Wall Simulation for the Domain Wall Displacement Detection (II)

Tadashi Kobayashi, Morio Masuda and Tsutomu Shiratori*
Dept. of Physics Engng., Mie Univ., Kamihama, Tsu, Mie 514-8507, Japan
*DM Project, Canon Inc., Shimomaruko, Ohta, Tokyo 146-8501, Japan

(Received October 2, 2000; Accepted November 9, 2000)

Abstract- Simulation for the Domain Wall Displacement Detection has been studied. Temperature dependence of the Gilbert's damping factor is inversely proportional to that of the net magnetization. Motion of the magnetization in the wall is similar to that for single domain due to large driving field. Wall coercivity is might be small enough not to affect wall velocity. Average wall velocity is estimated to be 50m/sec for linear velocity of 3m/sec. The external magnetic field of $\pm 200\text{Oe}$ considerably influences the wall velocity.

Key words: magneto-optical recording, Domain Wall Displacement Detection, gyromagnetic ratio, damping factor, wall velocity

1. Introduction

Following the paper of (I), the wall velocity of the displacement (denoted as D) layer during the front process in the Domain Wall Displacement Detection (DWDD)⁽¹⁻³⁾ has been calculated by the approximate estimate from the Landau-Lifshitz-Gilbert equation. The approximate estimate is useful for considering physical meaning rather than the micromagnetic simulation. The temperature dependences of the magnetization, the wall coercivity, the domain wall energy and the wall width of the D layer are used in this calculation.

2. Calculation method

Gyromagnetic ratio γ_{eff} and damping factor α_{eff} of heavy rare earth-3d transition metal (RE-TM) ferrimagnetic films are summarized in Table 1⁴⁾, where $M_{si} (> 0)$, γ_i and λ_i are the sublattice magnetization, the gyromagnetic ratio and the Landau-Lifshitz damping factor, respectively ($i = 1$: RE, 2: TM). Magnetization, of course, varies with temperature, and γ_i and λ_i are assumed to show no temperature dependence. Furthermore, g-factor of Gd and TM is assumed to be 2. γ_{eff} and α_{eff} are classified into two cases, that is RE $\neq$ Gd (non S state) and RE = Gd (S state). In the case of RE = Gd, γ_{eff} does not depend on temperature, and α_{eff} is inversely proportional to the net

magnetization M_s from the assumption that λ_i has no temperature dependence. This temperature dependence of α_{eff} is consistent with Ref. 5 that the line width of ferromagnetic resonance (FMR) of Gd-Fe is inversely proportional to M_s . Gd-Fe-Co is used as the D layer for the reason of small coercivity. So Eqs. (2) and (4) are used for this calculation.

Under the condition of $K_u \gg 2\pi M_s^2$ where K_u is an anisotropy constant, well-known relationships between wall velocity V and magnetic field H are also summarized in Table 2⁶⁾, where normalized wall velocity v and normalized magnetic field h defined as Eqs. (10) and (11) are used, where Δ_0 is the wall width parameter. The relationships are classified into three cases, that is $h < 1$ (lower than the Walker breakdown field), $1 < h$ (higher than the Walker breakdown field), and $1 < h$ and $1/\alpha_{\text{eff}} \ll h$ (much higher than the Walker breakdown field). Concerning α_{eff} in Eq. (9), the velocity reaches the maximum at $\alpha_{\text{eff}} = 1$.

Equation (9) is interpreted as

$$V = \frac{\alpha_{\text{eff}}}{1 + \alpha_{\text{eff}}^2} \gamma_{\text{eff}} \Delta_0 H = \frac{\Delta_0}{\frac{1 + \alpha_{\text{eff}}^2}{\alpha_{\text{eff}}} \frac{1}{\gamma_{\text{eff}} H}} \quad (13)$$

Table 1 Gyromagnetic ratio and damping factor for ferrimagnetic materials.

RE $\neq$ Gd	RE = Gd
$\gamma_{\text{eff}} = \frac{M_{s1} - M_{s2}}{\frac{M_{s1}}{ \gamma_1 } - \frac{M_{s2}}{ \gamma_2 }}$ (1)	$\gamma_{\text{eff}} = \gamma $ (2) ($ \gamma_1 = \gamma_2 \equiv \gamma $)
$\alpha_{\text{eff}} = \frac{\frac{\lambda_1}{ \gamma_1 ^2} + \frac{\lambda_2}{ \gamma_2 ^2}}{\frac{M_{s1}}{ \gamma_1 } - \frac{M_{s2}}{ \gamma_2 }}$ (3)	$\alpha_{\text{eff}} = \frac{\lambda_{\text{eff}}}{ \gamma M_s}$ (4) ($\lambda_{\text{eff}} \equiv \lambda_1 + \lambda_2$)

