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Magnetic Domain Configuration in Cobalt and Permalloy Micro-Structures

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We used atomic force microscopy to investigate the magnetic domain configurations in 65-nm-thick cobalt and permalloy rectangular micro-structures, in the virgin state, for various values of the aspect ratios. The two materials exhibited complex magnetic domain structures for lower aspect ratios, but exhibited single-domain structures for higher aspect ratios. In comparison with cobalt films, permalloy films showed much simpler domain structures and larger domain sizes. The domain sizes of cobalt and permalloy films were ~ 1 μm and ~ 2 μm, respectively, which were larger than those reported previously. This might have resulted from the large shape anisotropy of our samples.

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Studies on spin-dependent transport phenomena for spin-involved electronics (spintronics) in micrometric or nanoscale structures have focused on detecting and manipulating the spin information of conduction electrons, which can be realized by injecting a spin-polarized current from an itinerant ferromagnet into a non-ferromagnetic normal metal or a semiconductor [1–5]. The efficiency of the spin injection depends directly on the polarization of the ferromagnet electrode and the spin-relaxing scattering at the spin-injecting interface. Thus, it is necessary to choose a high-polarization material, such as a half-metallic ferromagnet, for the ferromagnet electrode. On the other hand, since magnetization can form in a multi-domain structure in a ferromagnet, preparing the ferromagnet electrode in a single-domain state, or at least a domain-aligned state, is crucial to injecting uni-directionally spin-polarized conduction electrons from a ferromagnet. Thus, it is very important to investigate the material or physical parameters characterizing the magnetization state in the ferromagnet electrode, especially the information on the development of its magnetic domain configuration.

The shape, the lateral size, and the thickness of micrometer-scale magnetic structures are well known to play a crucial role in the domain formation and magnetization-reversal characteristics of the structure [6, 7]. In this study, we used magnetic force microscopy (MFM) to investigate the magnetic-domain structures in patterned cobalt and permalloy ($Ni_{81}Fe_{19}$) thin films of rectangular shapes with various values of the aspect ratio.

Hard (soft) ferromagnetic cobalt (permalloy) thin films were fabricated into micrometric-scale rectangular shapes by using direct-write electron-beam (e-beam) lithography incorporating a JSM-5610 scanning electron micrscope (SEM), electron-beam evaporation, and a lift-off process. A bi-layer of an e-beam resist, consisting of a 950-K molecular weight positive-type PMMA resist and its co-polymer PMMA/MA, was coated on a Si substrate covered with a native ∼1-μm-thick oxide layer. A one-to-one mixture of MIBK:IPA was used to develop the bi-layer just after the designed patterns were e-beam exposed. Sixty-five-nm-thick cobalt and peramlloy films were e-beam deposited on the e-beam patterned Si substrates at a rate of 0.8 Å/s and 0.4 Å/s, respectively, at a chamber vapor pressure of a few times 10^{-6} Torr. The lift-off was done in an acetone bath, leaving only the patterned cobalt and permalloy micro-structures. During the deposition, no domain-aligning magnetic field was applied to the magnetic films. The patterns were designed to have a fixed length of 10 μm, but the width was varied in several steps from about 10 μm down to 0.75 μm with the corresponding different aspect ratios.

The morphology of the films was examined using atomic force microscopy (AFM). The images of the magnetic configuration of the films were taken using a multimode scanning probe microscope manufactured by Digital Instruments. A tapping-lift mode was employed for the AFM and the MFM scanning with a standard commercial cantilever at a scan height of 70 nm. The can-

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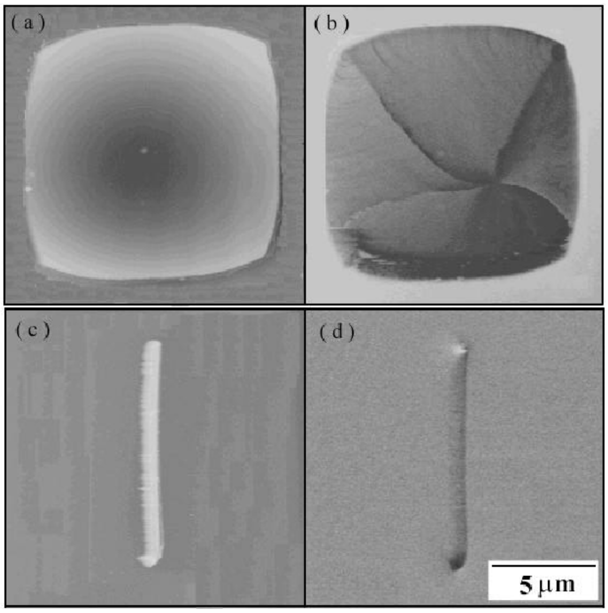

Fig. 1. (a) AFM image of a permalloy film with lateral dimensions of ∼11 μm × 11 μm and (b) the corresponding MFM image. (c) AFM image of a permalloy film with lateral dimensions of 11 μm × 0.75 μm and (d) the corresponding MFM image.

