In-plane Uniaxial Anisotropy and Magnetization Reversal Mechanism of FeCo Films by Strip Pattern

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Abstract Strip-like FeCo films were patterned by a traditional lithograph process from intrinsically isotropic continuous FeCo films. The strip-patterned FeCo film shows a strong in-plane uniaxial magnetic anisotropy with easy axis along the length direction of the strip. The angular dependences of remanence ratio, switching field, and coercivity indicate that the magnetization reversal mechanism of the strip-patterned FeCo film is coherent rotation and domain wall depinning when the applied field is near the hard axis and easy axis, respectively. The consistency of the experimental hysteresis loops of the strip-patterned FeCo film and calculated hysteresis loops with a simple in-plane uniaxial anisotropy model indicates that the strip-patterned FeCo film behaves as a single domain. The absence of the domain wall and the strong in-plane anisotropy field make the strip-patterned FeCo films have much potential for high-frequency application.

KEY WORDS: In-plane anisotropy; FeCo film; Strip patterned; Switching field

1 Introduction

Soft magnetic materials are widely used in the modern electronic devices, e.g., audiovisual, house appliances, electro magnetic compatibility devices, and so on [1, 2]. With the development of information technology, the demands on the density of information storage and speed of information transmission and conversion are increasingly high [3–9]. For the high-frequency applications of soft magnetic thin films, one need the magnetic thin films having a high saturation magnetization ($4\pi M_s$), a relatively large in-plane uniaxial anisotropy (IPUA) field (H_k) and a high electric resistivity in order to obtain a high ferromagnetic resonance frequency f_{FMR} and a low eddy current

loss [10–17]. Whereas, several methods to adjust IPUA have been studied both in micromagnetic simulations and experiments so far including exchange coupling bias [18, 19], micro-strip patterning which is related to shape anisotropy [20, 21], annealing under magnetic field [22, 23], stress which is related to magnetostriction and stress anisotropy [24, 25], and element compound additions which can refine the grain and benefit the field-induced anisotropy [26–28].

Fe₇₀Co₃₀ alloy has superior magnetic properties, for example it has the highest saturation magnetization (M_s) at room temperature among all the ferromagnets so far. Fe₇₀Co₃₀ alloy is suitable for using as recording heads for disk drivers, and it is also one of the key materials of write head and thin film inductor [29]. However, due to the isotropic magnetic property with high coercivity, general FeCo films are not suitable for high-frequency application. There have been several methods to tune the in-plane uniaxial anisotropy of FeCo films so far [30–32]. In this work, strip-patterned FeCo films were prepared via photolithograph process. IPUA was induced by the magnetic dipole interaction of the magnetic moments in

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different strips. In-plane uniaxial anisotropy property was confirmed by the hysteresis loops, which were measured under various applied field directions. In order to investigate the magnetization reversal mechanism of the in-plane uniaxial anisotropy FeCo films, the angular dependences of the remanence ratios (M_r/M_s), switching fields (H_s), and coercivities (H_c) were investigated. The hysteresis loops along different directions were reproduced theoretically using a simple model with uniaxial anisotropy.

2 Experimental

FeCo thin films used in this work were fabricated by direct current (DC) magnetron sputtering onto the glass substrates. The base pressure of the main chamber was 3.5×10^{-5} Pa. The DC power and Ar gas flow rate for sputtering 3-inch Fe₇₀Co₃₀ target were selected as 30 W and 15 mL/min, respectively. Cu and Ta targets with diameter of 3 inch in main chamber were also chosen to deposit a 20-nm seed layer and 5-nm protective overcoats, respectively. The DC powers for Cu and Ta were 10 and 30 W, respectively. The pressure during sputtering was 0.19 Pa. No external magnetic field was applied to the substrate during deposition. The thicknesses of Cu, FeCo, and Ta layers were controlled by depositing time and sputtering rate. The thickness of FeCo was controlled around 500 nm. Then, via further lithograph processing, the magnetic isotropic FeCo thin film would have strong in-plane uniaxial anisotropy. In this work, a Heidelberg Direct Write Laser instrument for exposure and ion beam milling device for pattern transfer were used to pattern a continuous FeCo film to strips with each strip being $15 \mu\text{m} \times 5,000 \mu\text{m}$ in dimension. The interval of two adjacent strips was set to $5 \mu\text{m}$. The optical photo of the sample was taken by an Olympus optical microscope. The magnetic properties of strip-patterned FeCo films were measured by a MicroSense EV-9 vibrating sample magnetometer (VSM) with the magnetic field resolution and sweep rates around 7.8 and 96.0 A/m per second, respectively. The easy-axis direction of the magnetization and in-plane angular dependent magnetic properties were measured by VSM using an automatic rotation sample accessory with the angle accuracy of 0.5° . A Durham micro-focused Magneto-optical Kerr Effect (MOKE) equipment NanoMOKE 2TM was utilized to study the magnetic properties of a single strip with a $3\text{-}\mu\text{m}$ -sized laser spot focused on the middle and end parts of the strip, respectively. The longitude Kerr signal was recorded with the applied field along the length direction of strips. Measurements on these samples were performed at room temperature.

