Grain geometry induced reversal behaviour alteration

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Abstract

According to the experimental investigations, it is reported that the magnetic switching field is varied by the stacking orders in the recording media composed of stacked structure. The lattice distortion due to the lattice mismatch between two layers has been suggested as an origin of the difference; however, it has not been clearly explained up to now. In this paper we studied the possibility of the contribution of the convex surfaces in recording media. The convex surfaces vary the ratio between local magnetic anisotropy and intergranular exchange coupling strength that influences the magnetic behaviours of the stacked granular structure. An analytic model including the local geometric inequivalency is presented. From the analytic equations, it is found that the uniaxial anisotropy of the concave bottom layer can be overcome more easily than other parts, with the assistance of the intergranular exchange. Consequently, the harder bottom layer can be reversed earlier than the softer top layer, under some appropriate conditions. The analytic results are proved by finite element micromagnetic simulations.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

A stacked granular magnetic structure, for example, the exchange coupled composite media \cite{1} and exchange spring media \cite{2}, are promising candidates for the next generation of perpendicular recording media. Since the suggestion of Victora \textit{et al} and Suess \textit{et al}, many theoretical and micromagnetics simulation reports are published. From the studies, they are supposed to have lower switching field in the materials which have higher crystalline anisotropy, while the thermal stability is maintained \cite{3-5}. In experimentally fabricated stacked structures, there are inconsistencies in oppositely stacked structures. In \cite{6, 7}, it is reported that the stacked layer has higher coercivities than a single hard layer, and in some cases the bottom layer is magnetically harder than the upper layer or its saturation magnetization is smaller than the upper layer. The authors of \cite{6} studied the behaviour as a viewpoint of the lattice distortion due to the contact of materials which have different lattice parameters. In this study, we focus on the influence of the convex and concave surfaces of the grains to explain the asymmetric magnetic switching behaviour. As we have discussed in the previous study, grain shape affects magnetic characteristics by influencing the intergranular exchange and magnetostatic interactions between the grains \cite{8}. In the cross-section TEM images, the Ru seed layer has convex top surfaces that induce the formation of a concave bottom surface and another convex top surface in magnetic recording layer \cite{9}. In this paper, the modified Stoner–Wohlfarth (SW) equations considering the grain shape are derived to expect reversal behaviour, by determining the site which has the least switching field in a grain. The analytic expectations are verified by comparison between finite element micromagnetics results with experimental results.

2. Analytic approach

Previously, it has been shown that the contribution of the intergranular exchange is explained by modifying the SW equation. Results of \cite{8} are summarized in the two equations,

\begin{equation}
    h_\parallel = -\cos^3 \theta - \frac{F_{\text{int,exch}}}{2aK_uV},
\end{equation}

\begin{equation}
    h_\perp = \sin^3 \theta,
\end{equation}

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where $F_{\text{int}}$ is the interfacial area between the exchange coupled grains, $A_{\text{int,exch}}$ is the intergranular exchange constant, $a$ is the lattice constant, $K_U$ is the uniaxial magnetocrystalline anisotropy, $V$ is the volume of a grain, $\theta$ is the angle between the applied field and easy axis and $h$ is the dimensionless reduced applied field, $h = (M_S/2K_U)H$. $M_S$ (A m$^{-1}$) is the saturation magnetization and $\mu_0H(T)$ is the applied field. The subscripts $\parallel$ and $\perp$ denote the parallel and perpendicular terms, respectively.

In equation (1), the intergranular exchange affects the switching field as a term of $A_{\text{int,exch}}/K_UV$, the ratio between the intergranular exchange strength and the anisotropy energy. In the atomic scale model this factor is equivalent all over the specimen; however, in real grains which are thicker than the exchange length, there is a local coherency of magnetization in a grain [10]. Hence, the contribution of the local geometric factor should be considered for the precise study of magnetization reversal. Figure 1 shows the geometry and introduces the magnetic properties that are used in the analytic model.

An analytic model including the local incoherent intergranular exchange is prepared as in figure 1. The required field for reversal of each site in a grain is derived individually. The edge length $l$ is the radius of each reversal site, assumed to be comparable to the exchange length $l_{\text{ex}}$. $V$ is the volume of a grain, $t$ is the thickness of elements. The magnetizations of the surrounding grains are assumed to be fixed along the z-axis. The local volumes of site 1, site 2 and site 3 are

$$V_1 = l^2 t \psi,$$

$$V_2 = \frac{l^2 t}{2} \pi,$$

$$V_3 = l^2 t (\pi - \varphi),$$

respectively, where the interfacial area $F_{\text{int}}$ is $lt$ for sites 1 and 3 and $2lt$ for site 2.