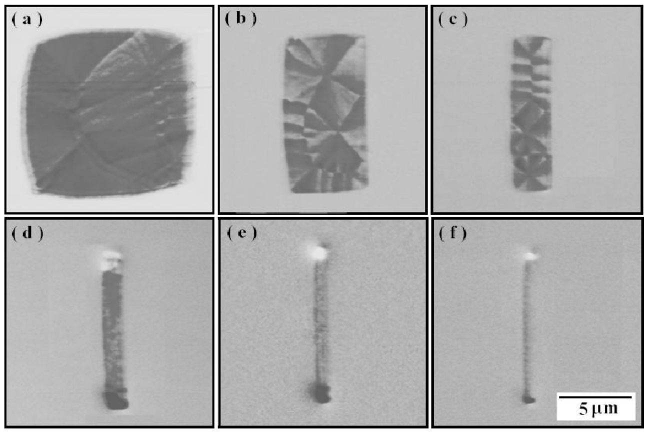

Fig. 2. MFM images of the cobalt films with their magnetic domain structures corresponding to the average dimensions determined by AFM images of (a) ∼11 μm × 11 μm, (b) ∼11 μm× 5.5 μm, (c) 11 μm × 2.8 μm, (d) 11 μm × 1.6 μm, (e) 11 μm × 1.2μm, and (f) 11 μm × 0.9 μm.

tilever was equipped with a Co-Cr tip with a medium magnetic moment of $\sim 3 \times 10^{-12}$ emu and a coercivity of ∼ 400 Oe [8]. Right before the measurement scan, the cantilever tip was magnetized perpendicular to the plane of the magnetic films.

In the tapping mode, the vibrating cantilever is run at a constant frequency close to the resonance in the sample's varying magnetic field. The subsequent change in the amplitude and the phase of the cantilever vibration is measured. The MFM images with a vertically magnetized tip reveal the second derivative of the vertical component of the magnetic field from the samples under study. The contrast of the images illustrates the stray field gradient on the film's surface and the corresponding phase change of the MFM tip.

In Fig. 1, two AFM images of permalloy films are shown along with the corresponding MFM images. The dimensions of the films were designed to be 10 μm × 10 μm and 10 μm × 0.7 μm, respectively. The actual lateral dimensions of the films, determined by AFM after the microfabrication processes, turned out to be about 10 % larger than the designed value. The shapes of the structures became a little rounded from the designed square and/or the rectangular geometry because of the proximity effect during the e-beam writing process.

The configuration of the magnetization for the two permalloy films is shown in the MFM images. As seen in Fig. 1(d), the high-aspect-ratio rectangular structure exhibits a single domain, with dark and bright spots at both ends. On the other hand, the large square island shows four-domain closure with a quite deformed triangular-domain vortex formation centered at an inner position. The gradual contrast change represents the nonuniform distribution of the magnetization inside the domains. The abrupt contrast change, on the other hand, corresponds to a local jump in the magnetization at the domain boundaries. The specific magnetic domain structure inside the patterned films is closely related to the size and the shape anisotropy [6,7] and is determined by a competition between the exchange energy and the shape-dependent demagnetization energy. Thus, the deformed triangular domain shape may have been caused by the rounded boundary of the island.

We turn to the detailed change in the magnetic domain structure of cobalt and permalloy films with various shapes. Figure 2 exhibits the MFM images of the magnetic domain structure for cobalt films of different sizes and the corresponding aspect ratios. The dimension of the cobalt film in each frame, determined from the AFM image (not shown), is specified in the caption. Bright and dark regions correspond to the north and the south poles, respectively, or vice versa. The cobalt films with a 1:1 (width:height) aspect ratio in (a) has a combination of 90° and 180° domain walls, but the domain located on the right side of the Bloch line exhibits complicated contrast changes, which may be a revelation of a nonuniformity in the magnetization or the formation of tiny multi-domains. One possibility is that it simply reflects the inhomogeneity caused in the film deposition process, which was seen to some extent in the corresponding AFM image (not shown). The MFM image for the film with a 1:2 aspect ratio in (b) shows well-defined, but complex, magnetic structures: a combination of a five-domain vortex, a four-domain vortex, and Bloch lines. Similar structures are also seen in the film with a 1:4 aspect ratio in (c). The average minimum lateral size of the square domain is ∼ 1 μm. Once

