Micromagnetic simulation with three models of FeCo/L1$_0$ FePt exchange-coupled particles for bit-patterned media*

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Compositing soft and hard materials is a promising method to decrease the coercivity of L1$_0$ FePt, which is considered to be a suitable material for bit-patterned media. This paper reports the simulation of three models of FeCo/L1$_0$ FePt exchange-coupled composite particles for bit patterned media by the OOMMF micromagnetic simulation software: the enclosed model, the side-enclosed model, and the top-covered model. All of them have the same volumes of the soft and hard parts but different shapes. Simulation results show that the switching fields for the three models can be reduced to about 10 kOe (1 Oe = 79.5775 A/m) and the factor gain can be improved to 1.4 when the interface exchange coefficient has a proper value. Compared to the other models, the enclosed model has a wider range of interface exchange coefficient values, in which a low switching field and high gain can be obtained. The dependence of the switching fields on the angle of the applied field shows that none of the three models are easily affected by the stray field of a magnetic head.

Keywords: exchange-coupled composite, bit patterned, micromagnetic

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1. Introduction

As the main information storage medium, hard disks with higher recording density and smaller bit size have attracted much attention. Bit-patterned media[1,2] are expected to be the next generation of recording media since their recording bits are separated and have very little magnetic interaction. The two big challenges here are to develop a practical preparation technology and to choose a suitable recording material. Research into candidate recording materials focuses on improving their magnetic anisotropy, which leads to greater thermal stability of the media and a reduction in coercivity, which ensures writability. L1$_0$ FePt with an ordered crystal structure possesses a very high uniaxial magnetocrystalline anisotropy of 6×10^7 erg/cc (1 erg = 10^{-7} J),[3,4] and thus it is widely investigated as a recording medium. However, its high coercivity (about 110 kOe, 1 Oe = 79.5775 A/m) becomes an obstacle in applications, since it is beyond the highest writing field that magnetic heads can supply (about 20 kOe).[5,6] To decrease the coercivity of hard magnetic materials, alternative compositions, combining them with soft materials, are an option. The exchange coupled composite (ECC) method is a suitable choice since it can decrease coercivity while maintaining thermal stability.[7–12] Fabricating the soft/hard composite structure is simple for layers, but a little complex for particles. In the present work, three models of FeCo/L1$_0$ FePt ECC particles were built and simulated by the micromagnetic simulation software OOMMF. Their switching fields and other properties were simulated and compared in order to find a better model that can be realized experimentally.

2. Simulations

FeCo alloy was chosen as the soft material for the composites, since it possesses the highest M_s (1900 emu/cc). In simulation its magnetocrystalline anisotropy was neglected. The parameters of L1$_0$ FePt were set to $M_s = 1140$ emu/cc, $K_u = 6\times10^7$ erg/cc. The size of the hard part is x: 8 nm, y: 8 nm, z: 6 nm, and its easy axis is parallel to the z axis. We conceived an interesting set of three models of soft/hard composition (see Fig. 1): enclosed[13] (the hard part is enclosed on the four vertical sides and the top by a 2-nm-thick soft part); side-enclosed (the hard part is surrounded by a 3-nm-thick soft part on the four vertical sides but not the top); and top-covered (the hard part is covered only on the top by a 12-nm-thick soft part). The soft/hard volume ratios of these three models are all about 2:1 (2.06:1 for the side-enclosed type), and thus comparisons among them are easy. The size of the finite element mesh is set to 1 nm. The intralayer exchange coefficient is set to 1×10^{-6} erg/cm,[14] whereas the interface exchange coefficient (σ) has a range from 50 erg/cm^2 to 1 erg/cm^2. The interface exchange energy density of cell i on one surface from matching cell j on the other is

$$E_{ij} = \frac{\sigma(1-\boldsymbol{m}_i\cdot\boldsymbol{m}_j)}{\Delta_{ij}}, \tag{1}$$

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where σ is the bilinear surface exchange coefficient, $\boldsymbol{m}_i$ and $\boldsymbol{m}_j$ are the normalized unit spins (i.e., magnetization directions) at cells i and j, and Δ_{ij} is the discretization cell size in the direction from cell i toward cell j. The gyromagnetic motion of magnetization is governed by the Landau–Lifshitz–Gilbert equation. The total energy includes the exchange energy, the magnetocrystalline anisotropy energy, the magnetostatic energy, and the Zeeman energy.

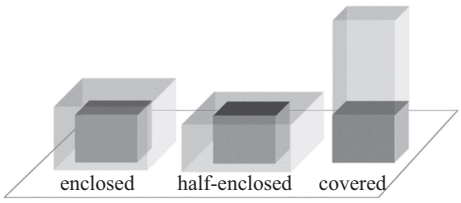


Fig. 1. The three models of the ECC particles. The dark parts represent the hard material, and the bright parts are the soft material.