The implementation of equations (3)–(5) leads the parallel terms of switching fields for each site,

$$h_{\parallel,1} = -\cos^3 \theta - \frac{A_{\text{int,exch}}}{a l \psi K_U},$$

$$h_{\parallel,2} = -\cos^3 \theta - \frac{2A_{\text{int,exch}}}{a l \pi K_U},$$

$$h_{\parallel,3} = -\cos^3 \theta - \frac{A_{\text{int,exch}}}{a l (\pi - \varphi) K_U}.$$

Combining the switching fields to the perpendicular terms of switching field $H_e$ given as equation (2) and with geometric and magnetic parameters as follows: $A_{\text{int,exch}} = 2 \times 10^{-13}$ J m$^{-1}$, $K_U = 5.0 \times 10^5$ J m$^{-3}$, $l = 3 \text{ nm}$, $a = 0.1 \text{ nm}$ and $\varphi = 150^\circ$, the astroids are drawn in figure 2. From the definition of the wetting angle within the range of $90^\circ$ and $180^\circ$, the strength of the local exchange fields is given by

$$H_{e1} < H_{e2} < H_{e3},$$

which induces the relationships among the switching fields as shown in figure 2.

In figure 2, the external field applied by an angle $\theta_0$ is denoted by the solid arrow. The distance from the origin to the intersection of the external field and the astroid, $H_{SW} = \sqrt{H_{e1}^2 + H_{e2}^2}$, is the local switching field for the site. According to the field direction, there are two switching fields.

One is from the anti-parallel (AP) state to the parallel (P) state $H_{SW1}$:

$$H_{SW1,3} < H_{SW1,2} < H_{SW1,1} < H_{SW}$$
and the other is from the P state to the AP state $H_{sw2}$:

$$H_{SW} < H_{sw2,1} < H_{sw2,2} < H_{sw2,3},$$

(11)

where $H_{SW}$ denotes the SW switching field, and the subscripts 1, 2, 3 indicate the number of each reversal site, respectively. The reversal will be triggered at the site which has the least local switching field. Equations (10) and (11) tell us that the switching site of a convex grain is determined by the site where the local intergranular exchange is the strongest (site 3, in the case of the reversal from the AP state to the P state) or the weakest (site 4, in the case of reversal from the P state to the AP state).

Based on the conclusions, in the case of the stacked media, it is thought that the bottom layer will be reversed more easily than the top layer, even in some conditions that the bottom layer is harder. In order to check the possibility of hard bottom reversal, the switching fields for the top and bottom layers are derived as follows:

$$H_{l,1} = -\frac{2K_{U,t}}{M_{S,b}}\cos^3\theta - \frac{2A_{int,exch}}{M_{S,b}\alpha}l\psi,$$

(12)

$$H_{l,2} = -\frac{2K_{U,t}}{M_{S,b}}\cos^3\theta - \frac{4A_{int,exch}}{M_{S,b}\alpha}l\pi,$$

(13)

$$H_{l,3} = -\frac{2K_{U,b}}{M_{S,b}}\cos^3\theta - \frac{2A_{int,exch}}{M_{S,b}\alpha}(\pi - \psi),$$

(14)

and

$$H_{l,1} = H_{l,2} = \frac{2K_{U,t}}{M_{S,t}}\sin^3\theta,$$

(15)

$$H_{l,3} = \frac{2K_{U,b}}{M_{S,b}}\sin^3\theta.$$  

(16)

The subscripts t and b denote the material parameters of different materials; the top material is t and the bottom one is b. The switching field of site 2 in the hard bottom layer is not considered, because it is definitely larger than that in the soft top layer. Since the bottom material is harder magnet, $K_{U,t}$ is smaller than $K_{U,b}$. The reduced field is derived by using the anisotropy field of the harder magnet $2K_{U,b}/M_{S,b}$, the external field $H$ can be substituted by the reduced applied field

$$h = \frac{M_{S,b}}{2K_{U,b}}H,$$

(17)

which leads to

$$h_{l,1} = -\frac{M_{S,b}K_{U,t}}{M_{S,t}K_{U,b}}\cos^3\theta - \frac{M_{S,b}A_{int,exch}}{M_{S,t}K_{U,b}\alpha}l\psi,$$

(18)

$$h_{l,2} = -\frac{M_{S,b}K_{U,t}}{M_{S,t}K_{U,b}}\cos^3\theta - \frac{2M_{S,b}A_{int,exch}}{M_{S,t}K_{U,b}\alpha}l\pi,$$

