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Metastable Domain Structures of Ferromagnetic Microstructures Observed by Soft X-Ray Magnetic Circular Dichroism Microscopy

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The benefit of combining soft X-ray magnetic circular dichroism and photoelectron microscopy is demonstrated by applying this combination to the observation of the magnetic domain structures of rectangular microstructures. The size and aspect-ratio dependence of the transformation of the domain structures by magnetic field pulses is investigated. The switching mechanism, which is very important in the application to magnetic storage, is discussed in terms of transformation between saturated and vortex domain structures.

KEYWORDS: magnetic microstructures, XMCD microscopy, PEEM, magnetic storage

Magnetic domain structures of microstructures and their magnetization processes have attracted much attention from the viewpoint of application to terabyte data storage and a new class of devices using the electron's spin degree of freedom. Needless to say, they are also very interesting from the fundamental point of view.

Recently, element-specific microscopic imaging of domain structures has become possible by the combination of photoelectron emission microscopy (PEEM) and magnetic circular dichroism in soft X-ray photoabsorption (XMCD).[1,2] XMCD is the phenomenon in which the core-level absorption intensity (I) of circularly polarized soft X-ray by a magnetic element depends linearly on the projection of the magnetic moment of the element on the photon spin.[3,4] For example, prominent XMCD is observed in the $2p \rightarrow 3d$ absorptions of Fe, Co and Ni. PEEM detects the lateral distribution of the intensity of secondary electrons (I_s) that are emitted from the sample. Since I_s is known to be proportional to I, PEEM-XMCD gives us XMCD at all points in the PEEM's field of view at once. One great advantage of PEEM-XMCD over other methods of imaging magnetic domains[5] is its element specificity.

In this study, we investigate the effect of magnetic field pulses on the domain structures of rectangular microstructures of Co thin film by means of XMCD-PEEM. We focus on the size and aspect-ratio dependence of the characteristic features, *e.g.*, the magnetic fields required for saturation and switching.

Rectangular microstructures of 30-nm-thick polycrystalline Co film were made on a Si substrate by electron-beam lithography and the lift-off technique. Both the length and the width of the rectangles were changed from 0.5 to 32 μm, in steps of a factor of 2.

Measurements were performed at room temperature using the circularly polarized soft X-ray beamline BL25SU of SPring-8, Japan.[6] The setup of the photoelectron microscope (Focus IS-PEEM[7]) was identical to that described in previous publications.[2,8] The lateral resolution was set to about 0.4 μm, while the field of view was set to about 50 μm. In order to improve the magnetic contrast, we took PEEM images at two photon energies corresponding to Co $2p_{3/2}$ and $2p_{1/2} \rightarrow 3d$ transitions under the same photon spin and generated an asymmetry image. This image is the distribution of $(I(2p_{3/2}) - I(2p_{1/2}))/(I(2p_{3/2}) + I(2p_{1/2}))$, which depends linearly on the projection of the magnetic moment on the photon spin. Pulsed magnetic field for magnetization was applied to the in-plane direction, i.e., parallel to the surface, by discharging a capacitor through a core-less solenoidal coil, and measurement was carried out under zero field.

Figure 1 shows the asymmetry image of PEEM-XMCD for the as-made rectangular microstructures. The circularly polarized soft X-ray was incident in the direction shown by the arrow on the lower right-hand corner with a grazing angle of 30° from the sample surface. White and dark gray parts correspond to the domains magnetized upward and downward, as indicated by arrows. Light gray parts are magnetized to nearly horizontal directions, and whether they are right or left can be deduced from the geometrical connection of the domains. In each microstructure, such a domain structure is realized as the stray field is decreased. Nearly 90° domain walls are most commonly seen and some nearly 180° domain walls can also be seen.

Next, magnetic field pulses were applied to the microstructures. First, in-plane pulses in the downward direction defined in Fig. 2 were applied. Starting from a magnetic field of about 10 Oe, pulses with increasing fields were applied. A PEEM-XMCD asymmetry image was recorded after each pulse. Figure 2 shows the domain structures after downward pulses. The sizes of the patterns are $L_x \times L_y = 2 \times 8$(a), 4×8(b), 8×8(c), 4×4(d), 8×4(e) and 8×2(f) μm^2.