3. Results and discussion

First, the descending branch of the hysteresis loop (from 0 to –100 kOe) was simulated with a step of 50 Oe. The magnetic field was applied with an angle of 3° to the easy axis in order to avoid numerical instability. Figure 2 shows the results for all three models with various σ. It can be observed that the magnetic reversals of the soft and hard parts are significantly separated when σ is small (1 erg/cm^2). In this situation, the switching fields of the hard parts have relatively high values of more than 7 T for all three models. When σ increases to 10 erg/cm^2, the reversal processes for the three models differ. For the enclosed model and side-enclosed model, the magnetic moments of the soft parts decline first, and then reverse with the hard part due to the strong exchange coupling. In this case, the hard part is affected by Zeeman energy and strong exchange energy simultaneously. Hence the switching field is low. However, for the top-covered model, the magnetic reversal of the hard part is later than the reversal of the soft part. Although the exchange energy density is high at the interface, the total exchange coupling energy is low because the interface area is small. Thus, the switching field of the top-covered model is higher than that of the other two models. Furthermore, when σ increases to 50 erg/cm^2, the magnetic moments of the soft part decline relatively weakly for the three models. Meanwhile, the switching field does not change for the enclosed model but decreases a little for the other two models.

The switching fields with various σ for the three models are shown in Fig. 3. For the enclosed model, the switching field decreases sharply when σ increases from 1 erg/cm^2 to 5 erg/cm^2, and then reaches its lowest value of 11 kOe at 8 erg/cm^2 and maintains it until 20 erg/cm^2. When σ increases to 30 erg/cm^2∼50 erg/cm^2, the switching field increases slightly to 11.5 kOe. This trend in the switching field is typical for ECC particles, which always possess an optimal interface exchange coupling strength that leads to the lowest switching field. However, the switching fields of the other two models decrease monotonously with increasing σ. This phenomenon may be due to the fact that the value of σ in our simulation is not high enough to reach the stage where the switching field increases. The smallest switching field, 9.5 kOe, appears in the side-enclosed model with a σ range from 30 erg/cm^2 to 50 erg/cm^2. It was also found that the switching field has a small value (about 11 kOe) in a large range of σ for the enclosed model. Conversely, for the top-covered model, low switching fields can be obtained in a smaller range. While the side-enclosed model has a low switching field range of σ, lying between those of the enclosed model and the top-covered model.

Gain ξ is a factor that signifies the benefit of thermal stability obtained from an ECC particle compared with a single hard magnetic particle under the same switching field,

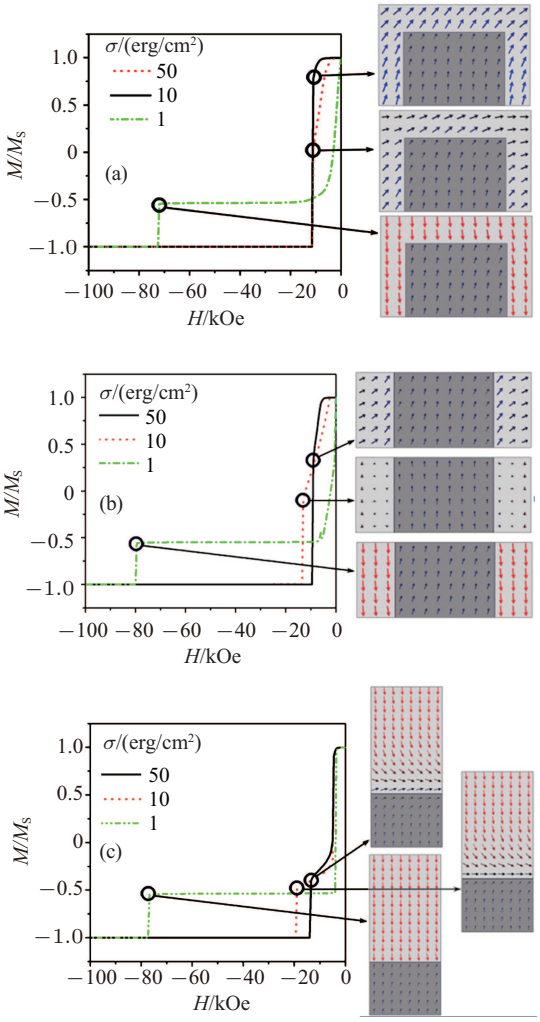


Fig. 2. (color online) Descending branches of hysteresis loops with various σ for three models: (a) the enclosed model, (b) the side-enclosed model, and (c) the top-covered model. The small graphs are the states of the magnetic moments of the cross sections just before reversal.

