Shape induced in-plane magnetic anisotropy rorientation in epitaxial hexagonal close packed cobalt dots

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The in-plane magnetic easy-axis reorientation was investigated for the arrays of (10·0) hcp Co rectangular dots 0.2 μm in width with a variable length from 3 to 5 μm perpendicular to the *c* axis. In the system, the magnitude of the shape anisotropy contribution is determined by a lateral aspect ratio of the dot, while the magnetocrystalline anisotropy contribution is temperature dependent. The torque curves for the dot arrays exhibited a characteristic fourfold symmetry due to the easy-axis reorientation. The reorientation angle from the initial easy axis was found to be dependent on the value of in-plane demagnetization factors as well as the temperature variable first and second magnetocrystalline anisotropy constants. The experimental results are in good agreement with the calculated effective magnetic anisotropy. [S0021-8979(00)37708-8]

I. INTRODUCTION

Recent interests on magnetic systems with reduced dimensions have been stimulated by rapid improvement of various microfabrication technologies. Magnetic properties of such submicron sized magnets are of great interest from viewpoints of fundamental magnetism as well as magnetic device applications. In particular, an array of laterally defined magnetic dots can be considered as a model system to study the demagnetization processes initiated by the competition among magnetostatic, exchange, and magnetocrystalline anisotropy energies.[1–3]

The dot array of well-defined geometry is generally fabricated by using electron-beam, x-ray, or optical microlithography. The lift-off process is used to produce a polycrystalline dot array,[4] whereas the etching process is necessary for obtaining an epitaxial dot array.[5] The shape-induced anisotropy dominates in the polycrystalline system due to the lack of macroscopic crystalline order, whereas the epitaxial dot array conserves the original magnetocrystalline anisotropy, which gives an important contribution to the effective magnetic anisotropy. For example, the easy-axis reorientation transitions in the (00·1) cobalt disks and the (10·0) Co rectangular dots have been observed.[6,7]

We present our further studies on the temperature dependent magnetic anisotropy of the (10·0) Co rectangular dot arrays with in-plane anisotropy.[7] The long edges of the dots are aligned perpendicular to the *c* axis to induce the competition between the shape and the magnetocrystalline anisotropies. The lateral aspect ratio of the rectangular dots determines the amount of the shape contribution to the effective anisotropy, while the magnetocrystalline anisotropy contribution varies as a function of temperature. We will demonstrate that a gradual increase of the shape anisotropy with respect to the temperature variable magnetocrystalline anisotropy results in the temperature dependent easy-axis reorientation.

II. EXPERIMENT

Arrays of magnetic dots were prepared as follows. First, a 0.1 μm thick (10·0) oriented hcp Co film was grown by molecular beam epitaxy at 473 K on a MgO (110) single crystal substrate covered with a (211) Cr buffer layer. The in-plane [001] axis, the crystallographic *c* axis of the obtained film is parallel to Cr [011] and MgO [001] axes. Secondly, the film surface was spin coated with a thin layer of negative resist and patterned by electron beam lithography. Finally, the arrays of the dots, 3 and 5 μm in length l, 0.2 μm in width w, were cut into the film by an argon ion etching procedure. The topography of the rectangular dot array was examined by means of scanning electron microscopy (SEM) and atomic force microscopy (AFM).

The magnetic properties were studied in the temperature range from 10 to 300 K in fields from −1 to 1 T. The experiments were carried out using a superconducting quantum interference device (SQUID) vector magnetometer equipped with a rotatable sample stage. The system allows us to measure simultaneously both components parallel $M_{\parallel}$ and perpendicular $M_{\perp}$ to the applied field direction. The magnetic torque curves were obtained by plotting $L = M_{\perp} H \sin\theta$ as a function of angle θ between the applied field H and the *c* axis. The domain structure in the remanent state was observed by magnetic force microscopy.

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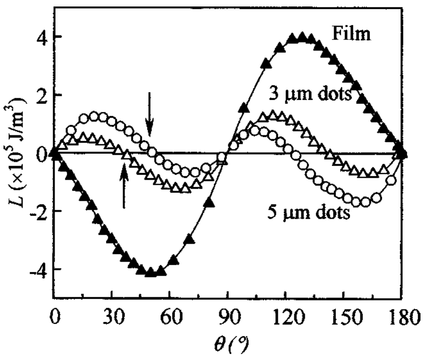

FIG. 1. Representative torque curves for a continuos (10·0) Co epitaxial film and 3 and 5 μm dot arrays measured at 300 K. The arrows indicate the reorientation angles.

