The effect of stress-induced anisotropy in patterned FeCo thin-film structures

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In this work, 1-μm-thick FeCo films with −320 MPa compressive stress and FeCo/NiFe films with 600 MPa tensile stress were patterned into 5×20 μm^2 elements. The stress anisotropy resulting from patterning was measured using x-ray diffraction to be 220 MPa for the tensile films and −170 MPa for the compressive films and is in agreement with finite element modeling. Scanning electron microscopy with spin-polarization analysis imaging shows that the domain structure of the elements was influenced by this stress-induced anisotropy. Calculations of the effect of stress anisotropy were performed on domain configurations for the patterned structures. Results indicate that tensile stresses should reinforce closure domains, while compressive stresses of magnitude greater than 50 MPa should result in an easy axis rotation, and are in agreement with the experimental results. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2170066]

I. INTRODUCTION

Polycrystalline FeCo (65% Fe and 35% Co) films are desirable as high magnetization pole materials (B_s=2.4 T) in high-density hard drives. However, FeCo is highly magnetostrictive and susceptible to stress-induced anisotropy. When these films are sputter deposited, they can have large isotropic in-plane residual stresses. In elongated patterned structures, these stresses can relax anisotropically, yielding significant in-plane magnetic anisotropy. This induced anisotropy may alter domain configurations, which may result in pole tip remanence[1] in recording heads as well as nonrepeatable readback signals.[2] In this work, we show that stress anisotropy due to patterning has a dramatic effect on the magnetic domains. 1-μm-thick films of compressive FeCo and tensile FeCo/NiFe multilayers were patterned into 5×20 μm^2 elements. The stress in these structures was measured both before and after patterning. Magnetic imaging showed that the direction of the easy axes in these structures was highly dependent upon the stress-induced anisotropy. Comparison of the experimental results to theoretical calculations of magnetic domain structure as a function of stress anisotropy indicates that tensile stresses reinforce closure domains, while compressive stresses rotate the easy axis direction transverse to the long axis of the patterned structures.

II. EXPERIMENT

1-μm-thick FeCo single-layer films and FeCo/NiFe (80% Ni and 20% Fe) multilayer films (ten bilayers of 100 nm of FeCo on 5 nm of NiFe) were deposited onto glass and Si substrates in a CVC Connexion system[3] via dc magnetron sputtering. The single-layer FeCo films were deposited at 100 W power, 4 mTorr of Ar pressure, and 300 W (−50 V) substrate bias with a 1 nm Cu underlayer in order to obtain soft properties.[4] Under these conditions, the uniform film stress was −320 MPa (compressive). The FeCo in the FeCo/NiFe multilayers was deposited at 500 W power, 4 mTorr pressure, and 300 W substrate bias, and the NiFe was deposited at 67 W power and 3 mTorr pressure. These multilayer films had a uniform film stress of 600 MPa (tensile).

The magnetic properties of the deposited films were measured using a SHB 108 BH looper and a DMS 1660 vibrating-sample magnetometer. The uniform film stress was measured via wafer curvature using a KLA-Tencor P15 profilometer. These films were patterned into arrays of 5×20 μm^2 elements using a Karl Suss contact aligner and a Commonwealth Ar-ion miller. The stress of the patterned elements was measured using x-ray diffraction (XRD) of the (110) and (211) peaks of the films, taking into consideration the film texture obtained through pole figure analysis and grain interactions.[5] Magnetic domain imaging of the patterned films was performed using scanning electron microscopy with spin-polarization analysis (SEMPA) at NIST.

III. RESULTS AND DISCUSSION

A. Stress and magnetic domains

The stress along the width (σ_W) and length (σ_L) of the structures measured through XRD is compared to the sheet film stress (σ_S) measured via wafer curvature and the expected values determined through simulation [$\sigma_W(c)$ and $\sigma_L(c)$] in Table I. The measured values of σ_W and σ_L in the patterned structures are in very good agreement with the expected values and are considered accurately measured values of the stress of the elements.[5] Table I shows a significant reduction in film stress due to patterning, resulting in a stress anisotropy of $\sigma_L-\sigma_W$. With the stress of the structures known, it is possible to determine how it affects the magnetic domain patterns.

