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Magnetization reversal processes in submicron Co dots and antidots arrays

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Abstract

Arrays of submicron polycrystalline and epitaxially grown (1 0 0) hcp Co dots and antidots were prepared in order to study the magnetization reversal processes influenced by well defined anisotropy, dipolar and exchange fields. The magnetization reversal processes for both polycrystalline and epitaxial Co dot arrays are found to be initiated by domain wall nucleation. The domain wall propagation is regulated by the evolution of the effective internal field. The antidots exhibit perculiar stripe domains in the remanent state. the direction of the stripes is well determined by the applied magnetic field direction. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Magnetic dots: Magnetization reversal: Domain structures

Laterally defined submicron magnetic structures are of great interest from both scientific and technological viewpoints. An array of submicron ferromagnetic dots is, for example, a possible patterned magnetic storage as well as a model system to study the demagnetization processes controlled by the competition among magnetostatic, anisotropy and exchange energies. The magnetic anisotropy in polycrystalline dots is mainly governed by their shape, whereas the competition between the shape and magnetocrystalline anisotropies plays an important role to generate the effective anisotropy in epitaxially grown single crystalline dots. On the other hand, an array of antidots cut into a continuous film spatially modulates local dipolar fields which complete with the intrinsic anisotropy of the film. Some interesting studies related to the above mentioned systems have been carried out for polycrystalline permalloy [1–3], Sm–Co [4], Ni [5], Fe [6] and (0 0 · 1) oriented hcp Co [7].

In the present work, we have investigated the magnetization reversal processes of arrays of submicron polycrystalline hcp Co rectangular dots and antidots with the variable aspect ratio. We will also show some results obtained for the array of (1 0 · 0) oriented hcp Co circular dots with a strong in-plane uniaxial anisotropy.

The polycrystalline Co films were deposited by a DC magnetron sputter method on Si substrates, whereas the (1 0 · 0) oriented epitaxial Co films were grown at 573 K on top of (1 1 0) MgO substrates with (2 1 1) oriented Cr seed layers by an rf magnetron sputter method. For both cases, the base pressure was below 2×10^{-7} Torr and Ar pressure during the deposition was about 3×10^{-3} Torr. X-ray diffraction analyses for the polycrystalline Co films showed that the films consisted of isotropic hcp crystallites. X-ray pole figures showed that the (1 0 · 0) oriented Co films grew with their in-plane [0 0 · 1] easy axis parallel to Cr [0 1 1] and MgO [0 0 1] axes. The arrays of the polycrystalline rectangular dots were fabricated using high resolution electron-beam lithography (JEOL 5000 SD) and a lift-off method. The arrays of the rectangular antidots and the circular dots were cut into continuous films using the electron-beam lithography followed by an Ar ion etching procedure. The pole figure

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taken after the fabrication ensured that the circular dot array has the (1 0 · 0) oriented epitaxial structure. The long edge length of the dot (or antidot) is defined as l, the width as w, and the aspect ratio as l/w. In the present study, the value of l was fixed at 0.5 μm and the aspect ratio was chosen to be 1, 3 and 4. The diameter of the circular dots is 0.5 μm. The thickness is typically 75 nm. the total number of the dots in an array is about 1×10^7 so that the saturation magnetic moment is about 10^{-5} emu.

Magnetic force microscope (MFM) observations were made in zero field by a scanning probe microscope (SEIKO SPI3800). Magnetization measurements were performed with a DC SQUID vector magnetometer, which can measure simultaneously the magnetization components both parallel $M_{\parallel}$ and perpendicular $M_{\perp}$ to the applied field direction. In order to avoid the effect of thermal fluctuation. all the measurements were carried out at 5 K in fields from -5 to 5 T.

MFM images for the arrays of both dots and antidots with designed dimensions, 0.5 μm × 2.0 μm × 0.075 μm are shown in Fig. 1. The spacing between dots is 0.5 μm. The images were taken in the remanent state after the saturation of the array in an applied field along the short edge of the dots. About 50% of the dots are in the single domain state as seen in the first dot of Fig. 1(a). In the bright area, there seems a 'S' shaped spin structure as sown in the numerical simulation by Fredkin et al. [8]. The other 50% of the dots consist of solenoidal domain structures, possiblly 13 closure domains, as in the second dot in Fig. 1(a). It seems that each dot behaves individually. This can also be understood from the fact that the demagnetizing field of about 125 mT for the direction along the short edge is much larger than the dipolar field of 2.5 mT calculated for this configuration. When the magnetic field is applied along the long edge, 90% of the dots are found to be in the single domain state and the others exhibit closure domains.

