Demagnetizing factors in patterned CoNiFe films with rectangular elements*

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CoNiFe patterned films with rectangular elements, all 600-nm wide but of different lengths, were fabricated and investigated by ferromagnetic resonance experiment and micromagnetic simulation. An in-plane magnetic uniaxial anisotropy was exhibited, and its value increases with the increase of the aspect ratio of the elements, which was fitted by the model, including a quasi-ellipsoid demagnetizing field and a non-uniform demagnetizing field. The relative importance of the non-uniform demagnetizing field decreased from 0.26 to 0.16 with the increase of the length–width aspect ratio of the patterned element from 1.5 to 10. The demagnetizing factors in the three principal axes were determined from the experimental data of ferromagnetic resonance, which agreed reasonably well with the values calculated by micromagnetic simulation. The calculation also indicated that the interaction between elements could be neglected when the edge-to-edge spacing between neighboring elements was larger than 3 μm in our patterned films.

Keywords: patterned film, shape anisotropy, ferromagnetic resonance

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1. Introduction

Magnetic arrays with micron and submicron elements have attracted a lot of attention recently due to their potential applications in magnetic random access memory (MRAM) and ultrahigh-density data storage,[1–4] as well as their unique behaviors. For continuous magnetic polycrystalline thin films, the magnetic anisotropy in the film plane is often negligible, but it becomes significant in patterned films as the lateral size of the elements in it decreases, which influences other properties such as hysteresis loop, coercivity, remanence, and saturation field.[5] The influence of shape on the properties of nanomagnets in the size range of 35 nm–500 nm with elliptical, triangular, square, pentagonal, and circular geometries was reviewed in 2000 by Cowburn.[6] He found that the competition between exchange energy and magnetostatic energy determined whether the nanomagnets exhibited single domain or incoherent magnetization and also controlled the non-uniformities in magnetization which lead to configurational anisotropy. Hillebrands' group also investigated magneto–dipole coupling in arrays of micron-size rectangular magnetic elements by magneto-optic Kerr-effect magnetometry, magnetic force microscopy, and Brillouin light scattering.[7,8] The theoretical and experimental studies of spin wave quantization in laterally confined magnetic structures also achieved excellent results.[9–11] Still, many new reports on shape anisotropy of magnetic nanodots and antidots have continued to appear very recently.[12–14] However, studies of the non-uniform part of shape anisotropy of the elements and the interaction between them by FMR are scarce. We have investigated the non-uniformity of demagnetizing field and magnetization in the patterned NiFe arrays by using FMR and proposed an FMR fitting expression in which the anisotropy can be approximately separated into quasi-uniform and non-uniform contributions. The quasi-uniform contribution is described by conventional demagnetizing factors and the non-uniform contribution is described by a higher order term.[15,16] In this paper, we further present the demagnetizing factors of CoNiFe patterned films with micron and submicron rectangular elements using the model with the quasi-uniform and non-uniform shape anisotropies by FMR experiment and micromagnetic simulation with LLG software. The agreement between the experimental and simulated results shows that our model is suitable in our cases.

2. Experiment and result

Magnetic single-layer films of Ta (5 nm)/CoNiFe (5 nm)/Ta (5 nm) were deposited on silicon substrates using ion-beam sputtering. The arrays of patterned elements were fabricated by electron-beam lithography and ion-milling. Each array consists of approximately 10^6 nominally identical,

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evenly spaced elements, with the inter-element edge-to-edge separation ranging from 1.25 μm to 6 μm. The width of all the elements is 0.6 μm, and the length is 0.9 μm (Fig. 1(a)) and 6 μm (Fig. 1(b)), respectively, as shown in Fig. 1. The length-to-width aspect ratio values are 1.5 and 10. The FMR experiment was performed at room temperature by using Brucker ER-200D-SRC ESR equipment with a TE102 rectangular resonant cavity at a microwave frequency of 9.78 GHz.

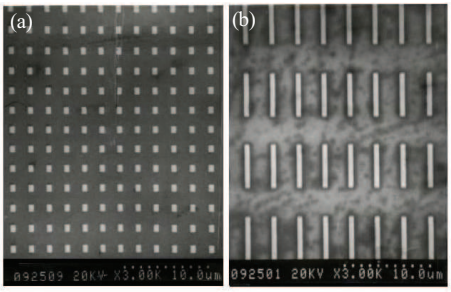


Fig. 1. SEM images of patterned CoNiFe films. The width of the patterned elements is 0.6 μm, and the length is (a) 0.9 μm and (b) 6 μm, respectively.

