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Micromagnetic simulation of magnetic hysteresis in hard/soft bilayered exchange spring magnets

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Abstract. We investigated the magnetization switching process in a bilayered exchange spring system through micromagnetic simulations. A typical exchange coupled magnetic hysteresis loop was observed in this work. The influence of magnetocrystalline anisotropy constant on the magnetization of the exchange spring structure was also studied. It is demonstrated that the film thickness of hard layer play a more important role than that of soft layer to the influence on coercive field and shape of the hysteresis loop.

Introduction

Recently, exchange-coupled multilayered magnetic system has attracted strong interest due to its numerous applications in the magnetic recording industry . They can be used as permanent magnets with giant magnetic energy production[1,2] or as giant magnetostrictive materials at low saturation field[3,4]. During the magnetization reversal process, the magnetic moments in soft phase rotate reversibly but the magnetic moments in hard phase do not rotate until the whole structure reversed, and the direction of the magnetization in soft phase depends on the distance from the magnetization to the hard/soft interface. This phenomenon is called the exchange-spring phenomenon[5].

In hard/soft exchange spring systems, the hard layers are mainly composed by ferromagnetic materials with high coercive field, such as SmFe, SmCo, FePt, and CoPt; and the soft layers are mainly composed by ferromagnetic materials such as Fe, NiFe, Co, and FeTaN. Most frequently studied hard/soft system includes SmCo/Fe[6,7], FePt/Fe[8], SmCo/NdCo[9], CoPt/Co[10,11], and SmFe/NiFe[12,13] system, etc. In order to decrease the device size of exchange coupled system, understanding the influence of anisotropy constant, layer thicknesses and interlayer coupling effect on the exchange coupling behavior is very important. In this paper, we employed the micromagnetic simulation to study the exchange spring effect and the hysteresis loop of the hard/soft bilayered system. We also discussed the influence of the anisotropy constant and the layer thickness on the nucleation field, coercivity and internal magnetization structure. Micromagnetic approach has been considered earlier for related problem[14], however, the influence of film thickness and anisotropy constant on magnetization process has not been discussed.

Fig. 1 shows a schemetic of exchanged coupled bilayered thin film structure in our simulation: For the soft layer, the anisotropy constant $K_1=5\times10^2$ J/m^3 , for the hard layer, anisotropy constant $K_2=10^5$ J/m^3, the easy anisotropy axes are parallel to each other and the external field H is applied along this axis. Film thicknesses are assumed as 89nm for each layer. For simplicity, we assume that the saturation magnetization and the exchange coupling constant of both the soft layer and hard layer are the same, i.e. $Ms_1=Ms_2=10^6$A/m, $A_1=A_2=10^{-11}$J/m.

Micromagnetic Simulations

The total free energy of the bilayered exchange spring system is given by

$$E = E_{ani} + E_{ms} + E_{exch} + E_{external} \tag{1}$$

where E_{ani}, E_{ms}, E_{exch} and $E_{external}$ are magnetocrystalline anisotropy energy, magnetostatic energy, exchange energy, external field energy and interface energy, respectively. The detailed expressions of the total free energy is

$$E = \frac{A}{M_{sj}^{2}} \int \left[grad\vec{M}(r) \right]^2 d^3 r + \int \left(\frac{K_j}{M_{sj}^{2}} \left\{ \left(\vec{M} \cdot \hat{u} \right)^2 \right\} \right) d^3 r - \int \vec{H}_{ext} \cdot \vec{M} d^3 r \tag{2}$$

where $\hat{u}$ is a unit vector along the anisotropy axis and $\vec{M}$ is the magnetization of the bilayer of magnitude M_{sj}. The interface coupling A_I is assumed to be equal to the exchange coefficient A.