Fig. 1 Optical image of the strip-patterned FeCo film **a** and the coordinate system with x axis parallel to the length direction of strips and y axis perpendicular to the length direction **b**

3 Results and Discussion

As shown in Fig. 1a, the continuous FeCo film fabricated by DC magnetron sputtering was perfectly etched into strip-patterned FeCo film. The size of the strip-patterned FeCo film was $5 \text{ mm} \times 5 \text{ mm}$, and each strip was $15 \mu\text{m} \times 5,000 \mu\text{m}$. The distance between two adjacent strips was around $5 \mu\text{m}$. Figure 1b shows the coordinate system, in which x axis is parallel to the length direction of the strips and y axis perpendicular to the length direction. The ϕ represents the angle between the applied field (H) and the x axis. The θ represents the deviating angle of stable position of M_s from the x axis direction in an external field H . The $-H$ represents the reversal magnetic field.

The isotropic magnetic property of the unpatterned FeCo film was gained due to no induced field applied during the film fabrication. The magnetic properties of FeCo thin films were measured by various techniques. Figure 2 shows the typical in-plane hysteresis loops of patterned FeCo films at various of ϕ . It can be clearly seen that a nearly square-like loop at $\phi = 0^\circ$ and a linear-like loop at $\phi = 90^\circ$ of a patterned film, which respectively corresponds to an easy magnetization direction and a hard magnetization direction. The demagnetizing factors along length direction, width direction, and out of plane direction can be defined as $N_x = 0$, $N_y = \varepsilon$, and $N_z = 1 - \varepsilon$, with $\varepsilon = t/W$ and $L \gg W$ [33], where t , W , and L are the thickness, width, and length of the strip, respectively. In this case of $\varepsilon = 0.033$, the maximum demagnetization factor is still in the out of plane direction. Then we can conclude that the FeCo film is easier to be magnetized along the length direction than the width direction. Thus, the obtained in-plane uniaxial anisotropy was ascribed to the shape anisotropy of patterned FeCo strips.

In order to investigate the magnetization reversal mechanism of the patterned FeCo strips, the angular dependences of the remanence ratios, coercivities, and switching fields were measured as functions of ϕ . Figure 3 shows the angular dependences of the remanence ratio and

Fig. 2 In-plane hysteresis loops of strip-patterned FeCo film with magnetic field in different directions: **a** $\phi = 0^\circ$; **b** $\phi = 40^\circ$; **c** $\phi = 60^\circ$; **d** $\phi = 75^\circ$; **e** $\phi = 85^\circ$; **f** $\phi = 90^\circ$

Fig. 3 Angular dependences of in-plane remanence ratio (solid squares), reduced remanence ratio (open circles), and a $|\cos\phi|$ dependence curve (red line)

the reduced remanence ratio. The reduced remanence ratio is the ratio of the remnant magnetization at ϕ to the remnant magnetization at $\phi = 0^\circ$. For any ϕ , M_s is theoretically always along the easy axis when the applied field H decreases to zero. Since the VSM measured the magnetic moment along the applied field direction, the measured

