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Magnetization Processes in Single Domain Permalloy Thin Films

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The micromagnetic simulation is used to investigate the reversible and irreversible magnetization processes of the single-domain elliptical permalloy thin films. The reversible magnetization curve, which has no hysteresis, obtained by magnetizing the single-domain elliptical permalloy thin film along the hard axis is almost linear as the magnetization curve of the single-domain ellipsoidal particle. For irreversible processes, which have hysteresis, the switching field of the ellliptical thin film is reduced compared with that predicted by the Stoner-Wohlfarth model due to the occurrence of non-uniform reversal.

Key words: Stoner-Wohlfarth model, Micromagnetic simulation, Magnetization reversal

1. INTRODUCTION

Various spintronic devices [1] such as magnetic random access memory (MRAM) use single-domain magnetic thin films as unit cells. A bit can be written by magnetic fields generated from electric currents passing through two perpendicular electrodes above and below each cell. It is therefore important to understand the magnetization properties in thin film elements in order to obtain the uniform performance and repeatability during accessing the unit cell. In this article we investigate the magnetization curves of the reversible processes by magnetizing the elements along the hard axis direction, and the hysteresis loops of the irreversible processes by remagnetizing the elements along the easy axis direction. Hysteresis loops corresponding to various field directions are also studied.

2. SIMULATION DETAILS

The 3-D micromagnetic simulations of submicron-sized elliptical thin films are made by the time integration of the Landau-Lifshitz-Gilbert (LLG) equation [2]. In our simulation, we take into account the terms of magnetostatic interactions, exchange interactions, anisotropy field, and Zeeman field. The typical parameters of the soft type permalloy film are as follows: exchange constant $C = 2A = 2\times10^{-6}$ erg/cm, and saturation magnetization $M_s = 800$ emu/cm^3. The uniaxial anisotropy constant [3] K_1 is assumed to be 10^3 erg/cm^3, which is actually too small to make any considerable influence on the total energy. The element is discretized into many small cubic cells to approximate the elliptical thin films. The size of the meshed cell is set to be lower than 7.5 nm, which is smaller than the exchange length of the permalloy material [4], $R_0 = C^{1/2}/M_s = 17.7$ nm, to promise the precision of our simulation. For the largest structures, a variable mesh size method is used to calculate the magnetostatic contribution to the total effective magnetic field at the cell centers. We set the damping constant α to be 1 to assure rapid convergence. When the largest magnetization angular variation between successive iterations is below 10^{-8}, the system is assumed to reach the equilibrium state in our calculation.

Our subdivision procedure produces some spurious oscillations of the surface magnetic charge on the lateral side of the elements around the averaged value corresponding to an ideally smooth surface. Nevertheless, for a numerical cell of small enough size, the corresponding oscillations of the demagnetizing field near the lateral surface are weak and cannot disturb a stable magnetization configuration to any great degree. Besides, deviations of the order of several nanometers from a smooth lateral surface are expected in the experiment.[5]

3. RESULTS AND DISSCUSSIONS

In order to understand the behaviors of the single-domain elliptical thin film under external magnetic field it is helpful to compare the magnetization processes of the ellipse and its corresponding Stoner – Wohlfarth [6] ellipsoid. The demagnetization factors of the corresponding ellipsoid, which has the same volume as the elliptical thin film, can be determined from the Brown-Morrish theorem [7]. The magnetization curves of the single-domain ellipsoidal particles are linear [7] when an external field is applied along the hard axis as shown in Fig. 1. For single-domain elliptical elements with different sizes the magnetization curves are close to the corresponding ones of the ellipsoidal particles, but the magnetization rotation towards the external field direction is not a rotation in unison because the demagnetization field inside is not uniform. In contrast to the Stoner – Wohlfarth ellipsoid, which saturates under a critical field, the elliptical elements do not saturate under a finite field but the magnetization only rotates

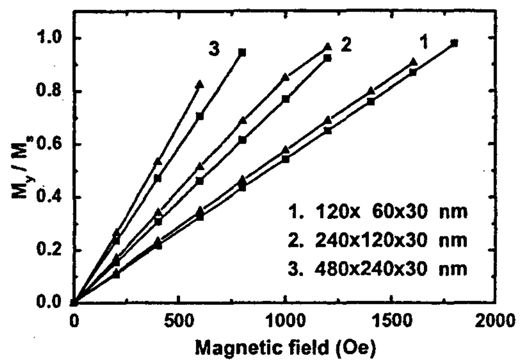

Fig. 1. Magnetization curves of the single-domain elliptical (▲) thin films and the corresponding Stoner-Wohlfarth ellipsoidal (■) particles, which respectively have the same volumes as the three elliptical thin films, when a field is applied along the hard axis. Three sets of curves correspond to three different particles with dimensions indicated by long-axis × short-axis × thickness.