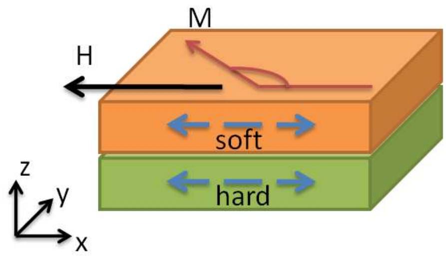

Fig. 1 Schematic of the soft/hard exchange spring nanostructure

The three-dimensional micromagnetic simulation is carried out by solving the Landau- Lifshitz-Gilbert (LLG) equations numerically:

$$\left(1+\alpha^2\right)\frac{\partial \overrightarrow{M}(r)}{\partial t} = -\gamma_0 \overrightarrow{M}(r) \times H_{eff} - \frac{\gamma_0 \alpha}{M_s} \overrightarrow{M}(r) \times \left(\overrightarrow{M}(r) \times H_{eff} \right) \tag{3}$$

where α is the damping constant, γ_0 is the gyromagnetic ratio, M_s is the saturation magnetization, and H_{eff} is the effective magnetic field

$$H_{eff} = -\frac{1}{\mu_0} \frac{\partial E}{\partial \overrightarrow{M}(r)} \tag{4}$$

where μ_0 is the permeability of vacuum, E is the total free energy in magnets.

Simulation Results and Disscussions

Fig. 2 shows the hysteresis loop for the exchange spring heterostructure, with the external applied field was applied along the x direction. It is clearly demonstrate an interesting constricted hysteresis loop. We firstly increase the magnetic field to saturation and then decrease it and finally reverse its direction to saturate magnetization in the opposite direction. When the external field was decreased to 10^4 A/m, we observed the magnetization rotation in soft layer. Further decrease the magnetic field, the magnetization sharply decreased. However, the magnetization in the hard layer didn't rotate, and lead to a high coercive field of 7×10^4 A/m. When a high external field of 8×10^4 A/m was applied along the opposite direction, the whole structure is switched to the –x direction, and the magnetization reaches full saturation.

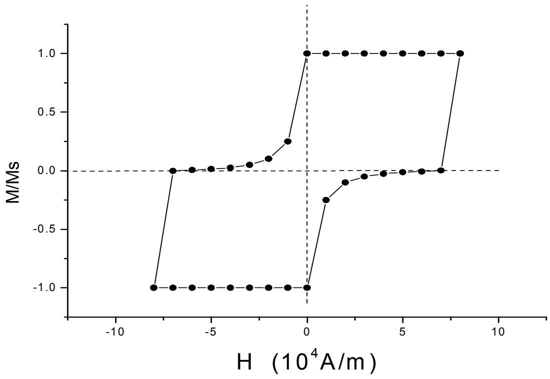

Fig. 2 Hysteresis loop calculated for the bilayer

Simulation results indicated that the magnetic magnetization in the soft/hard exchange spring structure rotates in the x-y plane during the switching process. To study the internal magnetic structure of the exchange spring bilayer structure, we plotted the angle between the direction of the average magnetization and the applied field in Fig. 3. Sublayers 1-10 are the soft layers, and sublayers 11-20 are the hard layers. The rotation angles varies in the range from 0 degree to180 degree. The seven curves represents different external field changing from 10^4A/m to 7×10^4 A/m along the –x direction. It can be seen that the rotation angle at the surface of soft layer is the smallest, which suggest that the magnetization is switched to the direction of applied field. For the layers near the soft/hard interface, the rotation angle become larger in order to decrease the magnetostatic energy. The magnetization in the hard layer didn't switched and the rotation angle is almost 180 degree, this is because the high magnetocrystalline anisotropy of hard magnetic material. When the external field is small, the whole structure demonstrate a 180 degree Bloch wall. With the applied field increases, the thickness of the bloch wall reduced, and the angle differences between the average magnetization in the soft and hard layer enhanced.