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TABLE I. Stress (in MPa) of $5\times 20\ \mu\mathrm{m}^2$ structures on Si. σ_W and σ_L were measured and $\sigma_W(c)$ and $\sigma_L(c)$ were calculated.

Film	σ_S	σ_W	σ_L	$\sigma_L-\sigma_W$	$\sigma_W(c)$	$\sigma_L(c)$
FeCo	−320	−110	−280	−170	−113	−246
FeCo/NiFe	600	120	340	220	161	355

The domain images of the FeCo and FeCo/NiFe films patterned into $5\times 20\ \mu\mathrm{m}^2$ structures are shown, respectively, in Figs. 1 and 2. While the tensile FeCo/NiFe structure shows a standard flux closure pattern, the magnetization of the compressive FeCo structure lies preferentially along the structure width. This is most likely due to the presence of compressive stress, which forces the easy axis of the magnetization to rotate 90° from the long axis.

In these structures, the effective stress-induced anisotropy field can be calculated using $K_u(\sigma)=(3/2)\lambda_s(\sigma_L-\sigma_W)$, where λ_s is the magnetostriction constant of the film. Both films were predominantly (211) textured and were assumed to have a magnetostriction constant of $\lambda_s=5.2\times 10^{-5}$, which was calculated for the $Fe_{65}Co_{35}$ target used for both films. Using the measured value of $M_s=2.2$ T for these films, the effective anisotropy fields in these structures were calculated as $H_k(\mathrm{FeCo})=-12$ kA/m (−150 Oe) and $H_k(\mathrm{FeCo/NiFe})=15.2$ kA/m (190 Oe). A negative anisotropy field corresponds to a field applied along the width of the rectangles, while a positive anisotropy field corresponds to a field applied along the length. In the compressive FeCo structure in Fig. 1, the high anisotropy field along the width is enough to rotate the easy axis away from the structure length which is expected to be the easy axis due to shape anisotropy. In the tensile structures in Fig. 2, the high anisotropy field along the structure length reinforces the shape-induced easy axis and flux closure domain pattern.

B. Theoretical calculations

To determine the behavior of domains as a function of stress anisotropy, the energy of $5\times 20\ \mu\mathrm{m}^2$ patterned elements with the domain configurations A–D shown in Fig. 3 was calculated. The total energy in each configuration was assumed to consist of the domain-wall energies and the anisotropy energy of each domain. To calculate the wall energies, a simple estimate of the energy of 90° and 180° Bloch and Néel walls was performed for 1-μm-thick FeCo films (NiFe was assumed to have a negligible effect on wall energies in the multilayers). The total wall energy was assumed to be comprised of exchange (E_{ex}), magnetocrystalline anisotropy (E_a), magnetostatic (E_{ms}), and magnetoelastic (E_{me}) energies.

In estimating the wall energy, the angle of the magnetization within the wall is assumed to vary linearly and allows the domain-wall surface energy due to magnetocrystalline anisotropy and exchange to be computed in the standard fashion (p. 413 of Ref. 6). To estimate the magnetostatic contribution, the wall is assumed to be a rectangular prism with $\langle M\rangle=0.6M_s$ transverse to the wall for Néel walls and normal to the film for a Bloch wall. In the 90° Néel walls, the adjacent domains are assumed to have $\langle M\rangle=0.707M_s$ normal

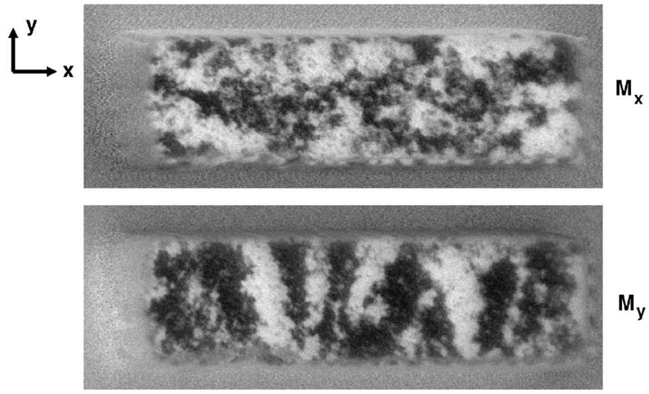

FIG. 1. SEMPA image of compressive FeCo structures.