Table 2 Wall velocity for the field under and over the Walker breakdown field under the condition of $K_u \gg 2\pi M_s^2$

$$K_u \gg 2\pi M_s^2$$

$h < 1$	$1 < h$	$1 < h \quad 1/\alpha_{\text{eff}} \ll h$
$v = h$ (5)	$v = \frac{1}{1 + \alpha_{\text{eff}}^2} \left(\alpha_{\text{eff}}^2 h + \frac{1}{h + \sqrt{h^2 - 1}} \right)$ (7)	$v = \frac{\alpha_{\text{eff}}^2}{1 + \alpha_{\text{eff}}} h$ (8)
$V = \frac{\gamma_{\text{eff}}}{\alpha_{\text{eff}}} \Delta_0 H$ (6)		$V = \frac{\alpha_{\text{eff}}}{1 + \alpha_{\text{eff}}} \gamma_{\text{eff}} \Delta_0 H$ (9)
$v = \frac{V}{2\pi M_s \gamma_{\text{eff}} \Delta_0}$ (10)	$h = \frac{H}{2\pi M_s \alpha_{\text{eff}}}$ (11)	$H = \frac{1}{2M_s} \frac{\partial \sigma_d}{\partial x} - H_w$ (12)

Numerator is wall width (parameter) and denominator is the same as time for reversal of magnetization in single domain⁷⁾. Motion of the magnetization in the wall is thought to be similar to that in single domain due to large magnetic field. The meaning of $\alpha_{\text{eff}} < 1$ is so-called underdamping in which though precession is violent, time for reversal of magnetization is long. On the other hand, $1 < \alpha_{\text{eff}}$ is overdamping in which though precession hardly occurs, time for the reversal is also long. The best condition for the reversal is critical damping $\alpha_{\text{eff}} = 1$ in which magnetization precesses somewhat and reverses rapidly (see Appendix).

Magnetic field H to drive the wall is defined as Eq. (12), where σ_d and H_w are the domain wall energy and wall coercivity of the D layer, respectively.

Temperature dependences of M_s , H_w , σ_d and Δ_0 are shown in the paper of (I).

Linear velocity of medium is 3m/sec and temperature profile is also shown in the paper of (I).

3. Wall velocity

3.1 Damping factor

Calculation parameter is damping factor. The damping factor α_{eff} is set up as $\alpha_{\text{eff}} = 1/M_s$, $10/M_s$ and $100/M_s$.

When $\alpha_{\text{eff}} = 1/M_s$, the wall position and the velocity are shown as a function of time in Fig. 1(a). The dotted lines are the results for $H_w = 0$. Since driving field due to temperature gradient $(1/2M_s)\partial\sigma_d/\partial x$ is much large than H_w , the results for the dotted and the solid lines are almost the same. At the initial stage of the wall motion, the velocity is very slow. The velocity, however, becomes very fast at the final stage. Considering the reason for this behavior, we show h , $1/\alpha_{\text{eff}}$ and α_{eff} in Fig. 1(b). The facts of $h > 1$ and $h \gg 1/\alpha_{\text{eff}}$ can be seen. Under these conditions, the velocity V is expressed as Eq. (9).

Concerning α_{eff} in Eq. (9), the velocity reaches maximum at $\alpha_{\text{eff}} = 1$. At the initial stage, h is small and α_{eff} is much smaller than 1. Then h becomes large and α_{eff} approaches 1 at the final stage. Therefore the velocity greatly increases. The average velocity, however, is slow due to the low velocity at the initial stage.

Next parameter is $\alpha_{\text{eff}} = 10/M_s$. Results are shown in Figs. 2(a) and (b) (pay attention to the scale of time). In this case, α_{eff} is not so much small from 1 at the initial stage, and the velocity is relatively fast. In addition to the relative fast velocity at the initial stage, α_{eff} approaches 1 near the peak of h . Hence the average velocity is fast. The time of the peak velocity is 5.9nsec from Fig. 2(a), and the

Fig. 1(a) Wall position and velocity with time and **(b)** normalized magnetic field and damping factor with time.

Fig. 2(a) Wall position and velocity with time and (b) normalized magnetic field and damping factor with time.

Fig. 3(a) Wall position and velocity with time and (b) normalized magnetic field and damping factor with time.

times of $\alpha_{\text{eff}} = 1$ and the peak of h are 5.1nsec and 6.9nsec, respectively from Fig. 2(b). Since h is low when $\alpha_{\text{eff}} = 1$ and $\alpha_{\text{eff}} = 4.7$ when the peak of h , the peak velocity appears when between the time of $\alpha_{\text{eff}} = 1$ and the time of the peak of h according Eq. (9).

Last of all, we calculated for $\alpha_{\text{eff}} = 100/M_s$. Remarkable peak of velocity which appears in Figs. 1(a) and 2(a), can not be seen in Fig. 3(a). Though h has a peak at the middle stage as seen in Fig. 3(b), the velocity does not show the remarkable peak because α_{eff} is very large. Accordingly the average velocity is slow due to the low velocity for all stages.

