Journal of Southeast University (English Edition) June 2002 Vol.18 No.2 ISSN 1003—7985

Ferromagnetic Resonance Study on the Permalloy Submicron Rectangular Arrays Prepared by Electron Beam Lithography*

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Abstract: In this paper, we report a ferromagnetic resonance study on the permalloy film of submicron-sized rectangular arrays prepared by electron beam lithography and the theoretical simulation to the non-uniform demagnetizing effect and ferromagnetic resonance data. By theoretical simulation, the magnetization, gyromagnetic ratio and g value of the sample are determined. The theoretical curves of the dependence of the resonance field on the field orientation φ_H fit well with the experimental data. When the steady magnetic field is applied near the film normal, a series of additional regular peaks (up to eight) appeared in the FMR spectrum on the low field side of the main FMR peak. The resonance field of these side peaks decreases linearly with the peak number. The possible physical mechanism of these multiple peaks was discussed.

Key words: ferromagnetic resonance, permalloy film, submicron arrays

The study on micron and submicron as well as nanometer scale magnets made by lithography techniques is one of the recent most attractive topics in magnetism. These so-called magnets, or particles, which usually consist of patterned arrays of separate magnetic elements of different shape, possess different magnetic properties from their parent bulk material by virtue of their extremely small size. The huge potential applications of micron and submicron scale patterned magnetic film in magnetic random access memory (MRAM)[1], high-density, low-noise magnetic storage media[2] is obvious. The magnetic anisotropy and the interaction between elements in micron and submicron patterned arrays were two of the most important properties, in the development of MRAM[3].

Conventional magnetic measurements are not sensitive enough to probe the anisotropy of micron and submicron scale patterned film. Some new techniques such as magnetic force microscopy[4] and magnetic-optic effect[5] can indeed image small-scale features, but they cannot give accurate quantitative information of magnetic anisotropy. Ferromagnetic resonance is a convenient and power tool for studying patterned magnetic thin films due to its high sensitivity and orientation dependence. FMR can provide information on the magnetization, gyromagnetic ratio, magnetic anisotropy and exchange interactions, etc. of thin films. However, FMR study of patterned magnetic structures is rather scarce. In this article we report the results of our study on the permalloy thin film patterned into arrays of 0.9 μm × 4.5 μm rectangular elements prepared by electron beam lithography.

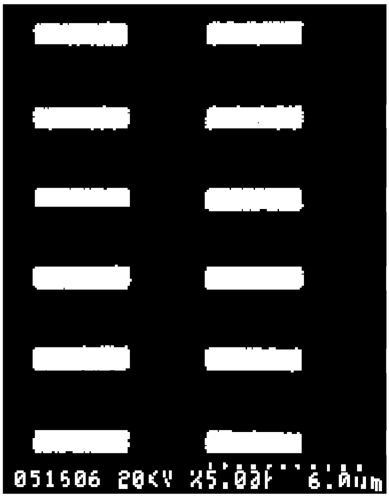

Fig. 1 SEM image of the sample

1 Experiment

The magnetic single layer films of the structure Ta(50Å)/NiFe(200Å)/Ta(50Å) were deposited on silicon substrates using ion-beam sputtering. Arrays of patterned element were fabricated using electron-beam lithography and ion milling. The element in the array has the width of 0.9 μm and the length-to-width aspect ratio is 5, with the space between elements of 3 μm × 3 μm, checked by scanning electron microscopy (SEM). The SEM image is shown in Fig. 1. FMR was performed with a Brucker ESR equipment of model ER-200D-SRC

Received 2001-10-22.
* The project supported by the National Natural Science Foundation of China (50171020).
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at a microwave frequency of 9.78 GHz at room temperature. The sample with 2 mm × 2 mm size was placed at the position where the intensity of microwave field is maximum and uniform in the TE102 rectangular microwave cavity. The intensity of DC applied magnetic field can scan automatically and its direction can be changed smoothly from in-plane to out of plane of the film.

