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Lock in of magnetic stripe domains to pinning lattices produced by focused ion-beam patterning

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With focused ion-beam irradiation it is possible to engineer the anisotropy of magnetic films on nanometer length scales. We used this technique to write square lattices of artificial domain-wall pinning centers in a perpendicular anisotropy GdFe film displaying a well-defined stripe domain pattern. We observe a clear lock in of the intrinsic meandering stripe pattern to the pinning lattices, resulting in highly ordered domain patterns. We find that at remanence the dots pin the domain walls, while in perpendicular applied magnetic fields they host the down domains. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2030412]

INTRODUCTION

The ongoing scale reduction of magnetic recording and magnetic device technology calls for refined methods of domain size engineering. One possibility is to modify the magnetocrystalline anisotropy and hence the domain-wall pinning landscape by ion irradiation.[1–3] In most cases, the irradiation reduces the atomic order, which leads to a reduction of the anisotropy. In FePt (or Pd) films an increased anisotropy was observed however, that originates from an increased chemical ordering.[3] Ion-beam modification has been used to fabricate domain patterns using lithographically generated masks and stencils. A more flexible method is focused ion-beam (FIB) patterning, which offers the possibility of local anisotropy engineering on a length scale comparable to the domain-wall width, and hence modify the pinning landscape without substantially altering the film morphology. In this study we use FIB irradiation to locally modify the anisotropy of amorphous[4,5] GdFe thin films.

Amorphous rare-earth transition-metal (RT) films exhibit a perpendicular magnetic anisotropy (PMA), making them suitable for magneto-optical recording.[5] Given the right combination of magnetic properties and thickness, the magnetization of thin films with perpendicular anisotropy self-organizes in meandering up and down domains. Such stripe patterns originate from the energetic competition of the short-range exchange stiffness and the long-range magnetostatic interaction.[6,7] Stripes can exist in a variety of morphologies not only depending on the magnetic stiffness and the applied field but also on the magnetic history.[8]

The domain walls between the up and down domains are normally pinned on defects such as dislocations, vacancies, impurities, and interstitials. Although the amorphous structure of RT films is very disordered on the atomic scale, it is very homogeneous over length scales greater than several nanometers. The pinning potential landscape is therefore very flat, making these systems a good test bed for domain theory studies. The magnetic structure of RT films is sperimagnetic.[9] a ferrimagnet in which the magnetic moments of at least one of the sublattices is dispersed around the magnetic anisotropy axis.

The precise origin of the PMA in RT films is still not completely resolved but is linked to the microstructure of the material[10] and preferential ordering during deposition.[11] It depends on growth parameters such as temperature, pressure, and deposition method. We have found that the ion-beam irradiation with fluences as low as 4×10^{13} ions/cm^2 of 125-keV Ar-ions suffices to disrupt this subtle effect and produces a transition to in-plane magnetization. In this paper we use a 30-keV-focused Ga-ion beam to produce square lattices of reduced anisotropy dots, with the aim of studying how the intrinsic self-organized stripe pattern adapts to artificial pinning lattices with competing length scales. We observe a strong lock in of the stripe domains to the lattice in a manner that depends on ion fluence and lattice parameter. However, in applied perpendicular fields, the irradiated dots are host to the domains that are magnetized in the direction opposite to the field.

EXPERIMENT

Using electron-beam evaporation we deposited a 40-nm-thick $Gd_{16.7}Fe_{83.3}$ film on Si(111) using a rotating sample holder at room temperature at a pressure of 1×10^{-9} mbar. A 2.5-nm-thick Al capping layer was deposited on top to protect the film from oxidation. X-ray diffraction scans showed no trace of structural order. Using a 30-keV Ga^+-ion beam that was focused to nominally 30 nm, nine square lattices of resolution limited dots were written in which the interdot spacing (150, 200, and 250 nm) and ion fluence (1×10^{15}, 2×10^{15}, and 5×10^{15} ions/cm^2) were varied.

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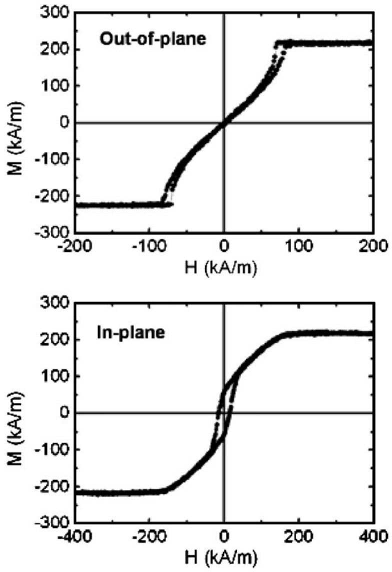

FIG. 1. Out-of-plane and in-plane hysteresis loops of pristine $Gd_{16.7}Fe_{83.3}$ measured with VSM.

