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Magnetic stripes and holes: Complex domain patterns in perforated films with weak perpendicular anisotropy

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Hexagonal antidot arrays have been patterned on weak perpendicular magnetic anisotropy NdCo films by e-beam lithography and lift off. Domain structure has been characterized by Magnetic Force Microscopy at remanence. On a local length scale, of the order of stripe pattern period, domain configuration is controlled by edge effects within the stripe pattern: stripe domains meet the hole boundary at either perpendicular or parallel orientation. On a longer length scale, in-plane magnetostatic effects dominate the system: clear superdomains are observed in the patterned film with average in-plane magnetization along the easy directions of the antidot array, correlated over several antidot array cells. [http://dx.doi.org/10.1063/1.4973284]

I. INTRODUCTION

Magnetic antidots have often been used to tailor the magnetic properties of extended films:[1–12] Depending on hole size and array geometry, they can enhance DW pinning,[2] modify magnetic anisotropy and easy axis direction[3] or, even, create ratchet effects on DW propagation.[4] For magnetic materials with in-plane anisotropy (i.e. magnetization confined to sample plane), magnetostatic effects at hole boundaries create periodic closure domain structures[1,3,5] with enhanced stability by the presence of pairs of half-vortices confined to hole edges.[6] Then, magnetization reversal occurs by the propagation of "composite DWs" that separate regions with different orientations of the closure domain structure relative to the applied field directions, so called "superdomains".[7,8] In the case of antidots perforated in materials with strong perpendicular anisotropy such as Co/Pt multilayers,[9,10] the interplay between out-of-plane stray fields and the antidot lattice has been used to enhance coercivity[9] and provides a promising alternative for the development of bit-patterned media.[10] As hole size is reduced and becomes comparable to material characteristic length scales (e.g. domain wall width), novel behaviors have been observed such as artificial spin ice[11] or magnonic crytals.[12]

Weak perpendicular magnetic anisotropy (wPMA) materials constitute an interesting intermediate case with relatively large in-plane and out-of-plane magnetization components in which the role of magnetic antidots has not been explored so far. Minimization of magnetostatic and anisotropy energy in these materials creates weak stripe domain patterns[13] in which the magnetization performs an out-of-plane oscillation around a relatively large in plane magnetization component (see sketch in Fig. 1(a)). In continuous films, the equilibrium stripe pattern tends to align with the last saturating field direction, due to "rotatable anisotropy", but it can become quite disordered (labyrinth) depending on magnetic history. It has been recently demonstrated that the competition between shape and rotatable anisotropies can be a tool to tailor stripe domain structure on a local scale in thickness modulated wPMA films.[14,15] Also strong rotatable anisotropy in arrays of wPMA dots has been used to create tunable exchange bias effects.[16] In this work, we have studied the effects of the magnetostatic shape anisotropy of a patterned antidot array on the remanent stripe domain configuration of perforated wPMA NdCo films with hole size comparable to stripe domain periods. Edge effects are

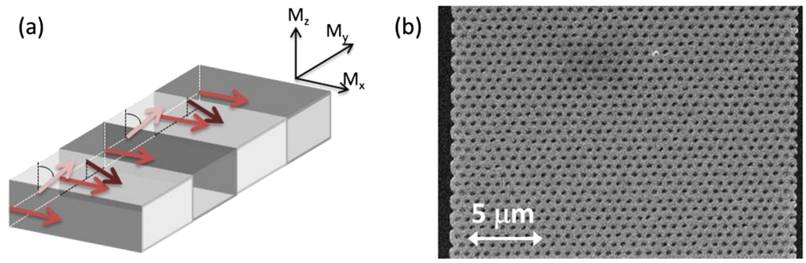

FIG. 1. (a) Sketch of stripe domain structure in wPMA thin film. (b) SEM image of antidot array fabricated on NdCo film by e-beam lithography.

found to control local orientation of the magnetization around each hole. On a longer length scale, "superdomains" are clearly observed, with average in-plane magnetization along the easy axis directions for in-plane shape anisotropy.