2 Theoretical Treatment of FMR and Fitting

Fig.2 shows the coordinate system in the theoretical treatment of FMR. The angle between the direction of DC applied magnetic field H and Z axis, the normal direction of the film plane, θ_H and the azimuth angle is φ_H. The intensity of applied field is strong enough to magnetize the sample into a single domain. The polar and azimuth angles of the magnetization M are θ and φ at equilibrium. The microwave field h is perpendicular to H all the time. Without considering the damping effect, the dynamics of precession of the magnetication is described by the well known Landau-Lifshitz equation[6-8]

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \gamma H \times M \tag{1}$$

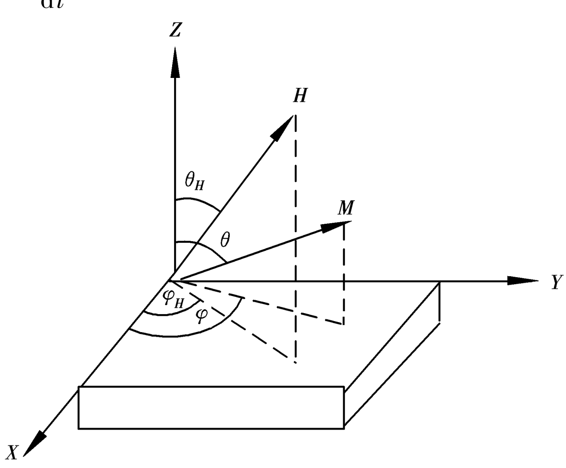

Fig.2 The coordinate system in the theoretical treatment of FMR

The following general expression of FMR resonance frequency is obtained by simultaneously solving the above Landau-Lifshitz equation and the equation for the free energy density minimization with respect to magnetization orientation.

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

where F_{ij} are the second derivatives of the free energy density F with respect to the spherical coordinates θ and φ of the magnetization in the thin film; γ is the gyromagnetic ratio, $\gamma = ge/2mc$ and g is the Lange splitting factor; M is the magnetization and ω is the angular frequency of the microwave field.

We use the following expression of the free energy density F of our patterned film

$$F = -MH[\cos\theta\cos\theta_H + \sin\theta\sin\theta_H\cos(\varphi - \varphi_H)] + K_u^{\perp}\sin^2\theta + \frac{1}{2}N_z M^2\cos^2\theta + \frac{1}{2}N_x M^2\sin^2\theta\cos^2\varphi + \frac{1}{2}N_y M^2\sin^2\theta\sin^2\varphi + \frac{1}{4}A(N_y - N_x)M^2\sin^4\theta\sin^4\varphi \tag{3}$$

The first term is the Zeeman energy, the second is the perpendicular anisotropy energy and the last four terms are demagnetizing energy. The demagnetizing field and its energy for a uniformly magnetized ellipsoidal sample is usually expressed by an expression using demagnetizing factors, such as N_x, N_y, N_z as the third to the fifth terms in the above equation. In the present case the rectangular element is non-ellipsoidal. Thus the magnetization and demagnetizing field are not uniform and the demagnetizing energy cannot be expressed by the expression simply containing demagnetizing factors. We proposed an approximate solution of this problem by addition of a higher order anisotropy term to reflect the effect of magnetization non-uniformity to the demagnetizing energy of a uniformly magnetized elliptic element as shown in the above equation which can fit our experimental data fairly well.

Substituting (3) into (2) and considering the equilibrium condition of magnetization orientation by minimizing the free energy density with respecting to θ and φ: $\partial F/\partial\varphi = 0$, $\partial F/\partial\theta = 0$, the theoretical expression for FMR frequency in terms of the steady magnetic field is obtained as follows.

$$\left(\frac{\omega}{\gamma}\right)^2 = \{H[\cos\theta\cos\theta_H + \sin\theta\sin\theta_H\cos(\varphi - \varphi_H)] - H_M^{/\!/}\cos2\theta + H_M^{/\!/}\cos2\theta\sin^2\varphi + AH_M^{/\!/}\sin^2\theta(3\cos^2\theta - \sin^2\theta)\sin^4\varphi\} \times \{H[\cos\theta\cos\theta_H + \sin\theta\sin\theta_H\cos(\varphi - \varphi_H)] - H_M^{\perp}\cos^2\theta + H_M^{/\!/}(\cos^2\theta\sin^2\varphi + \cos2\varphi) + AH_M^{/\!/}\sin^2\theta\sin^2\varphi(3\cos^2\varphi - \sin^2\theta\sin^2\varphi)\} - [H_M^{/\!/}\cos\theta\sin\varphi\cos\varphi + 3AH_M^{/\!/}\sin^2\theta\cos\theta\sin^3\varphi\cos\varphi]^2 \tag{4}$$