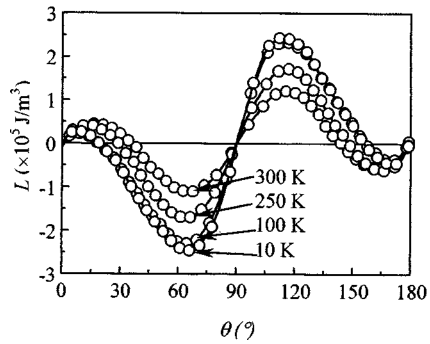

FIG. 2. Torque curves for a 5 μm dot array measured in the temperature range from 10 to 300 K.

III. RESULTS AND DISCUSSION

The magnetic properties of the (10·0) Co epitaxial film were examined before the patterning process. The Co film exhibits the in-plane uniaxial magnetic anisotropy with the magnetic easy axis parallel to the c axis of hcp Co. The value of coercivity is 0.2 T and the saturation field is 0.75 T. Torque curves measured in an applied field of 1 T were then fitted to the first derivative of the anisotropy energy, $E_a = K_1 \sin^2\theta + K_2 \sin^4\theta$, with respect to the angle θ,

$$L = -\frac{\partial E_a}{\partial \theta} = -K_1 \sin 2\theta - K_2 \sin 2\theta \sin^2\theta, \tag{1}$$

where K_1 and K_2 are the first and second magnetocrystalline anisotropy constants. This yields the anisotropy constants as a function of temperature. The obtained temperature variations of K_1 and K_2 are in good agreement with the previously reported values.[8]

The patterning of the dot array structure with their long edge perpendicular to the c axis significantly modifies the magnetic anisotropy of the system. Figure 1 compares the magnetic torque curves measured at 300 K for the film and the dot arrays with the different lateral aspect ratios $l/w = 15$ and 25. Both torque curves exhibit a characteristic fourfold symmetry unlike initial twofold one for the film. This means that the original easy c axis turns to be the hard axis and the magnetic easy axis directs at an angle of 32° from the c axis for $l/w = 15$ and 50° for $l/w = 25$. The x-ray pole figures for the arrays assure that a good (10·0) epitaxial structure remains in each dot, supporting the fact that the easy axis reorientation is purely originated from the competing shape induced demagnetization energy.

The total magnetic anisotropy energy of the dot array thus consists of the magnetocrystalline E_a and the shape E_s anisotropies as given below

$$E = E_a + E_s = (K_1 + K_s)\sin^2\theta + K_2 \sin^4\theta, \tag{2}$$

where K_s is the shape anisotropy constant written as $K_s = M_s^2(N_x - N_y)/2\mu_0$, M_s is the saturation magnetization, N_x and N_y are in-plane demagnetization factors parallel and perpendicular to the c axis, respectively. The resultant anisotropy therefore exhibits twofold symmetry when the effective first order constant $K_{1\,\mathrm{eff}} = K_1 + K_s$ and the second order constant K_2 have the same sign. An increase of the shape anisotropy K_s leads to a negative $K_{1\,\mathrm{eff}}$ with K_2 unchanged. This results in the easy-axis reorientation so that the easy axis tilts away from the c axis by an angle α. The reorientation angle α can be calculated from the equilibrium condition for Eq. (2) as

$$\alpha = \arcsin\left(\sqrt{-\frac{K_{1\,\mathrm{eff}}}{2K_2}}\right), \tag{3}$$

when the following condition is satisfied

$$-2 < \frac{K_{1\,\mathrm{eff}}}{K_2} < 0. \tag{4}$$

As in Eq. (3), the reorientation angle α depends on both the magnetocrystalline and shape anisotropy constants. The torque curves for 3 μm dots measured in the temperature range from 10 to 300 K are shown in Fig. 2. As the magnetocrystalline anisotropy contribution is pronounced with decreasing temperature, the angle α diminishes. Cooling the dot array mainly affects the contribution of the magnetocrystalline anisotropy, while the shape anisotropy stays almost constant in this temperature range since it varies as a function of M_s^2. Figure 3 shows the temperature dependence of the magnetocrystalline constants K_1 and K_2 together with the effective anisotropy constant $K_{1\,\mathrm{eff}}$ determined by fitting measured torque curves to Eq. (2). It is clearly seen that K_1 is far more sensitive to temperature than K_2 and determines the reorientation angle α. The difference in the in-plane de-

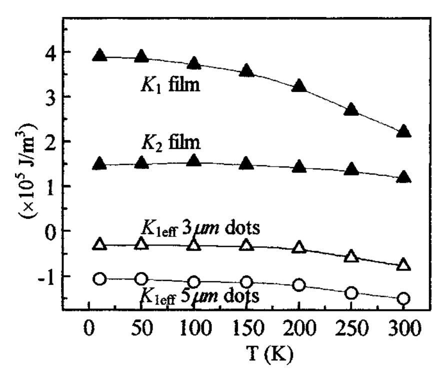

FIG. 3. Temperature dependence of the first and second magnetocrystalline anisotropy constants K_1 and K_2, the effective anisotropy constant $K_{1\,\mathrm{eff}}$ for 3 and 5 μm dot arrays.