II. EXPERIMENTAL

Hexagonal arrays of antidots have been fabricated on amorphous $NdCo_5$ magnetic films by e-beam lithography and sputtering.[6] $NdCo_5$ is an amorphous alloy with saturation magnetization M_S = 700 emu/cm^3 and out-of-plane anisotropy $K_N \approx 10^6$ erg/cm^3.[14] The ratio between K_N and magnetostatic energy $2\pi M_S{}^2$ is Q= $K_N/2\pi M_S{}^2$ = 0.3 <1, so that it can be considered a weak PMA material.[13] For thickness above 50 nm, Nd-Co films support weak stripe domains with typical pattern period Λ in the 100-150 nm range.[14]

To prepare the antidot arrays, a PMMA resist template with the desired geometry has first been fabricated onto a Si substrate; then, a 60 nm thick $NdCo_5$ has been deposited on top by co-sputtering from pure Nd and Co targets (sandwiched between 5 nm thick buffer and cover Al layers to avoid oxidation);[14] finally, the perforated films have been obtained by a lift-off process in acetone. Figure 1(b) shows a SEM image of the 50 µm ×50 µm hexagonal array of 350 nm diameter antidots with 700 nm inter-hole distance used in this study. The array geometrical parameters have been chosen to be comparable to stripe domain periods in this material. Arrays of antidots with similar geometry have also been prepared on in-plane anisotropy Co films for comparison.

The samples were magnetized with a 5 kOe in-plane field along the high symmetry directions of the antidot array. Then, domain structure was characterized by Magnetic Force Microscopy (MFM) at remanence with a Nanotech™ Atomic Force Microscope system with magnetic Nanosensors™ PPP-MFMR commercial cantilevers (spring constant 3 N/m). Measurements were performed in dynamical retrace mode at a 50 nm lift height over the topography profile acquired previously. It must be noted that stripe domains in wPMA material locally follow the orientation of the in-plane magnetization component. Thus, Magnetic Force Microscopy (MFM) images provide a contour map of the in-plane magnetization configuration in patterned films.[14,15]

III. RESULTS AND DISCUSSION

Figure 2 shows the stripe domain configuration of the NdCo film, after saturating it along the horizontal direction of the hexagonal array of antidots. A clear pattern of parallel horizontal stripes, with period Λ = 120 nm, fills the image. This indicates the uniform orientation of the average in-plane magnetization in the observed region (Fig. 2(a)). This configuration minimizes "rotatable anisotropy", that in wPMA materials tends to align the stripes with the last saturating field direction.[15] It is also favored by magnetostatic shape anisotropy of the antidot array, since this array direction was found to be an easy axis for in-plane magnetized hexagonal arrays of permalloy antidots.[3] However, the detailed domain structure around each hole is clearly different in the wPMA array from the typical closure structures found for in-plane magnetized materials (see comparison between Figs. 2(b)–(c)). Closure domains around an antidot at an in-plane anisotropy Co film (Fig. 2(b)) display the typical

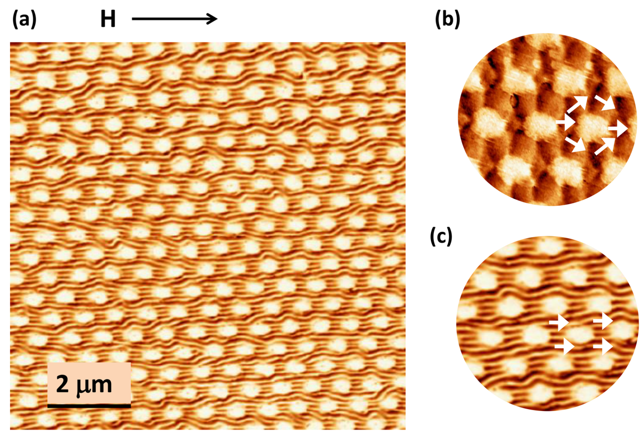

FIG. 2. (a) MFM image of the remanent domain structure of NdCo film with an hexagonal array of 350 nm wide antidots after applying a horizontal field (in-plane easy axis). Details of domain structure around an antidot are shown in (b) for Co film and (c) for NdCo film.

rhomboid shape corresponding to the circulation of the magnetization around the hole following a parallel boundary condition at the film/hole interface.[3,7,8] This closure structure minimizes in-plane magnetostatic energy, avoiding magnetic poles at the antidot.[6] On the contrary, in Fig. 2(c), stripes adopt a relatively straight pattern, showing two different preferred boundary conditions: i) there are groups of two or three short stripes that connect horizontal chains of antidots and meet the film/hole interface with perpendicular orientation, and ii) there are groups of one or two long stripes that run parallel to the hole boundaries in between these chains of antidots. Energy minimization in nanowires[17,18] has shown that stripes tend to orient either parallel or perpendicular near an edge independent of the applied field direction. Thus, the domain patterns observed in Fig. 2 indicate that edge effects are dominant in this wPMA antidot array, at least on length scales of the order of a few hundreds of nm, comparable to the stripe domain period.