These results are in good agreement with those simulated by the micromagnetics except for details⁸⁾. The motion of the magnetization in the wall is expected that the precession is violent for $\alpha_{\text{eff}} < 1$, the magnetization reverses rapidly for $\alpha_{\text{eff}} = 1$ and the magnetization reverses slowly for $1 < \alpha_{\text{eff}}$. This expectation can be confirmed by the micromagnetic simulation⁹⁾.

The damping factor α_{eff} of the displacement layer seems to be $\alpha_{\text{eff}} = 10/M_s$ from Ref. 10. The average wall velocity for $\alpha_{\text{eff}} = 10/M_s$ is about 50m/sec which can be compared with the reported result of 28m/sec (linear velocity is 1.5m/sec)¹¹⁾.

Substituting γ_{eff} , α_{eff} and H in Eq. (9) for Eqs. (2),

(4) and (12) and neglecting H_w , we get

$$V = -\frac{\lambda_{\text{eff}}}{M_s^2 + \frac{\lambda_{\text{eff}}^2}{|\gamma|^2}} \Delta_0 \frac{1}{2} \frac{\partial \sigma_d}{\partial x}. \quad (14)$$

From Eq. (14), a guideline for high wall velocity is that M_s is set up to 0, and large wall driving force $\partial \sigma_d / \partial x$ is desired. Though increase of the wall width parameter Δ_0 contributes increase of the velocity, that may degrade resolution of minute mark.

3.2 External magnetic field

Next, we consider the wall motion under external magnetic field. Figure 4 shows the results. H_{ex} of -200Oe prevents the wall motion and H_{ex} of +200Oe assists the wall motion. The magnetic field of $\pm 200\text{Oe}$ considerably influences the wall velocity. In the paper of (I), we discussed one possibility of the edge shift and the fluctuation of the jitter of reproduction signal by external magnetic field from the point of view of the start of the front process. Another possibility is the change of the wall velocity. If the velocity becomes slow, the reproduction signal is delayed and rises slowly. Therefore the change of the wall velocity results in both the change of the edge shift and the fluctuation of the jitter.

Fig. 4 Wall velocity with time under external magnetic field.

4. Conclusions

The wall velocity of the displacement (denoted as D) layer during the front process in the Domain Wall Displacement Detection (DWDD) was calculated by the approximate estimate from the Landau-Lifshitz-Gilbert equation.

Since driving field due to temperature gradient is much large than the wall coercivity, the wall coercivity does not much influence the wall velocity.

The best parameter of the damping factor α_{eff} is order of $10/M_s$, and Gd-Fe-Co of the D layer seems to have α_{eff} of order of $10/M_s$.

The average wall velocity is about 50m/sec which can be compared with the reported experiments.

The external magnetic field of ± 200 Oe considerably influences the wall velocity.

Appendix

Motion of magnetization in single domain can be calculated by the well-known method⁷⁾. Results are shown in Fig. A-1.

Fig. A-1 Motion of magnetization in single domain for (a) underdamping, (b) critical damping and (c) overdamping.

Acknowledgments The authors would like to thank Dr. Y. Nakatani at University of Electro Communications for helpful discussions and calculations.

References

- 1) T. Shiratori, E. Fujii, Y. Miyaoka and Y. Hozumi: Proc. Magneto-Optical Recording Int. Symp., Yamagata, 1997, *J. Magn. Soc. Jpn.*, 22 (Suppl. No. S2), 47 (1998).
- 2) T. Shiratori, E. Fujii, Y. Miyaoka and Y. Hozumi: Dig. Int. Symp. Optical Memory, Tsukuba, 1998, p. 46 (The Japan Society of Applied Physics, the Magnetics Society of Japan and Optoelectronic Industry and Technology Development Association).
- 3) T. Shiratori, E. Fujii, Y. Miyaoka, Y. Hozumi, T. Kobayashi and M. Masuda: Dig. Magneto-Optical Recording Int. Symp., Monterey, 1999, p. 60 (The Magnetics Society of Japan).
- 4) For example, R. Giles and M. Mansuripur: Proc. Magneto-Optical Recording Int. Symp., Tokyo, 1991, *J. Magn. Soc. Jpn.*, 15 (Suppl. No. S1), 299 (1991).
- 5) C. Vittoria, P. Lubitz and J. Schelleng: AIP Conf. Proc., 29, 196 (1976).
- 6) J. C. Slonczewski: AIP Conf. Proc., 5, 170 (1972).
- 7) For example, S. Uchiyama and M. Masuda: Magnetic Materials, p. 126 (Corona Publishing, Tokyo, 1980) (in Japanese).
- 8) Y. Nakatani, K. Kamata, T. Kobayashi and T. Shiratori: Dig. 23rd Ann. Conf. Magnetics Jpn., Kitakyushu, 1999, p. 84 (The Magnetics Society of Japan) (in Japanese).
- 9) Y. Nakatani: private communication.
- 10) P. Lubitz, J. Schelleng, C. Vittoria and K. Lee: AIP Conf. Proc., 29, 178 (1976).
- 11) M. Kaneko, T. Sakamoto and A. Nakaoki: *IEEE Trans. Magn.*, 35, 3112 (1999).