 5×5 array local hysteresis loop (right) corresponding to the 5×5 grids of Fig. 3.

MTXM results at lower spatial resolution have already indicated that the local magnetization reversal behavior is dominated by the domain nucleation.[11] The nucleation process is attributed to a switching of individual grains, which are found to be partially randomly distributed.[13] A typical line profile of the intensity across a domain boundary is shown in the inset of Fig. 2, clearly revealing the spatial resolution of the present MZP to be less than 15 nm. Due to the nonuniform illumination each magnetic image is normalized to a Gaussian-smoothed image of itself.

A quantitative analysis of the field-dependent average intensity of each image during the field cycling enables us to determine the magnetic hysteresis loop averaged over the full field of view (FOV) coresponding to 300×240 pixels, as demonstrated at the top of Fig. 3. Three representative domain patterns at 4×4 binning mode (FOV $\sim 2.2 \times 1.7\ \mu m^2$) during the field cycling are illustrated in the middle of Fig. 3. Qualitatively the domains nucleate initially at a certain position and expand by small amounts before merging with neighboring domains.

Due to the high spatial resolution the intensity information contained in each image can be processed for each pixel separately. By adjusting the grid size a local magnetic hysteresis loop on a nanometer scale is determined. In the case of using the grid of 15×15 pixel size, grids of 5×5 arrays are selected and magnified as an example, as shown at the bottom of Fig. 3. The local magnetic hysteresis loop of $\sim 100 \times 100\ nm^2$ area denoted by the bold square at the bottom of Fig. 3 is depicted at the left of Fig. 4, together with 5×5 array of hysteresis loops corresponding to the region of 5×5 array grid in Fig. 3. Interestingly, hysteresis loops exhibit significant variations at each grid area, which directly reflects the nonuniform local distribution of magnetic switching fields and susceptibility.

IV. CONCLUSION

High-resolution magnetic x-ray microscopy is able to study quantitatively and element specifically local magnetic hysteresis loops on a 15 nm length scale within a field of view of tens of micrometers in multicomponent-nanosized magnetic systems. Since even higher-resolution x-ray optical lenses can be fabricated in the near future, it can be foreseen that MTXM studies will contribute significantly to a microscopic understanding of the collective magnetization reversal phenomenon.

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