The experimental dots of resonance field ($H_{\rm res}$) of the patterned films as a function of the in-plane magnetic field orientation ($\phi_{\boldsymbol{H}}$), as shown in Fig. 2, exhibit well-defined in-plane uniaxial symmetry. Here, $\boldsymbol{H}$ is the applied field. The resonance field along the short edges of the rectangular element ($H_{\rm resy}$) is larger than that along the long edges ($H_{\rm resx}$), and the value of ($H_{\rm resy} - H_{\rm resx}$) becomes larger with the aspect ratio increasing from 1.5 to 10.

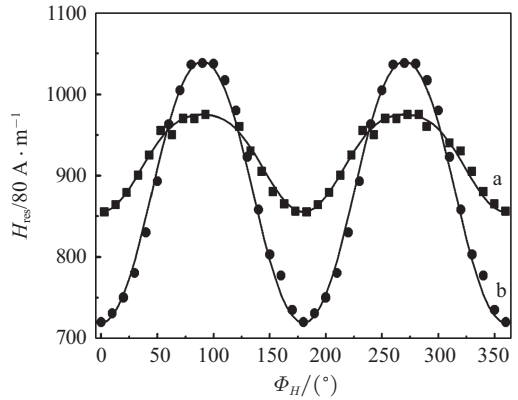


Fig. 2. FMR resonance field as a function of in-plane field orientation of CoNiFe patterned films with element aspect ratios of 1.5 (curve a) and 10 (curve b).

The demagnetizing field in a rectangular element is not uniform and thus cannot be expressed exactly by demagnetizing factors as in an ellipsoidal specimen. We propose an approximate way to express the demagnetizing field of the rectangular element by two terms containing uniform and non-uniform parts. The free energy of the rectangular elements can be expressed approximately as follows:[16]

$$\begin{aligned} F \;=\; & -MH[\cos\theta\cos\theta_{\boldsymbol{H}} + \sin\theta\sin\theta_{\boldsymbol{H}}\cos(\phi-\phi_{\boldsymbol{H}})] \\ & + K_{\rm u}^{\perp}\sin^2\theta + \frac{1}{2}(N_z - N_x)M^2\cos^2\theta \\ & + \frac{1}{2}(N_y - N_x)M^2\sin^2\theta\sin^2\phi \\ & + \frac{1}{4}c(N_y - N_x)M^2\sin^4\theta\sin^4\phi. \end{aligned} \tag{1}$$

Here, M and $K_{\rm u}^{\perp}$ are the magnetization and perpendicular anisotropy constants of CoNiFe, (θ,ϕ) and $(\theta_{\boldsymbol{H}},\phi_{\boldsymbol{H}})$ are the angles for the magnetization and applied field, respectively, in spherical coordinates. The first three terms are respectively the Zeeman energy, the surface perpendicular anisotropy energy, and the demagnetizing energy normal to the film. The last two terms are the approximate in-plane demagnetizing energy. N_x, N_y, and N_z are the demagnetizing factors in the long edges, short edges, and normal directions, respectively. The c term describes the effect of the non-uniform magnetization mostly near the edge, and the constant c varies with the length of the element.

The resonance fields $H_{\rm res}$ were calculated by using the following general equation derived from the Landau–Lifshitz equation without damping and the total free energy density minimization with respect to the magnetization orientation (θ,ϕ)[17]

$$\left(\frac{\omega}{\gamma}\right)^2 = \frac{1}{M^2\sin^2\theta}[F_{\theta\theta}F_{\phi\phi} - F_{\phi\theta}^2]. \tag{2}$$

Here, γ is the gyromagnetic ratio ($\gamma = ge/2mc$, g is the Lande factor, e is electron charge, m is the mass of electron, and c is the speed of light), F_{ij} is the second-order derivative of the free energy of Eq. (1) with respect to θ and ϕ. Substituting Eq. (1) into Eq. (2), we can obtain the theoretical FMR frequency or the resonance field as a function of field orientation based on different expressions for free energy.[18] The theoretical curves are lines in Fig. 2, and they fit the experimental data well, which indicates that the in-plane magnetic uniaxial anisotropy refers to shape anisotropy of the element. From the fitting, the various shape anisotropy fields are obtained for the patterned films with different aspect ratios and are shown in Table 1. The absolute value of c is 0.26 and 0.16 for the elements with the aspect ratios of 1.5 and 10, respectively, which indicates that the longer elements are magnetized more uniformly. The difference of the quasi-demagnetizing factors between the x and y directions, $(N_y - N_x)$, as well as that between the x and z directions, $(N_z - N_x)$, increases with increasing the aspect ratio. For a uniformly magnetized ellipsoid, the summation of three demagnetizing factors in the three principal axes is exactly 1. Assuming that the summation of demagnetizing factors is still approximately 1 for the patterned rectangular element, we determined the mean values of N_x, N_y, and N_z from the demagnetizing field fitted by FMR, and the data are shown in Table 1, where we see that non-zero in-plane demagnetizing factors are exhibited in the patterned film. On