When the steady magnetic field is in xy plane, it can be proved that $\theta = \pi/2$ when $\theta_H = \pi/2$ at the conditions of resonance field H_{res} and at the frequency of 9.78 GHz. The theoretical expression for resonance frequency in terms of the steady in plane magnetic field is obtained as

$$\left(\frac{\omega}{\gamma}\right)^2 = [H\cos(\varphi - \varphi_H) + H_M^{\perp} - H_M^{/\!/}\sin^2\varphi - AH_M^{/\!/}\sin^4\varphi] \times [H\cos(\varphi - \varphi_H) + H_M^{/\!/}\cos2\varphi + AH_M^{/\!/}\sin^2\varphi(3\cos^2\varphi - \sin^2\varphi)] \tag{5}$$

The corresponding equilibrium equation is

$$H\sin(\varphi - \varphi_H) + H_M^{/\!/}\sin\varphi\cos\varphi +$$

$$AH_M^{/\!/}\sin^3\varphi\cos\varphi = 0 \quad (6)$$

When the steady magnetic field is in xz plane, the theoretical expression for resonance frequency in terms of the out of plane steady magnetic field takes the following form:

$$\left(\frac{\omega^2}{\gamma}\right) = [H(\sin\theta\cos\theta_H + \sin\theta\sin\theta_H) - H_M^{\perp}\cos 2\theta] \times [H(\cos\theta\cos\theta_H - \sin\theta\sin\theta_H) - H_M^{\perp}\cos^2\theta + H_M^{/\!/}] \quad (7)$$

The corresponding equilibrium equation is

$$H(\sin\theta\cos\theta_H - \cos\theta\sin\theta_H) - H_M^{\perp}\sin\theta\cos\theta = 0 \quad (8)$$

In above equations, $H_M^{\perp} = (N_z - N_x)M - \frac{2K_u}{M}$ and $H_M^{\perp} = (N_y - N_x)M$.

Solving simultaneously Eqs. (5) and (6), Eqs. (7) and (8), respectively, we can obtain the theoretical curve of the resonance field as a function of field orientation θ_H in the xz plane and field orientation φ_H in the film plane for the patterned rectangular elements. Meanwhile, we can obtain the important parameters such as magnetization, gyromagnetic ratio, Lande splitting factor g, anisotropy field etc.

3 Result and Discussion

Numerical simulation is performed with the software Mathematica[9,10]. The parameters determined by fitting the theoretical expression with the experimental data are given in Tab.1. Fig.3 shows the experimental data of the resonance field as a function of field orientation θ_H in the xz plane, as well as the theoretical curves given by Eqs. (5) and (6). Fig.4 shows the experimental data of the resonance field as a function of field orientation φ_H in the film plane, as well as the theoretical curves of Eqs. (7) and (8). Dots stands for experimental data and the solid line stand for theoretical curve. The experimental data agree fairly well with the theoretical curves.

Tab.1 Magnetic parameter obtained by numerical simulation

Aspect ratio	A	γ	g	$H_M^{\perp}/(\mathrm{A \cdot m^{-1}})$	$H_M^{/\!/}/(\mathrm{A \cdot m^{-1}})$
5	−0.2	1.865×10^7	2.122	9.83×10^6	1.78×10^5

From Fig.4 and Tab.1, we can see that the rectangular elements cause a uniaxial anisotropy. Hard axial is along the short side and the easy axial is along the long side of the rectangular elements. The anisotropy of resonance field, the amplitude of the oscillation in the angular dependence of resonance field in the film plane is 24.3 A/m. The shape anisotropy field $H_M^{/\!/}$ obtained by numerical simulation is 178 kA/m as presented in Tab.1. While in the continuous film,

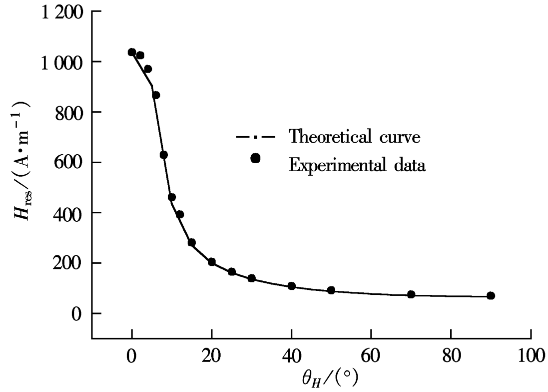

Fig.3 The experimental data and theoretical curve of the resonance field as a function of field orientation θ_H in the xz plane