Remarkable is that peculiar stripe domains appear in the antidots array at the remanent state as shown in Fig. 1(b). The stripe domains lie along the short edge of the antidot, which is the applied field direction. When the applied field is rotated towards the long edge of the antidot, the direction of the stripe domains also rotates as in Fig. 1(c). Furthermore, magnetization measurements show large remanent magnetization along the applied field direction. These results indicate that the main component of the magnetization directs parallel to the applied field and its sinusoidal deviation out of the film plane due to the perpendicular anisotropy results in the stripe domains. This picture is well supported by the fact that the period of the stripe domains $l = 0.14$ μm coincides well with the value $l = 0.13$ μm obtained form the relation [9] $\lambda = 4\pi(\mu_0 At/2M_s^2)^{1/3}$, where $A = 4.6 \times 10^{-11}$ J/m, $t = 75$ nm, and $M_S = 1.4$ T. The origin of the perpendicular anisotropy is considered as the released strain during the etching procedure, although the details are to be clarified. The evaluated magnitude of the perpendicular anisotropy from the period amounts to 3.2×10^5 J/m^3.

Fig. 1. Magnetic force microscope images of (a) Co rectangular dots and (b and c) antidots with the dimensions 0.5 μm × 2.0 μm × 0.075 μm.

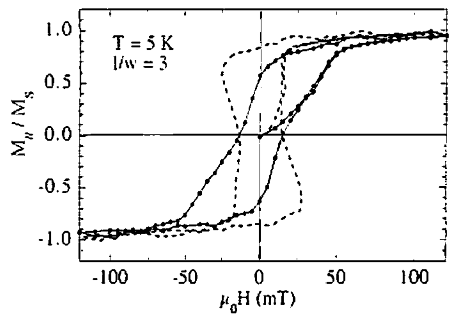

Fig. 2. $M_{\parallel}$ magnetic hysteresis loop for the array of the dots with the aspect ratio $l/w = 3$. The dashed line in the figure represents the hysteresis loop plotted with respect to the effective field $\mu_0 H_{eff}$.

Fig. 2 shows a typical $M_{\parallel}$ magnetic hysteresis loop for the array of the dots with the aspect ratio $l/w = 3$ measured along the long edge. The dashed line in the figure represents the hysteresis loop plotted with respect to the effective field $\mu_0 H_{eff}$ given by $\mu_0 H_{eff} = \mu_0 H - NM_{\parallel}$, where $\mu_0 H$ is the external field, and N is the demagnetizing factor. The value of N is evaluated to be 0.0235 by approximating the dot as a flat ellipsoid. The $M_{\parallel}$ is almost saturated above the in-plane demagnetizing field of about 35 mT, where the magnitude of the total magnetization calculated from $M = \sqrt{M_{\parallel}^2 + M_{\perp}^2}$ is constant. This implies that the coherent rotation dominates. Below this field, the magnetization reversal is considered as a two stage domain wall nucleation and propagation process. As shown by the $M_{\parallel}$ vs. $\mu_0 H_{eff}$ plot in Fig. 2, the initial magnetization reversal takes place via the domain wall nucleation at $\mu_0 H_{eff} = -25$ mT, which is the nucleation field of the individual dot. The same value of the nucleation field is obtained for all the dots irrespective of the aspect ratio. With a decrease in the magnetization, the effective field $\mu_0 H_{eff}$ exerted on the nucleated domain wall is reduced. This reduced $\mu_0 H_{eff}$ facilitates the

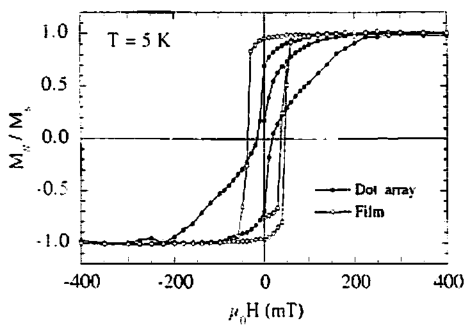

Fig. 3. $M_\parallel$ magnetic hysteresis loops of the (1 0 · 0) oriented epitaxial Co film and the circular dots array fabricated from the (1 0 · 0) Co film.

domain wall pinned at various potential barriers, resulting in the viscous propagation of the wall with keeping the effective field constant. The perpendicular component $M_\perp$ is also found to be developed significantly by the domain wall nucleation. This behaviour was similarly found in all the arrays with aspects ratios l/w from 1 to 4. Important is that the magnetic susceptibility due to the domain wall propagation is always given by $1/N$.