RESULTS AND DISCUSSION

In-plane and out-of-plane hysteresis loops of the pristine film (Fig. 1) were measured with vibrating sample magnetometry (VSM). The out-of-plane coercivity is zero which indicates that indeed the film can be considered defect free. From the saturation magnetization $M_s=221$ kA/m we can extract the demagnetization energy $K_d=(1/2)\mu_0 M_s^2$. The uniaxial anisotropy constant $K_u=2.1\times 10^{-4}$ J/m^3 was estimated from the in-plane nucleation field $H_{cr}=150$ kA/m as $(1/2)\mu_0 H_{cr} M_s$. Taking the exchange stiffness constant $A=1.4\times 10^{-12}$ J/m from Mimura *et al.*,[12] we obtain a specific wall energy $\gamma_m=4\sqrt{AK_u}$ of 5.9×10^{-4} J/m^2 and a domain-wall width $\delta=\pi\sqrt{A/K_u}$ of 26 nm which is approximately eight times smaller than the average domain period at remanence $\tau_{rem}=210$ nm. The values for A, obtained from a mean-field approximation, and K_u are estimations within ~20%. They depend on various parameters that are very difficult to obtain precisely. The properties of the pristine film have been summarized in Table I. Unfortunately we could not locate a facility where sufficiently large areas can be patterned from which the fluence dependence of the magnetization and anisotropy could be extracted.

Figure 2 shows the dot lattice as imaged with atomic force microscopy (AFM). The dots have an irregular and slightly elliptical shape with the long axis in the writing direction of the FIB. The full width half maximum (FWHM) diameter of the dots is found to increase with ion fluence from ~50 to ~70 nm, while the depth ranges from 1.5 to 2.5 nm. The white dots are, presumably, Al_2O_3 grains of 20–40 nm and some sporadic dust particles, visible on a sample that is flat within 4 nm.

TABLE I. Properties of the pristine $Gd_{16.7}Fe_{83.3}$ film.

Film thickness t (nm)	40
Saturation magnetization M_s (kA/m)	221
Nucleation field H_{cr} (kA/m)	150
Out of plane coercivity H_c (kA/m)	0
Uniaxial anisotropy constant K_u (J/m^3)	2.1×10^4
Demagnetization energy constant K_d (J/m^3)	3.1×10^4
Exchange stiffness constant A (J/m)	1.4×10^{-12}
Domain-wall width $\delta=\pi\sqrt{A/K_u}$ (nm)	26
Specific wall energy $\gamma_m=4\sqrt{AK_u}$ (J/m^2)	5.9×10^{-4}

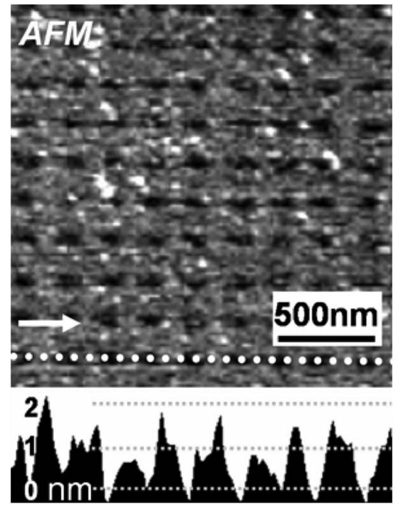

FIG. 2. AFM image of patterned $Gd_{16.7}Fe_{83.3}$ (200-nm spacing, fluence of 1×10^{15} ions/cm^2). The arrow indicates the FIB writing direction. The section is over the dotted line.

The interaction between the ion beam and the sample was simulated using the Monte Carlo package TRIM,[13] with which ion trajectories, atom displacement, and sputtering yields can be calculated. The simulations yielded an average Ga-ion penetration depth of 14 nm and indicated that the amorphous structure is altered by recoils down to 28 nm, or ~70% of the layer thickness. The predicted sputtering yield of 5.3 at./ion would result in a Gaussian-shaped dot depth of ~1.5 nm for a fluence of 1×10^{15} ions/cm^2, which is in reasonable agreement with AFM measurements (Fig. 2).