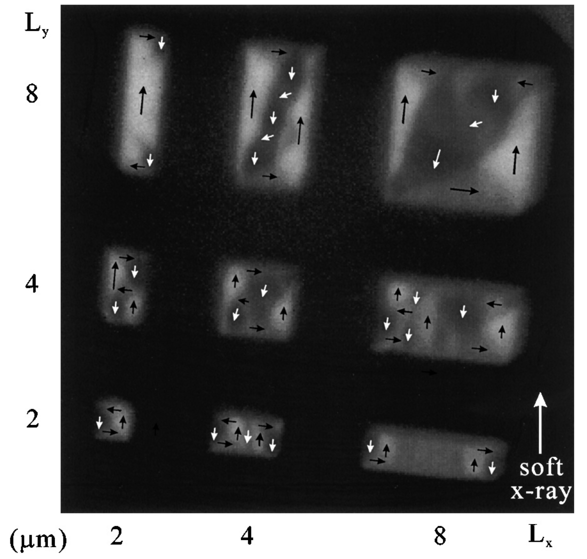

Fig. 1. As-made asymmetry image revealing domain structures of rectangular microstructures. Numbers at the sides show the width (L_x) and length (L_y) of the rectangles on corresponding columns and rows. The circularly polarized soft X-ray was incident in the direction shown by the arrow on the lower right-hand corner with a grazing angle of 30° from the sample surface. White and dark gray parts in the rectangles correspond to domains magnetized upward and downward, as indicated by arrows. Light gray parts are magnetized to nearly horizontal directions, and whether they are right or left can be deduced from the geometrical connection of the domains.

