Simulations for deformation processes of arbitrary domain shape in MO media

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Abstract- A new method is developed to simulate how a magnetic domain is stabilized in magneto optical recording. Based on the method in which dynamics of a domain wall is estimated from the calculation of force on the wall, the wall is assumed as the zero thickness line in arbitrary shapes. With this method the deformation processes of arbitrary domain shapes including not only circular and crescent ones can be treated. The deformation processes of the crescent-shape initial domains are performed under the uniform temperature and the uniform bias field.

Key words: magneto-optical recording, simulation, domain shape, domain dynamics, crescent shape domain, magnetic field modulation

1. Introduction

The theory for the stable radius of the domain nucleated in magneto-optical (MO) recording film is reported by G. B. Huth1). He discussed only the cylindrically symmetric case. S. Sugiyama and S. Tsunashima et al.2) reported that the minimum radius of the recorded domain. N. Hayashi and Y. Nakatani et al.3) reported that the micro magnetic method for the simulation of Magnetic AMplifying MO System (MAMMOS) phenomena by solving the Landau-Lifshitz-Gilbert (LLG) equation. Also, MO recording processes were simulated by T. Imazu et al.4) by estimating the value of an equivalent magnetic field to decide the magnetization reversal at the every point of divided meshes. As for the former the calculation time is very large, while for the latter the evaluation of the force on domain wall is ambiguous.

On the other hand, the magnetic field modulation (MFM) recording is useful method to record small domains with a wide range of writing power. In the MFM method written domains are in the crescent-shape.

A simulation method is newly developed for treating arbitrary shaped domains. It can simulate how a magnetic domain is stabilized and what is the finally stable domain shape for general shape domain. In this method, the dynamics of a domain wall motion is estimated from the calculation of the force exerted on the domain wall assumed as the thickness zero line.

2. Method

Fig.1 Model for simulation. Continuous solid line shows a domain wall, and rectangular meshes are used for calculating self demagnetizing field and Zeeman energy. Black color indicates the meshes where the wall is included.

2.1 Simulation method

Fig. 1 shows the model for simulation. The material is assumed to have sufficient uniaxial anisotropy to support magnetization normal to the plane. Continuous solid line shows a domain wall, and rectangular meshes are used for calculating self demagnetizing field and Zeeman energy only as mentioned later. The initial shapes of the domains have to be assigned first. Then, the forces on the domain wall are estimated from the gradient of the total energy with respect to the assumed movement of domain wall. So, in this method, the domain nucleation processes are not able to treat but the growing or shrinking processes can be simulated under the conditions include the distributions of the temperature and the external field.

The essential improvement made in this method is that domain deformation process is decided by the sequence of small step by step incremental movements of wall. The domain wall in any shape is assumed to be zero in thickness to in-plane direction of the film and is uniform toward the film thickness direction. The total energy, $E_t$, of a reversed domain in the film uniformly saturated downward relative to the same film without a reversed region is given by

\[ E_t = E_w + E_{sd} + E_{ex} \]  

(1)