Hysteresis loops of the (1 0 · 0) oriented epitaxial Co film and the circular dot array fabricated from the (1 0 · 0) Co film are shown in Fig. 3. the magnetic field is applied parallel to the magnetic easy [0 0 · 1] axis. The (1 0 · 0) Co film exhibits a rectangular hysteresis loop, showing a well defined uniaxial anisotropy. The uniaxial anisotropy energy is evaluated from the hard axis magnetization curve to be 2.44×10^5 J/m^3 which is in good agreement with the value for the bulk single crystal Co. Once the circular dot array is structured in the film, the hysteresis loop completely changes. This is purely due to the patterned structure since the X-ray pole figures assure the (1 0 · 0) oriented crystal structure. The shape of the hysteresis loop for the dot array is quite similar to that observed for the polycrystalline dot array. The magnetization is almost saturated above the in-plane demagnetizing field $NM_s = 200$ mT, where the value of N is 0.116 for each circular dot. The magnetization reversal takes place via the domain wall nucleation and propagation process. The nucleation field determined from the $M_\parallel$ vs. $\mu_0 H_{eff}$ plot is about 200 mT, which coincides well with the in-plane demagnetizing field. After the domain wall nucleation, the domain wall propagation is halted by the reduction of the effective internal field. The susceptibility again takes the constant value given by $1/N$. Fig. 4 shows the MFM images of the circular dot array in the remanent state together with the schematic figure. The domain structure consists of single domain and two domain structures. Interesting is that the two domain structures form a belt running perpendicular to the [0 0 · 1] axis sandwiched by the clusters of the single domains with a slightly inclined magnetization, suggesting that the

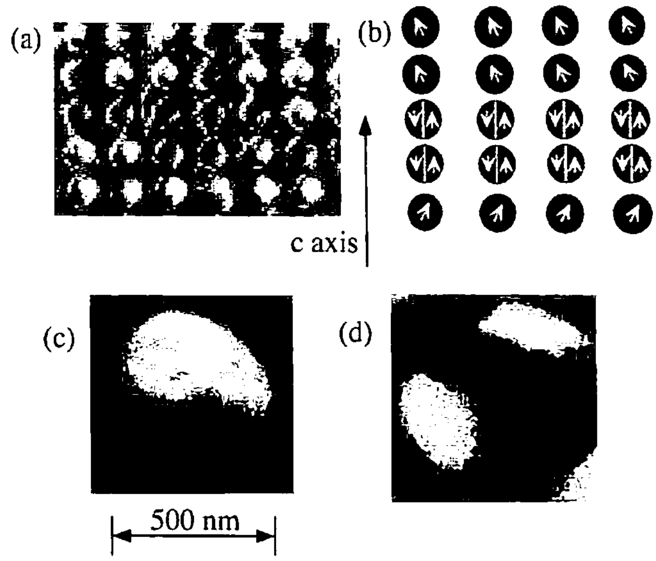

Fig. 4. (a) Magnetic force images of the circular dot array in the remanent state, (b) the schematic figure, and the magnified images of (c) the single domain and (d) the two domain structures.

collective magnetization reversal occurs unlike the case of the polycrystalline dot array although the evaluated dipolar field in the saturated state ranges only 2 mT.

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References

[1] J.F. Smith, S. Schultz, D.R. Fredkin, D.P. Kern, S.A. Rishton, H. Schmid, M. Cali, T.R. Koehler, J. Appl. Phys. 68 (1991) 5256.
[2] R.P. Cowburn, A.O. Adeyeye, J.A.C. Bland, Appl. Phys. Lett. 70 (1997) 2309.
[3] A.O. Adeyeye, J.A.C. Bland, C. Daboo, Appl. Phys. Lett. 70 (1997) 3164.
[4] O. Geoffroy, D. Givord, Y. Otani, B. Pannetier, F. Ossard, J. Magn. Magn. Mater. 121 (1993) 223.
[5] M.S. Wei, S.Y. Chou, J. Appl. Phys. 76 (1994) 6679.
[6] A.D. Kent, S. von Molnar, S. Gider, D.D. Awshalom, J. Appl. Phys. 63 (1994) 4237.
[7] M. Hehn, S. Padovani, K. Ounadjela, J.P. Bucher, Phys. Rev. B 54 (1996) 3428.
[8] D.R. Fredkin, T.R. Koehler, IEEE Trans. Magn. 26 (1990) 1518.
[9] S. Chikazumi, Physics of Ferromagnetism, Clarendon Press, Oxford, 1997, p. 451.

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