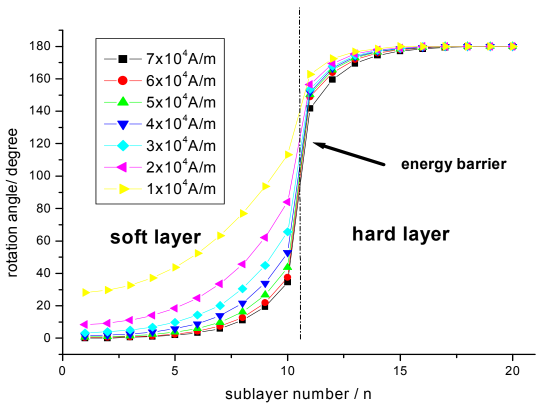

Fig. 3 Magnetic structures of the bilayer

In order to consider the effect of the magnetocrystalline anisotropy of soft magnetic material, we used different the anisotropy constant of soft layer, e.g. 10^2 J/m^3 and 10^3 J/m^3. Tab.1 shows the simulated results from our micromagnetic model with a soft layer K_1 of 10^2 J/m^3 , 5×10^2 J/m^3 and 10^3 J/m^3. The saturation magnetizations have minor differences at high external field, however, with a decrease in the external field, larger anisotropy constant lead to smaller saturation magnetization. It is implies that the change of anisotropy constant of soft layer has small influence at a high magnetic field during the switching process.

Table 1 Average magnetization of the bilayer structure with different value of K_1

K_1[J/m^3] \ **H**[A/m]	1×10^4	2×10^4	3×10^4	4×10^4	5×10^4	6×10^4	7×10^4
10^2	0.258	0.103	0.052	0.027	0.014	0.006	-0.002
5×10^2	0.250	0.100	0.050	0.027	0.014	0.006	-0.002
10^3	0.240	0.097	0.050	0.026	0.013	0.005	-0.002

We also changed the anisotropy constant of hard layer to see the influences of hard magnetic materials. Tab. 2 shows the average magnetization of the exchange spring sturcuture during the switching process with a anisotropy constant of hard mangetic material of 10^5 J/m^3 , 5×10^4 J/m^3 and 5×10^5 J/m^3 respectively. For the case of K_2=5×10^4 J/m^3, we see average magnetization of the exchange spring system quickly decrease to saturation. Its magnetic moments rotated entirely to the direction of the applied field with a coercive field of 3×10^4A/m. This is because the hard layer have the smallest anisotropy constant. For the case of K_2=10^5 J/m^3 and K_2=5×10^5 J/m^3, there is minor differences between their switching process and average magnetization. Based on the simulation results above, it is shown that the change of anisotropy constant of the soft layer has small influence on the magnetic structures and average magnetization of bilayered exchange spring magnets.

Table 2 Average magnetization of the bilayer structure with different value of K_2

K_2 [J/m^3] \ **H** [A/m]	1×10^4	2×10^4	3×10^4	4×10^4	5×10^4	6×10^4	7×10^4
5×10^4	0.204	0.060	-1	-1	-1	-1	-1
10^5	0.245	0.100	0.050	0.027	0.014	0.006	-0.002
5×10^5	0.316	0.138	0.064	0.014	0	0	0

We vary the thickness of the soft layer from 89nm to 44.5nm and 17.8nm. The calculated hysteresis loops are shown in Fig. 4.The curves a, b, c represents the hysteresis loop with the soft layer thickness of 89nm, 44.5nm, and 17.8nm, respectively. It is clearly shows that the maximum energy product climbs up with the decrease of the soft layer thickness. We also noticed that the moments of soft layer in exchange spring starts to rotate at a external field of 10^4A/m, 2×10^4A/m, 4×10^4A/m for curve a, b, c, respectively. However, the magnetization for the three cases reaches full saturation at the same external field of 8×10^4A/m. The nucleation field of new domains in the exchange spring structure increased, but there is no significant change in the coercive field.

We also vary the thickness of the hard layer from 89nm to 44.5nm 17.8nm. The calculated hysteresis loops for a hard layer thickness of 89nm, 44.5nm, and 17.8nm are presents in Fig. 5 as curve a, b, c, respectively. We see a decrease in the maximum energy product for exchange spring structure when the hard layer thickness reduced. Meanwhile, we noticed that a thin hard layer lead to a smaller coercive field of the bilayered structure. Especially, the magnetization for curve c reaches saturation at a small field of 5×10^4A/m. The nucleation field of new domains in the exchange spring bilayers remains the same. These simulation results are in excellent agreement with experimental reports of NiFe/SmFe system[12].