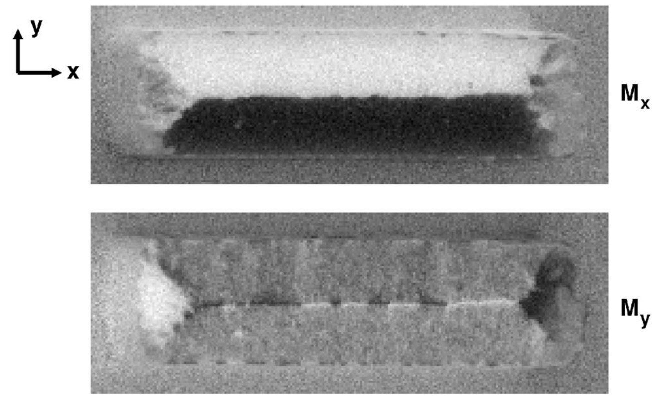

FIG. 2. SEMPA image of tensile FeCo/NiFe structures.

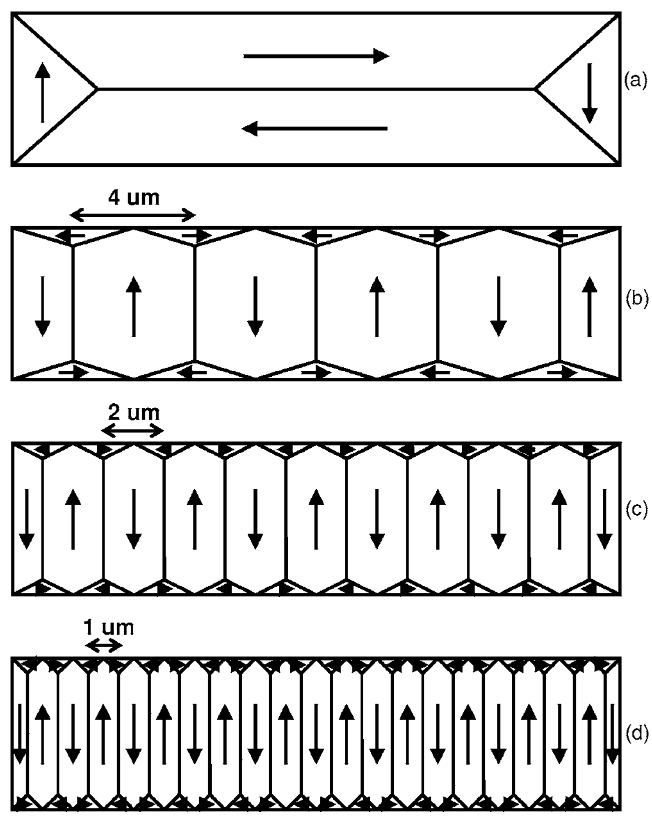

FIG. 3. Domain pattern configurations used to calculate total domain energies in FeCo structures.

TABLE II. Calculated domain-wall energies (in mJ/m^2), domain-wall width, and demagnetization factor for FeCo.

Wall type	E_t	δ (nm)	N	E_{ex}	E_a	E_{ms}	E_{me}
(a) 180° Bloch	4.8	41	0.06	2.4	0.4	2.3	0.04
(b) 180° Néel	19	10	0.98	9.5	0.01	9.5	0.01
(c) 90° Néel	2.5	20	0.68	1.3	0.02	1.2	0.01

to the walls. For each wall type, the demagnetizing factor N was calculated from the wall width δ and film thickness t.[7] The magnetoelastic contribution was estimated with the assumption of no physical displacement of material within the wall, and therefore may be calculated from the elastic moduli and the magnetic strain (p. 351 of Ref. 6). The material parameters used to calculate the wall energies in a 1-μm-thick FeCo film are $A=2.0\times10^{-11}$ J/m,[8] $K_u=1920$ J/m^3 [calculated from the measured $H_k=3.2$ kA/m (40 Oe) and $M_s=2.2$ T], $\lambda_s=(2/5)\lambda_{100}+(3/5)\lambda_{111}=5.2\times10^{-5}$ [calculated using $\lambda_{100}=18\times10^{-6}$ and $\lambda_{111}=104\times10^{-6}$ (Ref. 6)], $E=211$ GPa, and $\nu=0.29$.[9] The total energy of each wall type was minimized with respect to δ. The calculated total wall energy density (E_t) is shown in Table II along with δ, N, and the contributions from E_{ex}, E_a, E_{ms}, and E_{me}. Although FeCo is highly magnetostrictive, E_{me} is only 1% of the total energy, while E_{ex} and E_{ms} are dominant. In Table II, 90° Néel walls are the lowest in energy, followed by 180° Bloch and Néel walls.