the other hand, the demagnetizing factor along the film normal direction is less than that of continuous film (which is 1) because of the decrease of the lateral sizes in the patterned film. The demagnetizing factor in the film normal direction is 7 times higher than that in the long edge direction (easy axis) because the thickness is much smaller than the lateral sizes, and it becomes 8 times when the length–width aspect ratio of rectangular elements increases from 1.5 to 10.

Table 1. The various parameters of CoNiFe patterned films determined from FMR experimental data.

Aspect ratio	c	g	$(N_z - N_x)M_s/10^3$ A·m^{-1}	$(N_y - N_x)M_s/10^3$ A·m^{-1}	N_x	N_y	N_z
1.5	–0.26	2.14	823	5.97	0.116	0.120	0.764
10	–0.16	2.15	879	14.22	0.099	0.110	0.791

In order to confirm the validity of FMR fitted results, we simulated the shape anisotropy of a single rectangular element in a 3×3 array with the elements by using the LLG Micromagnetic Simulator.[19] The calculated demagnetizing factors in the three principal axes are obtained and shown in Table 2 with initial parameters as follows: saturation magnetization $M_s = 1.273 \times 10^6$ A/m, exchange constant $A = 10 \times 10^{-12}$ J/m, damping constant $\alpha = 0.08$, and cell size 5 nm × 5 nm × 5 nm. The magnetic anisotropy $K = 0$ due to the polycrystalline elements.

From Table 2, we see that the values of calculated demagnetizing values of both single element and 3×3 arrays are basically consistent with those from the FMR experiment and fitting. The demagnetizing factors calculated with 3×3 arrays model approximate the experimental data better than the single element model though their difference is tiny, implying that interaction between elements indeed exists but can be ignored. The spin configurations for the single element and central element in 3×3 arrays are shown in Fig. 3, respectively. The major area of spin configuration in the element shows uniform magnetization for both the single element and the array, and the uniform rotation is shown with the orientation of the magnetic field. The non-uniform magnetization at the edge in the single element is similar to that in the 3×3 arrays, but it is noted that the spin at the edge in 3×3 arrays (Fig. 3(b)) is more uniform than that in the single element (Fig. 3(a)), indicating that the interaction among elements reduces the demagnetizing field due to the effect of the compensation of the adjacent positive and negative poles.

Table 2. Demagnetizing values calculated by LLG Micromagnetic Simulator.

Aspect	Single element			3×3 elements		
ratio	N_x	N_y	N_z	N_x	N_y	N_z
1.5	0.123	0.129	0.748	0.120	0.122	0.758
10	0.103	0.112	0.785	0.102	0.112	0.786

3. Conclusion

In conclusion, the magnetic in-plane shape anisotropy of CoNiFe patterned films with rectangular elements with different length–width aspect ratios were investigated by using FMR experiment and LLG micromagnetic simulation. The demagnetizing factors in the three principal axes determined by the theoretical calculation and ferromagnetic resonance measurements agree well with each other. The shape anisotropy can be approximately separated into quasi-uniform and non-uniform contributions. The relative importance of the non-uniform demagnetizing field decreases with the increase of the length–width aspect ratio of the patterned elements. In addition, the results of micromagnetic simulation indicate that the demagnetizing factors show only tiny changes due to element interactions, which can be ignored when the edge–edge spacing between neighboring elements increases to 3 μm.

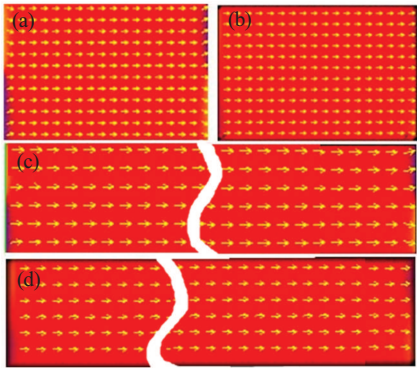


Fig. 3. (color online) The spin distributions in the elements with different aspect ratios obtained by micromagnetic simulation. The magnetic fields are along the long edge. (a) and (c) are for the single element; (b) and (d) are for the central element in 3×3 arrays with 1.5 and 10 aspect ratios, respectively.

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