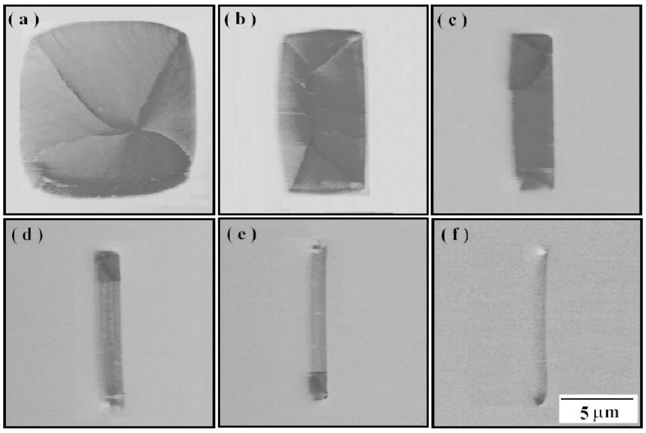

Fig. 3. MFM images of the permalloy films with their magnetic domain structures corresponding to the average dimensions determined by AFM images of (a) ~11 μm × 11 μm, (b) ~11 μm × 6 μm, (c) ~11 μm × 3 μm, (d) 11 μm × 1.7 μm, (e) 11 μm × 1.4 μm, and (f) 11 μm × 0.75 μm. Images in (a) and (f) are the same as the ones shown in Figs. 1(b) and 1(d).

the width of a rectangle becomes less than ~1.5 μm, the micromagnets show only a single-domain structure as in (d)-(f), although some contrast variation corresponding to a gradual magnetization change is still visible.

The domain structure is well known to move and change in shape when an external magnetic field is applied [9–13]. In this study, however, no effort was made to investigate the influence of an external field on the domain formation and its dynamics. Previous results [9] revealed single-domain formation in nano-structure cobalt thin films with lateral sizes less than 200 nm and thicknesses of 17 nm. The domain configuration is determined by a competition between the exchange energy and the demagnetization energy for a given geometry [14]. If the exchange energy predominates as in structures with a large aspect ratio, a single-domain formation is preferred. By contrast, if the demagnetization energy predomintes as in structures with a small aspect ratio, a domain vortex state is preferred. Thus, the domain structure is sensitive to the size and the shape of the micromagnets. The general domain-formation characteristics in our 65-nm-thick cobalt films are consistent with previous observations [9], but the domain size in our films turns out to be larger than observed before in cobalt films with similar lateral dimensions. We believe the difference stems from the larger shape anisotropy effect with the higher aspect ratio in our films.

In Fig. 3, the MFM images for various permalloy magnetic films are also shown with their magnetic domain structures. Again the dimensions for the MFM images were determined from AFM images and are specified in the caption. As seen earlier, the magnetic structure for the film with a 1:1 aspect ratio in (a) contains a well-defined domain vortex closure. The shape of the domain structure in the film with the aspect ratio of about 1:2 as in (b) is a combination of 90° walls and a 180° wall similar to the one in the 1:1 ratio cobalt island. The domain configuration in (c) is also much simpler than for the rectangular film with a corresponding aspect ratio in Fig. 2(c), almost single-domain-like structure over most of the sample region. For rectangular structures with higher aspect ratios, as in (d), (e), and (f), a single-domain structure forms except for one end of the magnet as in (d) and (e). We believe the formation of the domain walls in (d) and (e) was seeded by defects in the films themselves. In these soft magnetic permalloy films, the domains (~ 2 μm) are much larger and cleaner than those in the corresponding cobalt films.

The development of a smaller domain size in the strong ferromagnetic cobalt films is easily understood, because cobalt films with stronger exchange energy prefer splitting up into smaller domains to reduce the total magnetostatic energy [15]. For the higher aspect ratios beyond 1:10, however, both cobalt and permalloy films exhibit single-domain structures as the demagnetization energy becomes suppressed due to predominant geometrical contributions with the increased aspect ratios.

As seen in the high-aspect-ratio rectangular structures of both materials, the bright and the dark spots form only at ends of the structure. This fact indicates that the stray fields are dominant only at the ends of the rectangle. In spin-injection experiments, one prefers to inject spin-polarized electrons at the interface while minimizing the stray field interference to the electron-receiving electrodes. Our study indicates that one can achieve the goal by using a micromagnet electrode consisting of a soft-magnetic material and patterned with high aspect ratio.

In summary, we investigated the magnetic domain configurations in cobalt and permalloy rectangular microstructures with different aspect ratios. The two types of films had complex magnetic domain structures for lower aspect ratios, but had single-domain structures for higher aspect ratios. The cobalt films had more complicated domain structures than the permalloy films. The difference in this domain configuration is related to the contribution of the demagnetization energies. The domain sizes observed in cobalt and permalloy films were ~ 1 μm and ~ 2 μm, respectively. A soft-ferromagnetic micrometric structure with a high aspect ratio can be utilized to inject a spin-polarized current while minimizing the stray field interference to the current-receiving electrodes.

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