The domain patterns were imaged with magnetic force microscopy (MFM) using a commercial low moment tip to minimize tip sample interactions. Figure 3 shows the domain patterns of pristine and irradiated areas in the remanent state after out-of-plane saturation. The pristine areas show the typical maze pattern with a domain period of 210 nm. As is clearly visible in the irradiated areas, the dots tend to pin the domain walls, causing the domain pattern to lock in to the dot lattice in a way that depends on the interdot spacing and the FIB writing direction, indicated by a white arrow. For the 150-nm spacing the domains lock in diagonally, clearly because the diagonal spacing between the dots ($\sqrt{2}\times 150$ nm) closely matches the intrinsic domain period. This also holds for the 200-nm spacing and we observe a highly ordered quasi-one-dimensional grating, albeit with some wiggles in the domain walls and occasional domain branchings and truncations. The alignment of this lattice is along the writing direction of the FIB and must be due to the slightly elliptical shape of the dots with the long axis in the writing direction. Finally, for the 250-nm spacing, again the domains lock in along the writing direction albeit in a strongly wiggling fashion. This lock-in behavior is identical for all three ion fluences.

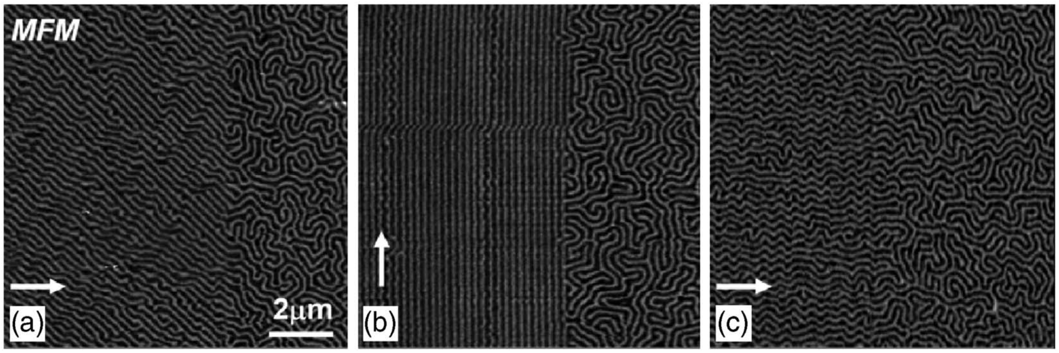

FIG. 3. MFM images of patterned $Gd_{16.7}Fe_{83.3}$ showing the dependence of the interdot spacing [(a) 150 nm, (b) 200 nm, and (c) 250 nm] to the lock in. The right sides are pristine areas.

Figure 4 shows another scan of the 250-nm lattice of Fig. 3(c) at remanence in which halfway a perpendicular field of 25 kA/m was switched on. As is well known,[6,7] in perpendicular fields the width of the up domains increases whereas that of the down domains slightly decreases, resulting in an overall increase of the domain period. This is indeed the case in the pristine area where the domain period immediately increases to ~250 nm. In the 250 nm lattice the wiggling lock-in patterns can now align themselves to the lattice where now the narrow down domains align themselves on the dots (Fig. 5), apparently because the Zeeman energy of the down domain is minimized there.

These results show that the stripe system is surprisingly stable and that for all ion fluences the dot lattice is unable to disrupt the nonlocal dipolar interactions that are responsible for stripe formation as will be discussed further below.

The pinning of the walls on the dots indicates a lowering of the specific domain-wall energy $\gamma_m = 4\sqrt{AK_u}$. This is most likely caused by a reduction of K_u due to a breakup of the pair interactions as a result of atomic displacements caused by the ion implantation. Assuming that the irradiated area has lost all magnetization one obtains huge pinning potentials of ~1 eV. We expect that with the small fluences the real pinning potential is several orders of magnitude smaller, but a real estimate is impossible to make at present.

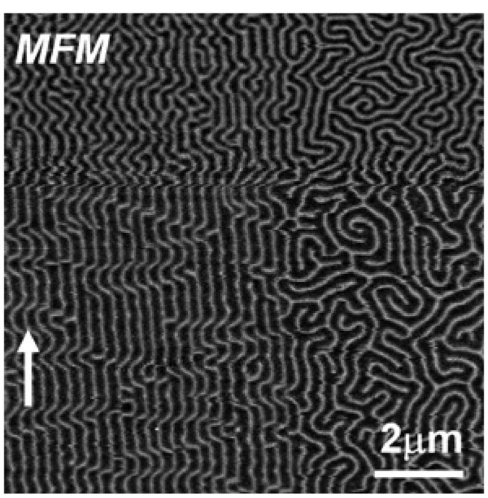

FIG. 4. MFM image of patterned $Gd_{16.7}Fe_{83.3}$ (250-nm spacing, fluence of 5×10^{15} ions/cm^2). An *in situ* perpendicular magnetic field of 25 kA/m is switched on halfway the scanning (lower part of the image). The upper part of the image shows the remanent state. Down domains are displayed in light grey.