remnant magnetization is $M_r = M_s \cos\phi$. Thus, the $\cos\phi$ dependence of remanence ratio should be satisfied. However, it can be seen from Fig. 3 that the reduced remanence ratio is perfectly described by a $|\cos\phi|$ dependence rather than the remanence ratio. It indicates that the saturation magnetization is slightly deviated from the easy axis, i.e., the length direction of the strips. There are two reasons to contribute to this deviation: One reason may be the H direction at $\phi = 0^\circ$ slightly deviate from the length direction of the strips. However, it can be ruled out, since the rotation angle accuracy of the VSM is less than 0.5° which means that the easy axis can be accurately obtained. Another reason is the remanence magnetization at the end of a strip is not along the length direction due to the shape anisotropy and the interaction between two adjacent strips with the stray fields produced by the strip arrays. In order to clarify this point, the hysteresis loops of a strip with laser spot focused on the middle and end parts of the strip were measured by MOKE and shown in Fig. 4. It can be clearly seen that the remanence ratio of the middle part is larger than that of the end part of one FeCo strip, which indicates that the easy axis direction of the end parts of a strip is obviously deviated from the length direction. Thus, an ideal $|\cos\phi|$ dependence of the reduced remanence ratio can be obtained and ascribed to the formation of in-plane uniaxial anisotropy, which forces the saturation magnetization along

Fig. 4 Normalized Kerr loops of one FeCo strip with laser spot focused on the middle **a** and end **b** parts of a strip

the length direction due to the strong shape anisotropy except the miss orientation of magnetization direction at the end of each strip.

As mentioned above, the strong shape anisotropy will force the magnetization along the x direction. It is worthy to investigate the magnetization reversal mechanism. As can be seen in Fig. 2, for a given value of ϕ , H can increase to a sufficiently high value, at which the magnetization will switch, namely switching field H_s . Along x direction, the magnetization reverses sharply at a small switching field of $H_s(0^\circ) = 14.1$ Oe (1 Oe equal to 79.6 A/m), as shown in Fig. 2a. For any ϕ , H has components of $H_{||} = H\cos\phi$ and $H_{\perp} = H\sin\phi$ along the easy axis and hard axis, respectively, where $H_{||}$ contributes to the magnetization reverse along x direction and $H_{\perp}$ brings the magnetization rotation toward y direction. At a constant value of applied field H , as ϕ ($0^\circ < \phi < 90^\circ$) increasing, $H_{\perp}$ increases and $H_{||}$ decreases, so the increasing trend of rotational component of magnetization is clear and presented in Fig. 2. Thus, the switching field for any ϕ should meet the requirement that the projection of H onto the x axis equals to $H_s(0^\circ)$, i.e., $H_{||}$ equals to the critical value of $H_s(0^\circ)$, at which the magnetization will switch. Thus, the angular dependence of the switching fields is $H_s(\phi)\cos\phi = H_s(0^\circ)$, i.e., $H_s(\phi) = H_s(0^\circ)\sec\phi$. Figure 5 shows the angular dependence of the switching fields. It can be seen that the experimental data are consistent with the theoretical $|\sec\phi|$ prediction. It indicates that the magnetization is always along the x direction at small external field H and the switching of magnetization at $H_s(\phi)$ consists of domain reversal along x direction.

The coercive field, at which the magnetization equals to zero, can be deduced from the hysteresis loops. The full angular range of coercivities is shown in Fig. 6. It

Fig. 5 Angular dependence of switching fields

Fig. 6 Angular dependence of coercivity H_c

can be clearly seen that a nonmonotonic behavior of coercivity between $\phi = 0^\circ$ and $\phi = 90^\circ$. The similar shapes of angular dependence of coercivity were also reported in the nanowire arrays [34], nanotube arrays [35], and magnetic thin films [36] with uniaxial anisotropy. The magnetization reversal mechanism of them cannot be singly explained by means of a coherent rotation, transverse reversal mode, or a vortex domain wall. According to previous works [26, 37], the magnetization reversal mechanism can be divided into two parts. When the applied field direction is close to the easy axis, the magnetization is reversed by the domain wall depinning, while the magnetization is reversed dominantly by coherent rotation when the applied field direction is close to the hard axis. The former gives to the Kondorsky relation of coercivity $H_c(\phi) = H_c(0^\circ)/\cos\phi$, and the later one gives to the Stoner–Wohlfarth

Fig. 7 Calculated (red line) and experimental (open squares) hysteresis loops at $\phi = 40^\circ$ **a**, 60° **b**, 75° **c** of strip-patterned FeCo film

relation of coercivity as $H_c(\phi) = (H_K/2) \sin 2\phi$, where H_K is the in-plane uniaxial anisotropy field and equal to 440 Oe in this sample. The calculated results according to these two models are also depicted in Fig. 6. The consistency of the experimental data and theoretical simulation indicates that the magnetization reversal mechanism can be understood as follows. When ϕ is close to 90° , $H_{\parallel} \ll H_{\perp}$, thus the coherent rotation is dominated, while when ϕ is close to 0° , $H_{\perp} \ll H_{\parallel}$, domain wall depinning is dominated.

