Vol 16 No 6, June 2007
1009-1963/2007/16(06)/1725-03
Chinese Physics
© 2007 Chin. Phys. Soc.
and IOP Publishing Ltd

The study of the shape anisotropy in patterned permalloy films*

Zhang Dong(张 栋)[a)b)†], Zhai Ya(翟 亚)[b)], and Zhai Hong-Ru(翟宏如)[c)]

[a)] *School of Physics Science and Information Engineering, Liaocheng University, Liaocheng* 252059, *China*
[b)] *Department of Physics, Southeast University, Nanjing* 210096, *China*
[c)] *National Laboratory of Solid Microstructure, Center for Materials Analysis, Nanjing University, Nanjing* 210093, *China*

(Received 17 September 2006; revised manuscript received 5 January 2007)

In this paper a systematic ferromagnetic resonance study shows that an in-plane magnetic anisotropy in the patterned micron octagon permalloy ($Ni_{80}Fe_{20}$) elements is mainly determined by the element geometry. The easy-axis is along the edge of the elements, and the hard-axis is along the diagonal. The shape anisotropy of the octagon elements is determined by square and equilateral octagon, and the theoretical calculation was studied on the shape anisotropy. The shape anisotropy of rectangular was calculated by using the same theory.

Keywords: patterned film, shape anisotropy, ferromagnetic resonance
PACC: 6860, 0758

Patterned small magnets and particles have recently attracted increasing interest due to their potential application in magnetic random access memory (MRAM) and ultrahigh-density data storage.[1−3] They show rather different behaviours from the continuous polycrystalline thin films.[4] Magnetic anisotropy is often negligible, but in patterned small elements it is one of the element shape anisotropy and is one of the most fundamental properties, for it influences other properties such as hysteresis loop, coercivity, remanence, and saturation field.[5] Ferromagnetic resonance (FMR) has proven to be a powerful tool for quantifying magnetic anisotropy of thin films due to its high sensitivity and capability of mapping out symmetry.[6,7] It also provides quantitative information on the magnetization, gyromagnetic ratio and exchange interaction. However, FMR study of patterned magnetic structures is scare. $Ni_{80}Fe_{20}$ films with 900 nm wide, 20 nm thick rectangular elements were studied in our previous work,[8] but the theory cannot explain the case of octagon as well as the rectangular element with aspect ratio 1.5. In this paper, we report some results of micromagnetic numerical calculation with new theory.

The arrays of patterned elements were fabricated by using electron-beam lithography and ion-milling. The width of the square is 900nm and thickness is 20nm. The width of the octagon is 10μm and thickness is 100nm. 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.

The experimental data points representing the evolution of the FMR field ($H_{\rm res}$) as a function of the orientation (ϕ_H) in the film plane of the patterned films are shown in Fig.1. For the square elements, the in-plane anisotropy is clearly fourfold, and $H_{\rm res}$ is higher along the diagonal directions than along the square edges. For the octagon elements, the in-plane anisotropy is approximate fourfold, and there are eight peaks. It looks like fourfold with added weaker eightfold, and $H_{\rm res}$ is the highest along the diagonal directions, and higher along the short edges, and lowest along the long edges of the octagon elements.

Neglecting the magnetostatic interaction between the elements, and using an approximation of a homogeneously magnetized ellipsoid for a octagon element, we can write the total free energy density F as

$$\begin{aligned} F = & -MH[\cos\theta\cos\theta_H + \sin\theta\sin\theta_H\cos(\phi-\phi_H)] \\ & + K_{\rm u}^{\perp}\sin^2\theta + \frac{1}{2}(N_z - N_x)M^2\cos^2\theta \\ & + \frac{1}{2}CA_sM^2\sin^2\theta\sin^2 4\phi \end{aligned}$$