where, $E_w$, $E_{sd}$ and $E_{ex}$ are the energy of domain wall, stray field and external magnetic field, respectively.
The gain in wall energy is expressed as
\[
\frac{d}{dr}E_w = \frac{d}{dr}\int_0^L \sigma_w h \, dl \,
\]
\[
= \int_0^L \frac{d\sigma}{dr} h \, dl + \sigma_w h \frac{dl}{dr} \, . \tag{4}
\]
where \(\sigma_w\) is the wall energy density and \(dl\) is defined as differential length along with \(L\). From the displacement of the wall \(dr\), \(L\) changes to \(L'\). Then, the expression for the force due to the wall energy becomes
\[
f_w = -\frac{1}{L'h} \frac{d}{dr} E_w = -\frac{1}{L'} \int_0^L \frac{d\sigma}{dr} dl - \sigma_w \frac{1}{L'} \frac{dl}{dr} \, . \tag{5}
\]
The gain in dipole-dipole (dd) interaction and in those with the external field can be written as the unified form.
\[
\frac{d}{dr} (E_{dd} + E_{ex}) = 2\int M (H_{dd} + H_{ex}) \, ds
\]
\[
+ 2\int M \frac{dM}{dr} (H_{dd} + H_{ex}) \, dv
\]
\[
+ 2\int M \frac{d}{dr} (H_{dd} + H_{ex}) \, dv \, . \tag{6}
\]
dv is defined as differential volume derived from \(dr\), \(h\) and \(L\), and the differential area \(ds\) is defined as depicted in Fig. 2. The simplest assumption for Eq. (6) is that the distribution of magnetization, stray field and external field toward the \(r\) direction are negligibly small. Thus, the final expression for the gain in dipole-dipole interaction and in those with the external field becomes
\[
\frac{d}{dr} (E_{dd} + E_{ex}) = 2\int M (H_{dd} + H_{ex}) \, ds \, . \tag{7}
\]
Then, the expression for the force becomes
\[
f_{dd+ex} = -\frac{1}{L'h} \frac{d}{dr} (E_{dd} + E_{ex}) = -2M (\overline{H}_{dd} + H_{ex}) \, . \tag{8}
\]
where \(\overline{H}_{dd}\) is the dipolar field contributed by all the other spins which are averaged over the \(z\) coordinate. In the film with a thickness \(h\), for every point specified by \(r, z\) where \(r\) is a two dimensional vector in the film, the dipolar field \(H_{dd}(r, z, r)\) contributed by the cylinder with length \(h\) located at another point \(r_i\). The site position \(r_i\) has been digitalized as shown in Fig. 1. The averaged field in this point is expressed as
\[
\overline{H}_{dd}(r, r) = \frac{1}{h} \int H_{dd}(r, z, r) \, dz \, . \tag{9}
\]
\(H_{ex}\) is the external field, and \(M(r)\) is the magnetic moment of the spin in the position of \(r\).

Then the total force \(f_t\) is:
\[
f_t = f_w + f_{dd+ex} \, . \tag{10}
\]
Finally, we need to calculate the force \(f_w\) given by the
coercivity. It can be written in a unified form similar to Eq. (6).

\[ f_c = \frac{1}{L'h} \frac{d}{dr} E_c = 2MH_c \] (11)

Now the stable condition can be obtained as shown below. The shape of domain is determined by a force balance between the wall pressure and the wall coercivity. The stability condition can be expressed by

\[ |f_c| = |f_\omega + f_{st-ex}| = f_c \] (12)

Since no sign is attributed to the coercivity, absolute magnitude of the left term is used in determining the regions of stability. If the wall pressure lower than this coercivity force, no movement will take place and the domain shape will be stable.

2.3 The relationships between calculation step and time

In this simulation, the domain wall is moved according to the value of the force on the wall. The wall velocity depends on the force. We assumed the averaged velocity \( \bar{v} \) linearly depend on the force during \( \Delta t \). Then the displacement \( \Delta d \) of the wall is written as

\[ \Delta d = \bar{v} \Delta t = A f \Delta t, \] (13)

where \( A \) is a constant and decided from an experimental value of wall velocity. Under this assumption the calculation step is related to the \( \Delta t \). Thus the time-evolution of the deformation of the wall can be calculated.

3. Results

3.1 Cylindrical domain

We performed simulations of cylindrical domains with the same condition as Huth\(^1\) for MnAlGe and GdCo. Table 1 shows the comparison of the stable radius of the domain reported by Huth and estimated from our simulations. Under the external field \( H_{ex} = 100 \) Oe, stable diameters are 2.53, 0.95 \( \mu \)m for MnAlGe and GdCo, respectively. Obtained values are well agreed with the results of Huth's theory within about 1% of errors. These differences may originate from the mesh quantization error at the calculations of \( E_{st} \) and \( E_{\omega} \).