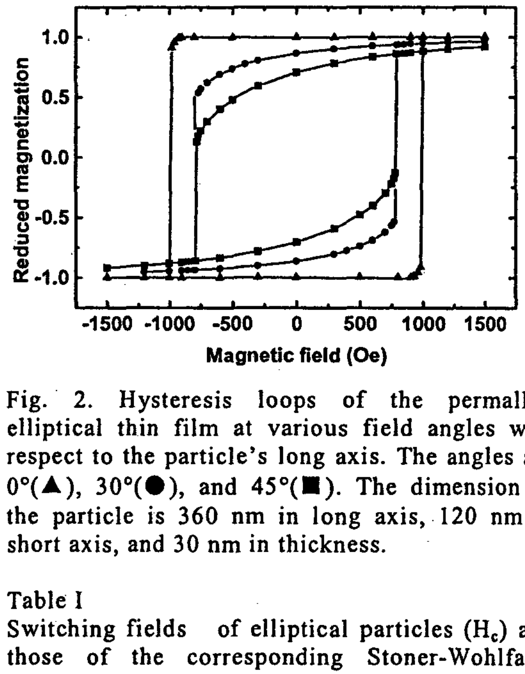

Fig. 2. Hysteresis loops of the permalloy elliptical thin film at various field angles with respect to the particle's long axis. The angles are 0°(▲), 30°(●), and 45°(■). The dimension of the particle is 360 nm in long axis, 120 nm in short axis, and 30 nm in thickness.

Table I
Switching fields of elliptical particles (H_c) and those of the corresponding Stoner-Wohlfarth ellipsoids ($H_{c,SW}$) with different sizes and aspect ratios.

Size (nm)	Field angle	$H_{c,SW}$ (Oe)	H_c (Oe)
360×120×30	0°	1787.20	1000
	30°	937.85	790
	45°	894.87	790
720×240×30	0°	1149.00	520
	30°	603.46	440
	45°	575.80	440
240×120×30	0°	1300.00	750
	30°	682.53	495
	45°	651.25	470

gradually as the field increases. This magnetization process is reversible and hence the hysteresis is zero.

For the irreversible cases, we simulate the hysteresis loops of elliptical elements with different sizes and different field angles with respect to the element's long axis as shown in Fig. 2. The hysteresis loop of elliptical elements is approximately rectangular when an external field is along the particle's long axis, but the corner is rounded compared with the Stoner – Wohlfarth ellipsoidal particle because the magnetization becomes nonuniform before switching. Besides, the switching field reduces significantly compared to the Stoner-Wohlfarth ellipsoidal particle due to the nonuniform remagnetization process. This process initiates with several vortices nucleated at the boundary, followed by the penetrating of these vortices across the element, and then completes by the annihilation of the vortices. When the external fields are applied in different directions, the hysteresis loops show similar behaviors as the Stoner-Wohlfarth ellipsoidal particle and the switching fields are also reduced.

Table I shows the simulation results of the switching fields of elliptical elements with different sizes and the corresponding analytical results of the Stoner-Wohlfarth model. For the Stoner-Wohlfarth model the switching fields are reduced when the fields are not along the easy axis. It is the same for the elliptical elements. For the two elliptical elements with aspect ratio 3:1, the switching fields are almost the same for 30 and 45 degrees field directions because before reversal the total magnetic moment deviates from the easy axis towards the field direction, and the magnetization at the two ends of the long axis is bended by the boundary. Vortices are easily nucleated in the regions where the magnetization curvature is large enough. However, for the elliptical elements with aspect ratio 2:1, the curvature at the two ends is smaller so vortices are not easily nucleated as the above case, and therefore the field direction has more apparent influence on the switching fields.

In summary, we use micromagnetic simulation to investigate the reversible and irreversible magnetization processes of the single-domain elliptical permalloy thin films. For the reversible processes without hysteresis, the magnetization curve is almost linear as the magnetization curve of the single-domain ellipsoidal particle. For irreversible processes with hysteresis, the switching field of the ellliptical thin film is reduced compared with that predicted by the Stoner-Wohlfarth model due to the occurrence of non-uniform reversal.

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