(19)

$$h_{l,3} = -\cos^3\theta - \frac{A_{int,exch}}{K_{U,b}\alpha}(\pi - \psi),$$

(20)

and

$$h_{l,1} = h_{l,2} = \frac{M_{S,b}K_{U,t}}{M_{S,t}K_{U,b}}\sin^3\theta,$$

(21)

$$h_{l,3} = \sin^3\theta.$$  

(22)

From these equations, the radius of the soft magnet astroid is determined by the ratio of anisotropy constants and saturation magnetization $M_{S,b}K_{U,t}/M_{S,t}K_{U,b}$, and the horizontal shifts of them that induces exchange field are function of $M_{S,b}/M_{S,t}K_{U,b}$ and $1/K_{U,b}$, respectively. This is shown in figure 3(a). By varying the parameters in these equations, we can derive another conclusion that the soft magnet does not trigger the reversal process in all cases. If $M_{S,b}K_{U,t}/M_{S,t}K_{U,b}$ is not sufficiently small, the astroid of the soft magnet does not shrink under the range of the astroid of the hard magnet. Then the switching field of the top soft magnet $H_{sw1,1}$ is larger than $H_{sw1,3}$. The same behaviour occurs if the exchange field of the bottom layer is very strong. In this case the astroid of the hard magnet moves far from the origin, and then the curve of the 1st quadrant moves out of that of the soft magnet (figure 3(b)).

3. Micromagnetic simulation

In order to verify our hypothesis, finite element micromagnetic simulations are performed. The structure is developed from
the hexagonal model with a grain diameter of 6 nm and an intergranular phase boundary thickness is 1 nm. The detailed geometry of the convex surface in a grain is generated by the surface evolver, using surface energy minimization under given boundary conditions: the surface tensions $\gamma$ and the wetting angle $\phi$ between the interface and the vacuum surface [11]. Considering the seed layer deposited prior to the magnetic layer leads to a convex top surface, the bottom surface of the magnetic grain is set to concave. The volume and the interfacial area of a grain are kept constant. The geometric parameters of our model, grain diameter $= 6$ nm, total thickness $= 16$ nm, intergranular phase thickness $= 1$ nm, are adopted from the TEM investigation [9].

Due to the extremely large number of finite element nodes and elements in a full granular structure, a quasi-granular structure is prepared as in figure 4. In a quasi-granular structure, the surrounding grains are simplified as facing walls around the grain. Their magnetizations are fixed by applying $10^4$ times higher crystalline uniaxial anisotropy constant. The magnetizations of three neighbours are pointing up and down, respectively. The bit is assumed to be located at the transition boundary between two oppositely magnetized bits. In order to study the shape effect of the convex and concave surfaces, all magnetization behaviours are compared with those of the flat model, a widely used model in micromagnetic simulations. All magnetic and geometry features, including volume, grain boundary area, layer thicknesses, top view shape and size, are the same in these two models.

4. Results and discussion

The modified SW equations from equations (12) to (16) enable us to estimate the local switching field of a grain with the given parameters. The nucleation site is expected to be the part which has the smallest local switching field. Since in all cases the local switching field $H_{sw,1}$ is larger than $H_{sw,2}$, the switching field is determined by comparing $H_{sw,2}$ of the soft magnet and $H_{sw,3}$ of the hard magnet. The analytic equations are used to derive a phase diagram of the exchange spring media with a convex surface, as shown in figure 5.

The magnetic parameters are adopted from the experiments. Saturation magnetization of the soft magnet and the hard magnet $M_{S,t}$ and $M_{S,b} = 4.78 \times 10^5$ Am$^{-1}$. For simplicity, they are assumed to be the same value. Uniaxial crystalline anisotropy of the soft magnet $K_{U,t}$ is varied from 0 to $5.0 \times 10^5$ J m$^{-3}$ and that of the hard magnet is fixed to $K_{U,b} = 5.0 \times 10^5$ J m$^{-3}$, respectively [6, 9]. Intragranular exchange constant $A = 1 \times 10^{-11}$ J m$^{-3}$, intergranular exchange constant $A_{int.exch}$ is 2% of $A$, which corresponds to the intergranular exchange coupling strength $J = 2$ mJ m$^{-2}$, and the wetting angle $\phi$ is equally varied from 90° to 150° for the soft and hard materials.