*Project supported by the National Natural Science Foundation of China (Grant No 50171020) and the Foundation for youth of Liaocheng University (Grant No X051050).
†E-mail: zhangdong@lcu.edu.cn

$$+\frac{1}{2}(1-C)A_sM^2\sin^2\theta\sin^2 2\phi. \quad (1)$$

Here (θ,ϕ), and (θ_H,ϕ_H) are the angles for the magnetization and applied field vectors respectively in spherical coordinates. The various terms are respectively the zeeman energy, the perpendicular anisotropy energy, the demagnetizing energy normal to the film and the in-plane demagnetizing energy, and the last two terms refer to the shape anisotropy energy due to the non-uniform demagnetizing effect. $N_x$and N_z are the demagnetizing factors in three orthogonal direction. C $(0 \le C \le 1)$ is the ratio between the adjacent edges of the octagon and images the effect of octagon. When $C = 0$, Eq.(1) is the free energy of square element, and when $C = 1$, it is the free energy of equilateral octagon.

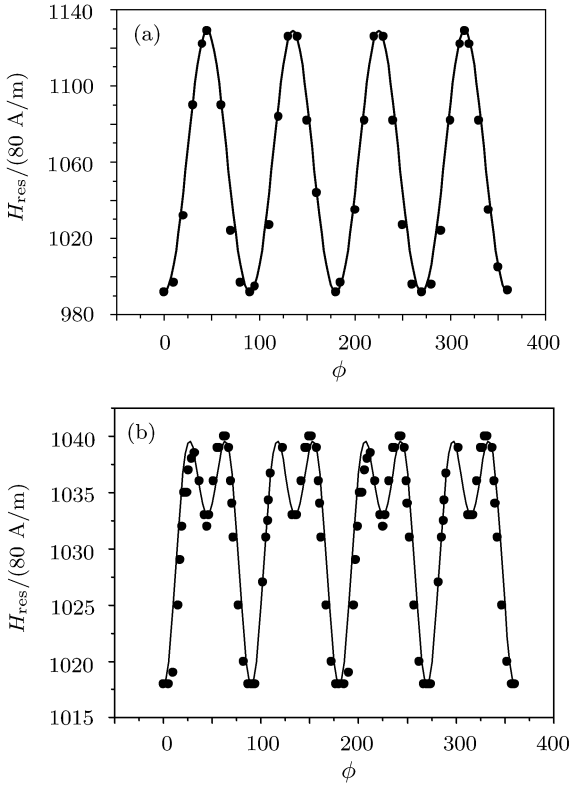


Fig.1. The variation of the resonance field as a function of the in-plane orientation of the magnetic field. The dots represent the experimental data and the lines represent the theoretical curves: (a) square elements; (b) octagon elements.

We use the following general expression for FMR resonance frequency derived from the Landau-Lifshitz equation and the total free energy density minimization with respect to the magnetization orientation (θ,ϕ):[9]

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

Where F_{ij} are 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. The solid curves in Fig.1 are the theoretically fitted curves based on Eq.(1), which agree very well with the experimental data points. The factor C, Fig.1(a), of octagon is 0.18, and it is the ratio between the two adjacent edges of the elements. The theoretical values from Eq.(1) fit with the experimental data very well. We can obtain the curves of shape anisotropy in any octagon elements including square elements. The contribution of the equilateral octagon for the shape anisotropy is weaker than that of square in the values because of its weaker shape anisotropy. In previous theory, the uniform factor C is 4 in this case, so it cannot be explained well.[8]

The variation of the resonance field as a function of the in-plane orientation of the magnetic field can be obtained by using Eqs.(1) and (2) in any octagon with the factor C changed. Certainly, one must measure the resonance field in some angles at first. Some theoretical curves are showed with variational C in Fig.2. With rise of the factor C, the shape anisotropy is approximately eightfold more. The shape anisotropy can be approximately separated into square and equilateral octagon contribution, and the dominant contribution is determined by the factor C, the ratio between the adjacent edges.