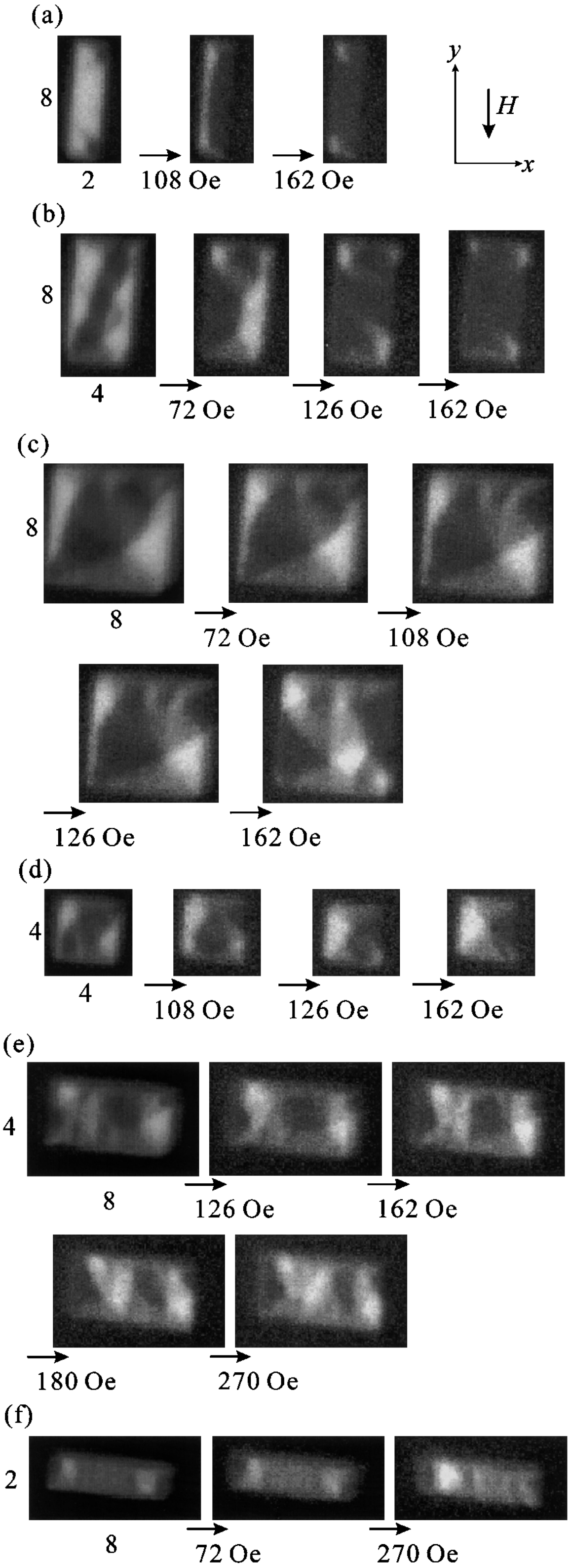

Fig. 2. Magnetization processes of rectangular structures by downward magnetic field pulses of $L_x \times L_y = 2 \times 8$(a), 4×8(b), 8×8(c), 4×4(d), 8×4(e) and 8×2(f) μm^2 patterns are displayed. Downward magnetization corresponds to dark gray. Rectangles tend to be nearly saturated more easily by magnetic pulses along their longer sides. For details, see the text.

In the case of $L_x < L_y$, with the longer side parallel to the magnetic field, vortex domain structures, i.e., structures with rotating magnetization directions, were first realized as in the 108 Oe (72 Oe) image for the 2×8 (4×8) μm^2 pattern. This transition is characterized by the growth of seed domains, i.e., the dark gray areas in the as-made patterns (Figs. 2(a) and 2(b)). Next, they became nearly saturated as in the 162 Oe (126 or 162 Oe) image for the 2×8 (4×8) μm^2 pattern. Domains with magnetization opposite to the applied field shrinked into small domains at the corners. The magnetization processes of these $L_x < L_y$ patterns are further discussed below.

The magnetization processes of 8×8 and 4×4 μm^2 squares resembled each other up to 108 Oe. For higher magnetic fields, the magnetization process was quite size-dependent. The domain structure of the 4×4 μm^2 square was transformed into a vortex structure at 162 Oe, which remained up to 288 Oe pulse. This demonstrates the stability of the vortex structure in small squares. The larger 8×8 μm^2 square retained its complex domain structure up to 288 Oe pulse.

In the case of $L_x > L_y$, with the shorter side parallel to the applied field, a magnetic field pulse induces a transformation from one complex domain structure to another. The realized domain structures contain two typical domain configurations: one is the vortex structure and the other is the stripe structure with upward and downward magnetizations. The former is characterized by 90° domain walls and the latter, by 180° walls. Only the 32×16 μm^2 rectangle among all $L_x > L_y$ rectangles was nearly saturated by the 288 Oe or lower pulse. The tendency that a rectangle is more easily saturated when the magnetic field is applied along its longer side can be understood qualitatively from the shape anisotropy.

Next, we investigated the magnetization reversal processes of $L_x < L_y$ rectangles. For this, we chose $L_x < L_y$ rectangles that were saturated by the largest-available 288 Oe downward pulse, and investigated the effect of upward pulses. (The resulting patterns are not shown here.) We define two transition fields for each rectangle. The coercive field H_C is the magnetic field of the pulse by which the downward saturated structure is changed into a different structure. The saturation field H_S is the field which is necessary for saturation in the upward direction.

The L_x and L_y dependences of H_C and H_S are shown in Fig. 3. Rectangles can be categorized into two groups. The saturated domain structure of one group is directly transformed into the reversed saturation, which leads to $H_C = H_S$. This type corresponds to what Hefferman *et al.*[9] called 'type A' and is seen in the smaller L_x region of Fig. 3. In the other group, named 'type B', the saturated domain structure is first transformed into the vortex structure at H_C, and then is saturated in the direction of the pulse at H_S. This type is recognized in the larger L_x region of Fig. 3. It might seem unnatural that the H_C of $2 \times 4\ \mu\text{m}^2$ is zero. This reflects the experimental result that after this rectangle was saturated by the downward pulse, it transformed by itself into a vortex structure. This indicates that the vortex structure is very stable in this rectangle. The trigger for the transformation might be thermal fluctuation or an external stray field.