Generally speaking, the magnetization reversal process is quite sophisticated due to the hysteresis of the magnetization and the hysteresis loop is hard to be theoretically simulated. As mentioned above, the magnetization motion process is clear for our sample. Thus, we try to calculate the in-plane angular hysteresis loops based on the particular magnetization reversal mechanism. As we let the applied field H deviate an angle ϕ from the easy axis, so the free energy density of the FeCo film is given by

$$F = K_u \sin^2 \theta - H M_s \cos(\phi - \theta), \quad (1)$$

where θ is the angle between M_s and the easy axis and K_u is the uniaxial anisotropy energy constant. The first term is the uniaxial anisotropy energy, and the second term is the potential energy.

We set the first derivation of Eq. (1) over θ to zero, which gives the equilibrium position of M_s , and then lead to the following equation:

$$H = (2K_u \sin \theta \cos \theta) / (M_s \sin(\phi - \theta)). \quad (2)$$

The projection of M_s onto the applied field direction can be expressed as follows:

$$M/M_s = \cos(\phi - \theta). \quad (3)$$

To plot the hysteresis loop for a given value of ϕ , we find θ with various values of H from Eq. (2), and we find the reduced magnetization in the applied field direction from Eq. (3). It should be drawn attention that the angle ϕ would alter for different directions of applied fields. Let $\phi = 30^\circ$, for positive values of H , the angle θ will vary between 0° and 30° . For selected values of H , corresponding values of θ and M are found from Eqs. (2) and (3), respectively. When H is negative, $\phi = 180^\circ - 30^\circ = 150^\circ$, and we can find a critical value θ_c at which the magnetization will flip. θ_c was found by setting the first derivative and the second derivate of Eq. (1) with respect to θ to zero, simultaneously. Values of θ and M are again obtained from Eqs. (2) and (3). Then we can get the various corresponding values of M with H . The calculated loops are shown in Fig. 7 for $\phi = 40^\circ$, 60° , and 75° . It can be clearly seen that the calculated results are in good correspondence with the experimental data except slight deviations.

The good correspondence shows that the strip-patterned FeCo film can be assumed as a single domain and its magnetization always along the length direction of the strip due to the strong shape anisotropy. It indicates that there will be lack of the domain wall in this kind of the strip-patterned FeCo films. There are two kinds of relaxation mechanism of permeability for the high-frequency soft magnetic application at microwaves. One is related to the domain wall motion at low frequency, and the other one is the natural ferromagnetic resonance [38]. The existence of the domain walls in a soft magnetic thin film will result in the low-frequency domain wall resonance component at microwaves, which will decrease the cut-off frequency of the soft magnetic thin film. The natural ferromagnetic resonant frequency is proportional to the square of the in-plane anisotropy field of a soft magnetic thin film. However, the change of the anisotropy field of the patterned FeCo films can be realized by changing the shape anisotropy of a strip. Thus, the advantage of the lack of the domain wall and tunable anisotropy field makes the strip-patterned FeCo films have much potential for high-frequency application.

4 Conclusions

In conclusion, traditional photolithograph technique was used to fabricate the strip-like FeCo arrays. A strong in-

plane uniaxial anisotropy was obtained for the strip-patterned FeCo film due to the change of the shape anisotropy from intrinsically isotropic continuous FeCo film. The magnetization reversal mechanism of patterned FeCo films was coherent rotation and domain wall depinning when the applied field was near the hard axis and easy axis, respectively. The consistency of the calculated and measured hysteresis loop of patterned FeCo films indicates that the strip-patterned FeCo film behaves as a single domain. The strip-patterned FeCo films with strong and tunable anisotropy field and lack of domain wall have much potential for high-frequency application.

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