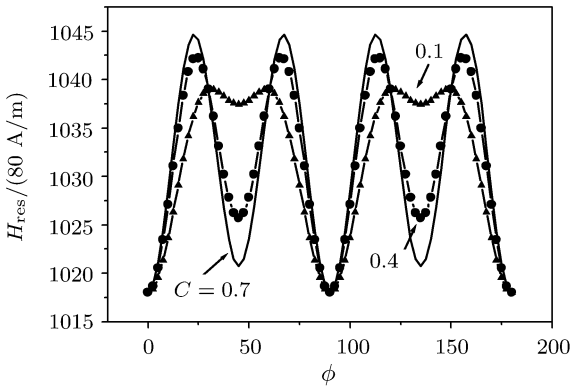


Fig.2. The theoretical curves of the variation of the resonance field as a function of the in-plane orientation of the magnetic field with different C.

So we can write the total free energy density F of

the rectangularity as

$$F = -MH[\cos\theta\cos\theta_H + \sin\theta\sin\theta_H\cos(\phi-\phi_H)] + K_{\mathrm{u}}^{\perp}\sin^2\theta + \frac{1}{2}(N_z - N_x)M^2\cos^2\theta + \frac{1}{2}(1-C)A_sM^2\sin^2\theta\sin^2\phi + \frac{1}{2}CA_sM^2\sin^2\theta\sin^2 2\phi.$$

The factor C means the effect of the square element for the rectangularity. Figure 3 shows the data of the theoretical curve and experimental dots of the rectangular element with size of 10 μm $\times$6 μm $\times$0.1 μm(C = 0.1).

In conclusion, our FMR study has demonstrated a unique capability for pinpointing in-plane magnetic anisotropy of patterned elements, and we calculated the shape anisotropy of octagon and rectangular elements in theory successfully. With decrease of the aspect ratio, the effect of shape anisotropy of the square element became obviously that of rectangular and octagon element.

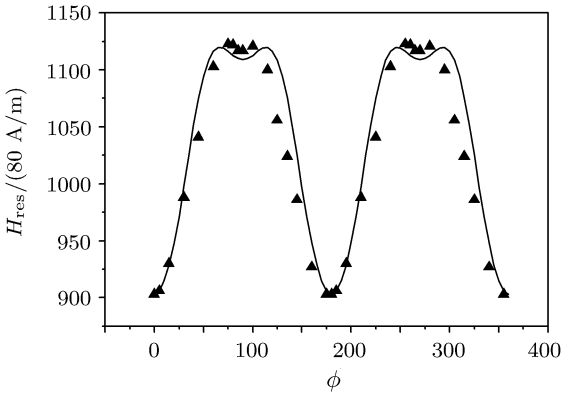


Fig.3. The theoretical curves of the variation of the resonance field as a function of the in-plane orientation of the magnetic field with element size of 10 μm $\times$6 μm $\times$0.1 μm.

References

[1] Prinz G A 1998 *Science* **282** 1660

[2] Bai J M, Liu X X, Xu H, Wei F L and Yang Z 2000 *Acta Phys. Sin.* **49** 1595 (in Chinese)

[3] Feng W C, Gao R W, Li W, H G B and Sun Y 2005 *Chin. Phys.* **14** 1649

[4] Liu C Y, Wang Y and Li J 2000 *Acta Phys. Sin.* **49** 786 (in Chinese)

[5] Hao Y, Walsh M, Farhoud M, Ross C A, Smith H I, Wang J Q and Malkinshi L 2000 *IEEE Magn.* **36** 2996

[6] Platow W, Anisimov A N, Dunifer G L, Farle M and Baberschke K 1998 *Phys. Rev.* B **58** 1

[7] Chen H Y, Li Z C, Fu S J, Jin S Z and Liang R Y 1999 *Acta Phys. Sin.* **48** 936 (in Chinese)

[8] Zhai Y, Shi J, Zhang X Y, Shi K, Xu Y X, Huang H B and Lu Z H 2002 *J. Phys.: Condens. Matter* **14** 7865

[9] Kittle C 1958 *Phys. Rev.* **105** 1295