When the magnetic field is applied along the in-plane vertical direction, which is a hard axis direction for in-plane magnetostatic shape anisotropy, the stripe domain configuration becomes more complex (see Fig. 3(a)). Once again, stripe domains meet the antidots either at parallel or perpendicular orientation (i.e. minimizing edge effects) but they follow longer meandering paths in between the antidots not aligned with the saturating field direction (i.e. not fulfilling the "rotatable anisotropy" condition). For holes connected by short perpendicular stripes, the average in-plane magnetization orientation in the interhole region is parallel to the stripes direction, as indicated by the short segments in Fig. 3(b). Magnetization in the interhole regions is mostly oriented at 0°, 60° and 120° (angles measured from horizontal direction), which correspond to the easy axis directions for in-plane magnetized arrays of antidots[6] indicating that in-plane magnetostatic anisotropy has overcome rotatable anisotropy in the patterned film. The largest fraction of the image corresponds to the easy directions closest to the vertical orientation of the last applied field (about 80% segments lie either at 60° or at 120°) with a smaller fraction at the horizontal direction (about 7%). Segments at 60° and 120° tend to cluster in regions that extend over a few array unit cells with homogeneous average in-plane magnetization (Fig. 3(c)), that would correspond with the "superdomain" structures observed for in-plane magnetized antidot arrays.[7,8] Domains at 0° are much smaller (in some cases they are just isolated segments). Boundaries between superdomains (i.e. superdomain walls) are relatively subtle and do not present the strong magnetic charges typical of superdomain walls on in-plane anisotropy antidot arrays.[7,8] Some of the observed superdomain walls are sharp 120° orientation turns localized at antidot rows perpendicular to the applied field direction (see horizontal dotted lines in Fig. 3(c)). On the other hand, domain boundaries closer to the applied field direction are not so well defined, and involve a certain degree of disorder in the stripe pattern (see e.g. at the bottom part of Fig. 3(c), the small horizontal domain surrounded by bifurcations in the stripe pattern). In both cases, defects at the stripe pattern and/or perpendicular stripes at hole edges allow to accommodate the change in average magnetization direction at the boundaries on a length scale of the order of stripe domain

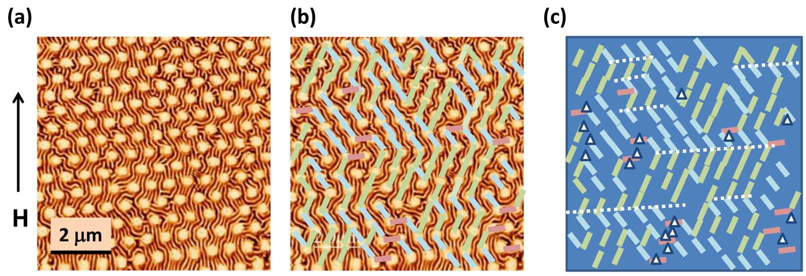

FIG. 3. (a) MFM image of the remanent domain structure of NdCo film with an hexagonal array of 350 nm wide antidots after applying a vertical field (in-plane hard axis); (b) Average in-plane magnetization orientation in between each pair of antidots deduced from "short stripes" orientation; (c) "Superdomains" structure deduced from the MFM image. White dotted lines indicate superdomain walls. Triangles mark the position of bifurcations and endpoints (topological defects) within the stripe pattern.

period Λ, smaller than the antidot array unit cell, which reduces magnetic charges at superdomain walls.

IV. CONCLUSIONS

In summary, we have studied the remanent stripe domain configuration of perforated wPMA NdCo films after saturating them along easy and hard axis direction of the hexagonal array of antidots. On a local length scale, of the order of the stripe domain period, edge effects within the stripe pattern dominate the behavior of the system: stripes meet the holes either at parallel or perpendicular orientation, overcoming in-plane magnetostatic anisotropy that favors parallel boundary conditions. On a longer length scale, average in-plane magnetization follows the easy axis directions for in-plane shape anisotropy of the hexagonal array of antidots, indicating the dominance of in-plane shape anisotropy. Clear "superdomains", i.e. regions with correlated average in-plane magnetization, are also observed in the system extending either over the full sample (for easy axis remanence) or over a few unit cells of the antidot array (for hard axis remanence).

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