For a fixed L_y, H_C decreases monotonically as L_x increases. The magnitude of the slope seems to be larger for smaller L_y. What might be happening at H_C in the magnetization process is that the end domains such as the white areas in the 162 Oe image of $L_x \times L_y = 4 \times 8\ \mu\text{m}^2$ (Fig. 2(b)) grow until the tips of the domains touch each other, or even before they touch, the creation of a new domain wall might take place near the end domains, which then moves across the rectangle.[9] If we compare such end domains of rectangles with different L_x as $L_x \times L_y = 4 \times 8$ and $2 \times 8\ \mu\text{m}^2$, the end domains of the rectangle with larger L_x extend more into the rectangle. Therefore, the switching process is realized by a smaller field pulse in a rectangle with a larger L_x.

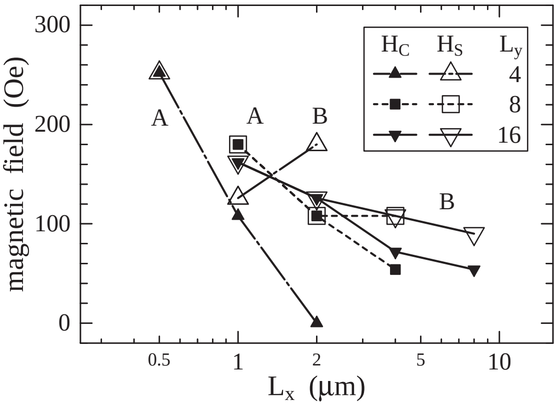

Fig. 3. Dependence of the coercive field H_C and the saturation field H_S on the width (L_x) and the length (L_y) of rectangles where the magnetic field is in the y-direction. For a fixed L_y, H_C decreases as L_x is increased. While H_S coincides with H_C for smaller L_x, it deviates from H_C for larger L_x.

On the other hand, the slope of H_S in the type-B region might be due to the shape anisotropy. However, the shape anisotropy of a thin film should be weak. In fact, the H_S values in the type-B region are all about 100 Oe, except for $L_x \times L_y = 2 \times 4\ \mu\text{m}^2$. This H_S value of about 100 Oe can be considered as the saturation field of an infinite plane of the film. The exceptionally large value of H_S for $2 \times 4\ \mu\text{m}^2$ can be attributed to the above-mentioned strong stability of its vortex domain structure. The stability of such structures becomes irrelevant for larger rectangles.

In conclusion, domain structures and their magnetization processes were investigated by XMCD-PEEM for 30-nm-thick Co rectangles with sides of 0.5–32 μm. By applyin magnetic field pulses parallel to the longer sides of the rectangles, saturated domain structures were realized. The magnetization reversal processes of these rectangles were characterized by the length and width dependences of the coercive and saturation fields. Vortex domain structures were found to be very stable in small squares and small rectangles with aspect ratios near one.

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1) J. Stöhr, Y. Wu, M. G. Samant, B. B. Hermsmeier, G. Harp, S. Koranda, D. Dunham and B. P. Tonner: Science **259** (1993) 658.
2) C. M. Schneider: J. Magn. Magn. Mater. **175** (1997) 160.
3) G. Schütz, W. Wagner, W. Wilhelm, P. Kienle, R. Zeller, R. Frahm and G. Materlik: Phys. Rev. Lett. **58** (1987) 737.
4) C. T. Chen, F. Sette, Y. Ma and S. Modesti: Phys. Rev. B**42** (1990) 7262.
5) A. Hubert and R. Schäfer: *Magnetic Domains* (Springer, Berlin, 1998) Chap. 2.
6) Y. Saitoh, T. Nakatani, T. Matsushita, T. Miyahara, M. Fujisawa, K. Soda, T. Muro, S. Ueda, H. Harada, A. Sekiyama, S. Imada, H. Daimon and S. Suga: J. Synchrotron Rad. **5** (1998) 542.
7) FOCUS GmbH: Am Birkhecker Berg 20, D-65510 Hünstetten, Germany.
8) W. Kuch, R. Frömter, J. Gilles, D. Hartmann, Ch. Ziethen, C. M. Schneider, G. Schönhense, W. Swiech and J. Kirschner: Surf. Rev. Lett. **5** (1998) 1241.
9) S. J. Hefferman, J. N. Chapman and S. McVitie: J. Magn. Magn. Mater. **95** (1991) 76.