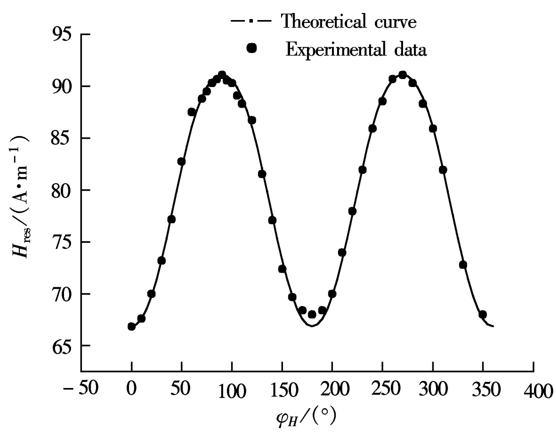

Fig.4 Experimental data and theoretical curve of the resonance field as a function of field orientation φ_H in the film plane

there is no shape anisotropy in the film plane.

The value of g factor and effective magnetization $H_M^{\perp} = (N_z - N_x)M - \frac{2K_u}{M}$ (see Tab.1) differ little from those obtained from the continuous film with the same material and thickness, which shows that factor g and magnetization change little when the continuous thin film is fabricated to patterned thin film.

When the steady magnetic field is applied near the film normal, a series of peaks (up to eight) appears on the low field side of the main peak as shown in Fig.5. The intensity of the above curve is as ten times as the below. The resonance field of the side peaks decreases linearly with the peak number. The separation of these peaks was about 23.9 A/m. The experimental observation of the multiple peaks in small elements by FMR has not been seen in the literatures. For continuous film of the same material multiple peaks of spin waves were observed only when the thickness was much thicker than ours, about 100 nm up to 300 nm and according to the early theories the separation of peaks is inversely proportional to the square of the film

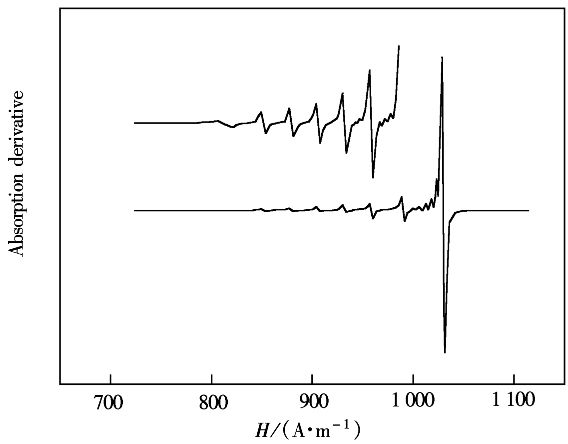

Fig.5 FMR spectra of external magnetic applied along the film normal

thickness or directly proportional to it, which cannot explain our results. Our data is similar to the recent observation of spin wave excitation by Brillouin light scattering[11], in which, however, the static field was in the film plane while in this paper the field was along the film normal. We speculate that our spin-wave-like spectra are related to the non-uniform demagnetizing effect and non-uniform magnetization in the small rectangular patterned element. The further study on the mechanism of our multiple peak spectra and its relation with the non-uniform magnetization is being undertaken.

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电子束光刻亚微米矩形阵列的坡莫合金薄膜铁磁共振谱的研究

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摘　要　报告了对电子束刻蚀的亚微米矩形阵列坡莫合金 NiFe 薄膜系统的铁磁共振(FMR)研究及对矩形阵列不均匀退磁场和铁磁共振谱进行的理论拟合．计算出样品的有效磁化强度 M，回旋磁比 γ 以及兰德因子 g 等参数，并且得出了共振场与所加磁场方位关系的理论曲线．结果与实验曲线一致．研究证明矩形单元导致了单轴平面磁各向异性．本文还发现了在外磁场加在垂直于膜面的方向时，在主共振峰的低场侧出现了一系列规则的卫星峰，并对这一系列的子峰出现可能的机制进行了探讨．

关键词　铁磁共振，坡莫合金薄膜，亚微米阵列

中图分类号　O482.54