As a result, the phase diagrams of the simulation are shown in figure 5(a). Each line denotes the cases of different intergranular exchange $A_{int.exch}$. Its ratio to the intragranular exchange $A$ is attached on the lines. The region above the line stands for the conditions when site 3 of the hard bottom magnet is reversed in the smaller switching field and the region under the line is for site 1 of the soft top magnet. As the intergranular exchange increases, the hard bottom reversal occurs in more space in the phase diagram. When the two stacked layer has the same $K_U$ and the bottom layer has smaller $M_S$, a similar tendency is predicted by equations (19) and (21). In this case the size of the bottom layer’s astroid shrinks, which induces a smaller switching field.

The expectations from the analytic approaches are confirmed by micromagnetic simulation results with given material and geometric parameters. The wetting angles are set as 90°, 120° and 150°, with selected magnetic anisotropies for the soft magnet. The results from micromagnetics are shown in figure 5(b), when the intergranular exchange coupling strength

Figure 4. A quasi-granular structure located in the transition between two bits.
Figure 5. (a) Phase diagrams of the hard bottom reversal for various intergranular exchange constants. Attached numbers are the ratio between the $A_{\text{int}}$ and $A_{\text{exch}}$. (b) Comparison between the analytic results and finite element micromagnetics when $A_{\text{int,exch}} = 2 \times 10^{-13}$ J m$^{-1}$.

$J = 2$ mJ m$^{-2}$. The tendency of the simulation results agrees well with the trend of the analytic results. The result of the flat model is shown as the case of which wetting angle is 90$^\circ$. The micromagnetic results show a sort of intermediate region where the reversal occurs by the top and bottom sites. In this region, the contribution of the hard bottom layer on the reversal process is increasing as the $K_{U,\bot}$ increases.

In the flat model, all reversals are initiated from the soft magnet; however, there are some conditions that induce hard bottom magnet reversal in the case of convex model. Moreover, when the soft magnet has the same $K_U$ value to the hard magnet, it can be regarded as a single layer. In this case all conditions show the bottom initiated reversal except for the flat model; side wall nucleated magnetization. The magnetization configurations for selected cases are shown in figure 6, three pictures stand for the magnetization configurations of $M_z/M_s$, namely 0.8, 0.6 and 0.4, respectively, from left to right for each case. Differences from the flat model are clearly seen in the detailed magnetization process.

The asymmetric magnetization reversal process also results in the asymmetric coercivity according to the stacking order. Figure 7 shows the coercivity of the flat model and convex models, as a function of the anisotropy constant of the soft magnet. In contrast to the flat model, the coercivity of the convex model depends strongly on the stacking order.

If the soft magnet is located at the bottom and its anisotropy is very low, close to 0, the reversal has two steps. At first, most of the bottom layer is reversed assisted by site 3 on the edge of the concave surface. But, despite the reduction of the nucleation field, the magnetic energy of the grain is not enough to switch the hard magnet. Therefore, the pinning field which determines the coercivity which is required to move the domain wall from the soft to the hard layer is decreased if the hard layer is the bottom. The nucleation field of the soft layer becomes larger than the pinning field if a $K_U$ value of the soft layer is above half of that of the hard layer. Hence, the coercivity of the soft bottom layer is less than in the flat model and the hard bottom convex model in the region. In our system, the reduction of the coercivity in this case was up to 20%. The tendency agrees with the experimental reports. The stacked magnetic layer structure has higher coercivity when the bottom has stronger anisotropy or smaller saturation magnetization.
Figure 7. The comparison of the coercivity between the flat model and the convex model, as a function of the anisotropy constant of the soft layer.

[7, 9]. The coercivity increment exceeding that of the single layer was not explained in our study. Nevertheless, the trend of the simulations agrees quite well with the experiments. This nucleation and switching field alternation mechanism contributes even in the single layer media, the coercivity of the convex model is about 10% smaller than the flat model.

5. Conclusion

We studied the origin of the different coercivities depending on the stacking sequence, from the viewpoint of the grain shape effect. The SW equation is modified to implement the geometric effects. Parts of a grain can be considered independently according to their local shape, owing to the different ratios between local intergranular exchange and local anisotropy energy. Since the local contributions of magnetic energies are different in every site in a grain, the switching fields and behaviours were alternated by varying the magnetic and geometric parameters. A phase diagram of local reversal is calculated from the modified SW equations, and they are verified by finite element micromagnetic simulations. From the coercivity result, which agrees quite well with the experimental report, the grain shape can be one of the experimental evidence that induces the asymmetric coercivities by different stacking orders. Moreover, from the result that the coercivity of the convex model is lower than that of the flat model in the single layer model, it is concluded that the micromagnetic results for the convex granular structures are overestimating the real value of the coercivity.

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