CONCLUSION

This paper reports on the behavior of magnetic domains on a FIB-patterned amorphous $Gd_{16.7}Fe_{83.3}$ thin film with perpendicular magnetic anisotropy, studied with magnetic force microscopy. We observe a pronounced lock in of the stripe domains to the dot lattices with an orientation that depends mainly on the interdot spacing and the writing direction of the FIB. At remanence the domain walls align themselves on the dots, whereas in perpendicular field the down domains are positioned there. We conclude that the ion implantation causes a local reduction of the growth-induced PMA, which can be controlled precisely by varying the ion fluence per dot. This mechanism can be used to control domain patterns and study the rigidity of stripe domain lattices in applied fields. Future studies using more finely focused ion beams will concentrate on the effect of these artificial pinning landscapes on the dynamics of domain nucleation and wall propagation, and the use of local probes to measure the modified magnetic parameters in order to bring this work to a more quantitative basis.

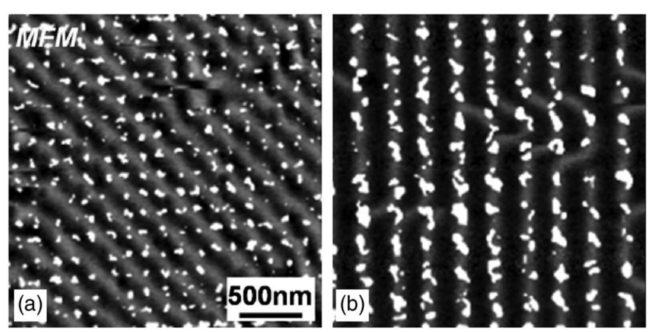

FIG. 5. MFM images of patterned $Gd_{16.7}Fe_{83.3}$ with overlay of dots (in white) extracted from the corresponding AFM image. At remanence (150 -nm spacing) the dots pin the domain walls (a) whereas in a 25-kA/m perpendicular field (250-nm spacing) the down domains are positioned at the dots (b).

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[1] C. Chappert *et al.*, Science **280**, 1919 (1998); T. Aign *et al.*, Phys. Rev. Lett. **81**, 5656 (1998).
[2] G. J. Kusinski, K. M. Krishnan, G. Denbeaux, G. Thomas, B. D. Terris, and D. Weller, Appl. Phys. Lett. **79**, 2211 (2001).
[3] D. Ravelosona, C. Chappert, V. Mathet, and H. Bernas, Appl. Phys. Lett. **76**, 236 (2000); D. Ravelosona *et al.*, Mater. Sci. Eng., C **15**, 53 (2001).
[4] P. Hansen, C. Clausen, G. Much, M. Rosenkranz, and K. Witter, J. Appl. Phys. **66**, 756 (1989).
[5] M. Mansuripur, *The Physical Principles of Magneto-Optical Recording* (Cambridge University Press, Cambridge, UK, 1995).
[6] C. Kooy and U. Enz, Philips Res. Rep. **15**, 7 (1960).
[7] V. Gehanno, Y. Samson, A. Marty, B. Gilles, and A. Chamberod, J. Magn. Magn. Mater. **172**, 26 (1997).
[8] E. A. Jagla, Phys. Rev. E **70**, 046204 (2004).
[9] J. M. D. Coey, D. Givord, A. Liénard, and J. P. Rebouillat, J. Phys. F: Met. Phys. **11**, 2707 (1981).
[10] A. G. Dirks and H. J. Leamy, J. Appl. Phys. **49**, 1735 (1978).
[11] F. Hellman, P. W. Rooney, and E. M. Gyorgy, J. Appl. Phys. **73**, 5793 (1993); D. Mergel, H. Heitmann, and P. Hansen, Phys. Rev. B **47**, 882 (1993).
[12] Y. Mimura, N. Imamura, T. Kobayashi, A. Okada, and Y. Kushiro, J. Appl. Phys. **49**, 1208 (1978).
[13] J. F. Ziegler and J. P. Biersack, http://www.srim.org (2005).