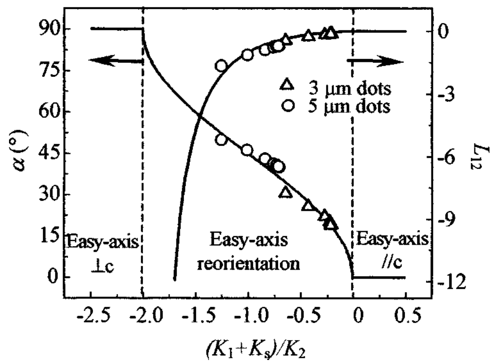

FIG. 4. The reorientation angle α and the amplitude ratio of two torque peaks as a function of $(K_1+K_s)/K_2$. The solid lines are the calculated curves.

magnetization factors (N_x-N_y) can be deduced from the shape anisotropy constant $K_s=K_{1\ \mathrm{eff}}-K_1$ as -0.33 and -0.38 for 3 and 5 μm dots, respectively. The experimental values of (N_x-N_y) are comparable to the values -0.32 and -0.35 determined by using an analytical expression for the ideal prisms.[9] The reorientation angle α and the amplitude ratio L_{12} of two torque peaks as a function of dimensionless parameter $K_{1\ \mathrm{eff}}/K_2$ are shown in Fig. 4. All the experimental data of α and L_{12} for both 3 and 5 μm dots lie on the solid lines calculated from Eqs. (2) and (3).

The above discussion on the easy-axis reorientation is based on the torque measurements for the saturated samples. The remanent magnetization of the dots should also depend on the magnitude of the effective magnetic anisotropy if the single domain structure is preserved. To clarify this, the angular variations of the parallel $M_\parallel$ and perpendicular $M_\perp$ components in the remanent state were examined. Figure 5 shows $M_\parallel$, $M_\perp$, and the total remanent magnetization M_r determined as $M_r=\sqrt{M_\parallel^2+M_\perp^2}$ versus the angle θ for the 3 μm dot array. The plot can be classified into two angular regions A and B, reflecting characteristics of the demagnetization process. In region A, the components $M_\parallel$ and $M_\perp$ are

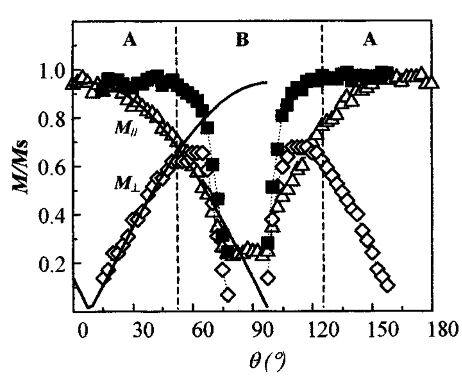

FIG. 5. Angular dependence of the parallel $M_\parallel$ and perpendicular $M_\perp$ components of the remanent magnetization and the magnetization M_r calculated as $M_r=\sqrt{M_\parallel^2+M_\perp^2}$ for a 3 μm cobalt dot array.

well described by the cosine and sine functions as indicated by the solid lines, and the total M_r remains constant. This implies that the demagnetization process takes place via coherent rotation in the cobalt dots with a single domain structure and the magnetization vector directs along the reoriented easy axis. Further increase of the angle θ in region B leads to a sudden decrease in $M_\parallel$, $M_\perp$, and M_r due to the appearance of a multidomain structure. The MFM images taken in the remanent state prove that the single domain structure with the magnetization parallel to the reoriented easy axis stabilizes in the dots in region A and the multidomain structure in region B. Well-defined stripe domains parallel to the *c* axis are observed when the magnetic field is applied along the long edges of the dots. Similar results were obtained for the 5 μm epitaxial cobalt dot array.

IV. CONCLUSIONS

We have reported the temperature dependent in-plane magnetic anisotropy reorientation observed in rectangular $(10\cdot0)$ oriented hcp Co dot arrays. The torque curves exhibit a characteristic anisotropy with in-plane fourfold symmetry unlike the initial twofold one for the continuous film. The reorientation angle was found to be dependent on the value of in-plane demagnetization factors as well as the temperature dependent first and second magnetocrystalline constants. The stripe domains with the magnetization parallel to the *c* axis are observed in the remanent state when the magnetic field is applied parallel to the long edge of the dots. However, the single domain structure with the magnetization along the reoriented easy axis can be stabilized when the applied field is parallel to the *c* axis. The calculation of the effective magnetic anisotropy governed by competition between the magnetocrystalline and shape anisotropies explains the experimental data very well.

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