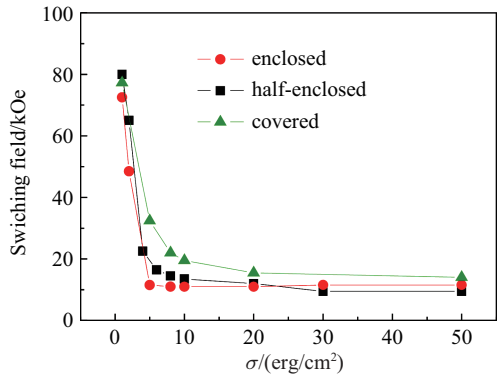


Fig. 3. (color online) The switching fields for the three models with various interface exchange coefficients.

magnetic moment and volume.[5] It is defined as

$$\xi = \frac{2\Delta E}{H_{\mathrm{SW}} M_{\mathrm{S}} V}, \tag{2}$$

where ΔE is the uniaxial anisotropic energy (including demagnetic energy), which is also the energy barrier for the thermal reversal of the magnetic moment. M_{s} and V are the average M_{s} and total volume of a particle, respectively. The gain is 1 for a perpendicular magnetic recording particle and 2 for a 45° declined recording particle, which is the highest value that ECC media can reach in ideal conditions. Figure 4 shows the change in gain with σ. For the enclosed model, the gain maintains high values (about 1.4) in a wide range of σ from 5 erg/cm^2 to 50 erg/cm^2. However, for other models the gain increases gradually with σ and reaches high values in a relatively narrow range. The highest gain value, 1.47, was obtained in the top-covered model with a σ of 50 erg/cm^2.

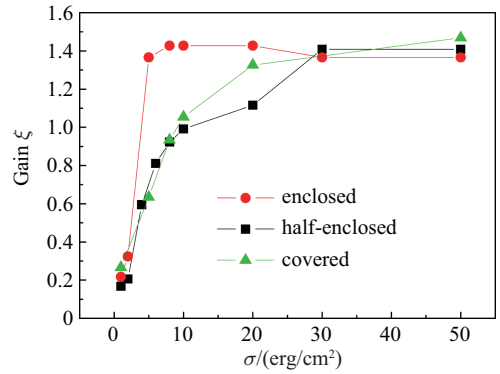


Fig. 4. (color online) The gain values for the three models with various interlayer exchange coefficients.

The stray field of the magnetic head is an important factor that can induce recording noise. The reason for this is that for perpendicular recording media, the particles near the ones that are being written are easily reversed by a stray field, since the switching field is lowered when the magnetic field is not applied perpendicularly but at a declined angle. In order to investigate the affect of such a stray field, the dependence of the switching field on the magnetic field angle was simulated for all three models. The σ that leads to the lowest switching field in each model was chosen for simulation. Figure 5 shows that the switching field for the enclosed model decreases slightly at the beginning and then increases with the increasing angle of the applied field. Unlike that, the switching fields of other models increase directly with the field angle. The dependence of the switching field on the field angle of these three models are very different from the Stoner–Wohlfarth model, in which the switching field under a 45°-applied field is only half of the one under a 0°-applied field. This is because the magnetic reversal process of an ECC particle is not a coherent reversal but is similar to the domain wall motion since the magnetic moments of the soft part always decline earlier than those of the hard part. These results indicate that all three models will have good signal to noise ratios.

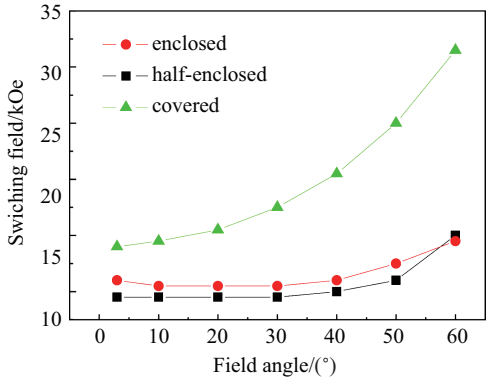


Fig. 5. (color online) The effect of the field angle on the switching field for the three models. 0° means that the field is applied parallel to the easy axis. Enclosed model: $\sigma = 20$ erg/cm^2, side-enclosed model: $\sigma = 30$ erg/cm^2, top-covered model: $\sigma = 50$ erg/cm^2.

4. Conclusions

Three soft/hard composite ECC particles were modeled to study the prospect of decreasing the switching field of $L1_0$ FePt particles. According to micromagnetic simulation results, all three of the modeled particles can obtain a low switching field around 10 kOe with a moderate value of the σ between the soft and hard parts. Among the three, the enclosed particle has a relatively wide range of σ, within which a low switching field and a high gain factor can be reached. This result indicates that the preparation of real particles with good properties would be easier by imitating the enclosed model than with the other two configurations, considering the variation in exchange coupling strength in real applications. Meanwhile, all three models perform well with regard to the dependence of switching field on applied field angle. In summary, the enclosed ECC particle is a better choice in the design of bit-patterned media with ECC recording particles.

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