3.2 Crescent shape domain

For deformation processes of arbitrary domain shape, under the uniform temperature and the uniform bias field the simulation for the domain with initial crescent-shape shown in Fig. 4 (a) is performed. The conditions of simulation are as follows, 1) 20 nm thick TbFeCo film, 2) the film temperature \( T_f = 180^\circ \text{C} \), 3) \( H_{ex} = 0 \) Oe. Fig 3 shows the temperature dependence of the saturation magnetization and the coercive force\(^5\) used in the

| Table 1 Stable radius of the domain reported by Huth\(^1\) and estimated from the simulations |
|-----------------------------------------------|----------------|
|                                               | MnAlGe     | GdCo       |
| Results by Huth\(^1\)                         | 2.55 \( \mu \)m | 0.96 \( \mu \)m |
| Simulated results                             | 2.53 \( \mu \)m | 0.95 \( \mu \)m |

Fig 3 Temperature dependence of the saturation magnetization (dotted line) and the coercive force (solid line) for Tb\(_{27}\)Fe\(_{53}\)Co\(_{12}\) film\(^8\).

![Fig 4 Change of domain shape](image)

Fig 4 Change of domain shape: (a) initial, (b) 5, (c) 10, (d) 20, (e) 30 and (f) 40 steps after, under the uniform temperature at 180\(^\circ\)C and the uniform bias field of 0 Oe in TbFeCo film. Parameters assumed in the calculation are given in the text. Under the assumption the wall velocity is 100m/s, the 40 calculation steps correspond to 0.8 ns.
velocity is 100m/s, the 40 calculation steps correspond to 0.8 ns. The movement of the domain wall is confirmed at \( T_l = 180^\circ C \).

The shape of whole domain, especially the top part of crescent, tends to be round with the increase of calculation steps. Fig. 5 shows the distribution of the force \( f_w f_e, f_{dd} \) and \( f_t \) for each section on the domain wall for the initial crescent-shape shown in Fig. 4 (a). Around the top part (Fig. 4 (a)(2)) and convex part (Fig. 4 (a)(3)) \( f_w \) and \( f_t \) are same. Also, at around the inside of domain wall (Fig.4 (a)(3)) \( f_w \) is dominant. On the other hand, the shape of the domain wall did not change under the condition of \( T_l = 50^\circ C \). So, the domain will quench with a rapid cooling process after laser irradiation stopped. To write crescent-shape domains the rapid quenching of the film temperature can play an important role.

Other simulations are performed for the cases of the mark length 0.1 \( \mu \)m and 0.05 \( \mu \)m with the same domain width of 0.45 \( \mu \)m. The temperature of the film is uniformly 80\(^\circ\)C and no magnetic field is applied. Fig. 6 (a), (b), show the distribution of the force on the domain wall in the cases of 0.1 \( \mu \)m and 0.05 \( \mu \)m, respectively. Around the top part, the total force for reducing the domain size is increasing similar to the case of 0.2 \( \mu \)m shown in Fig. 5. Around the convex part as depicted as\( \circ \) in Fig.4 (a), the total force \( f_t \) is very small as a consequence of balance of \( f_w \) and \( f_{dd} \) in the case of 0.1 \( \mu \)m. However, for the case of 0.05 \( \mu \)m, since \( |f_{dd}| \) becomes larger than \( |f_w| \) the total force \( f_t \) at around \( \circ \) is become expansive.

At around the concave part \( \circ \), the total force is always expansive due to the large value of \( |f_w| \), and for the case of 0.05 \( \mu \)m expanding force is increasing with increasing of \( |f_{dd}| \). In other words, the expanding force at around concave part of crescent is increasing with decreasing of mark length.

4. Conclusions

A new method is developed to simulate how a magnetic domain is stabilized in magneto optical recording. With this method the time-evolution of the deformation for arbitrary domain shapes including not only circular and crescent ones can be treated. The deformation processes of the crescent-shape initial domain are performed under the uniform temperature and the uniform bias field. The results show clearly that the temperature and the shape of domain affect the force distribution on the domain wall.

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References