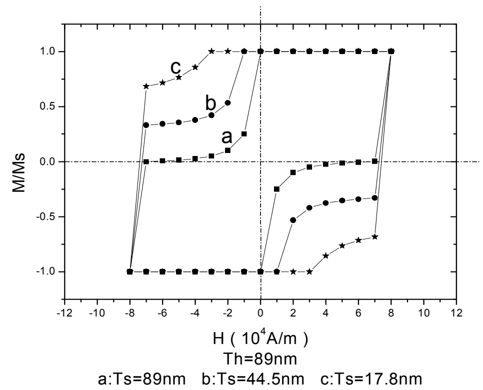

Fig. 4 Hysteresis loops of the bilayers with different thickness of soft layer

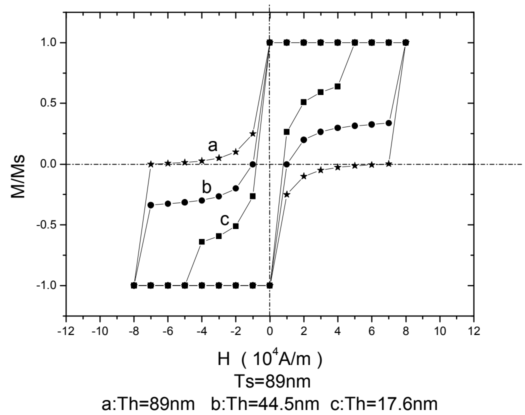

Fig. 5 Hysteresis loops of the bilayers with different thickness of hard layer

To understand the effect of the total thickness of the exchange spring system on the hysteresis loop, let us examine the hystereis loops of with a total bilayer thickness of 90nm and 35nm. The soft/hard ratio of exchange spring system is maintained as 1:1. Fig. 6 shows the calculated hysteresis loops. With the decrease of the total thickness, we see the nucleation field increases, which implies that the magnetic moments in the thinner layers are more difficult to rotate. It is interesting to see that the bilayer of 90nm thick (curve b in Fig.6) has the maximum mangetic energy product. The coercive field of curve a and b are 8×10^4A/m, but for curve c, the coercive field is only 5×10^4A/m. The rectangle shaped hyesteresis loop c is similar to the loops of hard magnetic materials. It seems that the exchange coupling effect was weakened when the film thickness is very small.

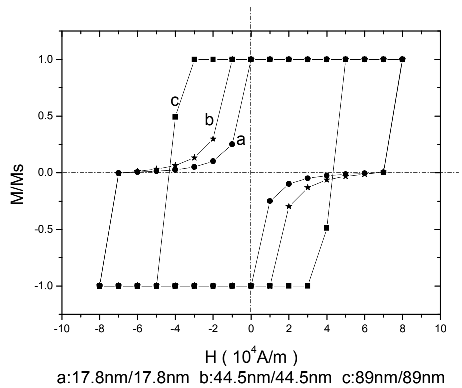

Fig. 6 Hysteresis loops of the bilayers with different thickness of soft and hard layer while keeping the ratio of their thicknesses 1:1

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Conclusions

Hystereis loops for soft/hard bilayerred exchange spring structures are examined by micromagnetic simulations. A typical hystereis loop is obtained in our simulation and it is in good agreements with previous experimental observations. It is shown that the anisotropy constant in soft layer has a strong influence on the magnetic properties at a small applied field. However, for a large applied field, the magnetic properties are mainly influenced by anisotropy constant of hard layers. Varying the thickness of soft layer while keeping the thickness of hard layer as a constant, the nucleation field increases with the decrease the soft layer thickness. Varying the thickness of hard layer while keeping the thickness of soft layer as a constant, the coercive field reduced with the decrease in the thickness of hard layer. Finally, it is shown that the exchange coupling between the soft layer and hard layer is weakened for a very thin bilayered thin film.

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