The wall energies of the patterns in Fig. 3 were calculated with the assumption of 180° Bloch walls and 90° Néel walls. The anisotropy energy density of the domains in patterns A–D was assumed to be $E_a(\sigma)=K_u\sin^2\theta$, where θ is the angle between the domain magnetization and the easy axis (located along the structure length). Considering both the domains and the domain-wall energies, the differences between the transverse states (B–D) and the longitudinal state (A) were calculated, and are shown in Fig. 4 as a function of stress anisotropy. Positive-energy values indicate that pattern A is favored, while negative values mean that patterns B–D are favored. Figure 4 shows that pattern A is lowest in energy for positive stress anisotropy values, while pattern B is lowest in energy for negative stress anisotropies less than −50 MPa. Between approximately −50 and −95 MPa, domain patterns B–D become more favorable than domain pattern A. Although at least −50 MPa of stress anisotropy is needed for easy axis rotation, the likelihood of rotation increases as stress anisotropy becomes more negative.

The comparison of the stress anisotropy values in Table I to the domain configuration energies in Fig. 4 shows that at the FeCo anisotropy value of −170 MPa, the easy axis is expected to lie along the structure width, similar to that of configuration B. This is consistent with the domains in Fig. 1. For the FeCo/NiFe anisotropy value of 220 MPa, pattern A is expected, and is consistent with the domains in Fig. 2. The observed and calculated relationship between domain structure and stress anisotropy is in agreement with the micromagnetic simulations of FeCo structures with residual stress,[10] indicating that the simple calculation described in this paper may be used to predict the general domain configuration in a patterned element. Coupled with simulations of stress anisotropy based on uniform film stress,[5] it is possible to predict domain patterns without fabricating structures.

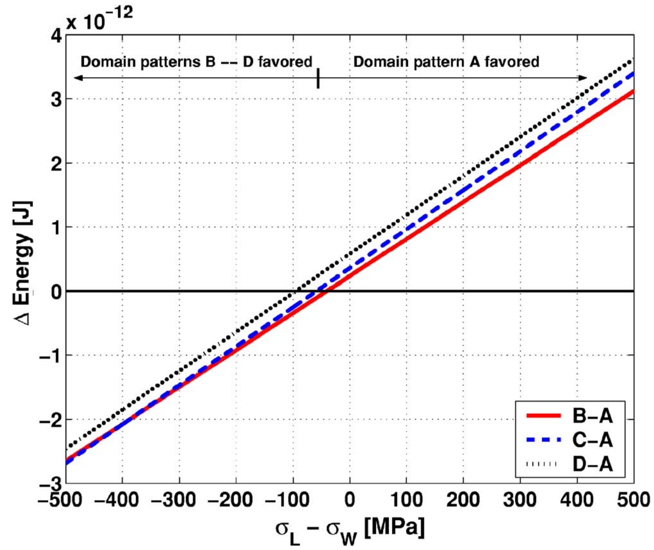

FIG. 4. Domain pattern energy for domain patterns B–D calculated with respect to pattern A.

IV. CONCLUSIONS

This paper shows that stress-induced anisotropy in patterned 1-μm-thick, 5×20 μm^2 FeCo structures affects the magnetic domain pattern in each structure. Through theoretical calculations, it was shown that a positive stress anisotropy reinforced the shape anisotropy- induced easy axis along the length of the structures, and that a negative stress anisotropy of less than −50 MPa resulted in an easy axis rotation. The relationship between the experimentally observed domain patterns and the stress anisotropy is in good agreement with the theoretically calculated behavior.

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[3]Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.
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