Magnetization Reversal Time in Ferromagnetic and Ferrimagnetic Materials

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Magnetization reversal time in ferrimagnetic material is compared with that in ferromagnetic material. Since ferromagnetic material is in a state of underdamping, the reversal time is relatively long. A formula for reversal time in ferrimagnetic material is deduced under the assumption that the effective Gilbert damping parameter α_{eff} is inversely proportional to the net angular momentum. In the case of $g_1 = g_2$, where g_1 and g_2 are the g-factors of the first and second sublattices, respectively, the reversal time in ferrimagnetic material is much shorter than that in ferromagnetic material because α_{eff} in ferrimagnetic material can be adjusted so that $\alpha_{\text{eff}} = 1$. Furthermore, in the case of $g_1 \neq g_2$, the reversal time becomes much shorter than that when $g_1 = g_2$ because a large net magnetization and small net angular momentum can be realized.

Key words: magnetization reversal time, ferrimagnetic material, damping parameter, g-factor, angular momentum

1. Introduction

High-density magnetic recording requires a short time for writing due to the tiny mark size. For example, the time for writing is only 10^{-1} ns for a few Tbpsi at a rotation speed 10,000 rpm in a 3.5-inch hard disk drive. A new problem therefore arises as to whether the reversal time of magnetization is sufficiently short. In this paper, we discuss the possibility of high-speed reversal of magnetization in ferrimagnetic material in comparison with that in ferromagnetic material.

2. Magnetization reversal time in ferromagnetic material

It is well known that the magnetization reversal time τ in ferromagnetic material can be calculated by

$$\tau = \frac{1 + \alpha^2}{\alpha} \frac{1}{|\gamma| H_{\text{ext}}}, \quad (1)$$

where α , $|\gamma|$, and H_{ext} are the Gilbert damping parameter, the gyromagnetic ratio, and the external magnetic field, respectively. Under an anisotropic field H_k , the equation should be modified as follows:

$$\begin{aligned} \tau' &= \frac{1 + \alpha^2}{\alpha} \frac{1}{|\gamma|} \left(\frac{1}{2(H_{\text{ext}} - H_k)} + \frac{1}{2(H_{\text{ext}} + H_k)} \right) \\ &= \frac{1 + \alpha^2}{\alpha} \frac{1}{|\gamma|} \frac{H_{\text{ext}}}{(H_{\text{ext}}^2 - H_k^2)} > \tau, \end{aligned} \quad (2)$$

in which τ' is longer than τ .

The results of calculating τ' under the assumption that the Gilbert damping parameter $\alpha = 0.04$ ¹⁾ and the gyromagnetic ratio $|\gamma| = 1.76 \times 10^7$ 1/(Oe·s) are shown in Fig. 1. It is necessary for the fast reversal of magnetization that H_{ext} be sufficiently larger than H_k .

Fig. 1 Magnetization reversal time as a function of the external magnetic field in ferromagnetic material.

Considering the limitation on the head field H_{ext} and the thermal stability determined by the magnetic anisotropy H_k , the reversal time may be comparable with the writing time of 10^{-1} ns for high-density recording. Since $\alpha = 0.04$, the motion of the magnetization is considerable to be underdamping. If we can control the value of α and increase the critical damping up to $\alpha = 1$, τ' can be decreased. However, such a mean is unknown. One possibility to avoid the above problem may be the employment of ferrimagnetic materials. The details are explained below.

3. Magnetization reversal time in ferrimagnetic material

3.1 Effective Gilbert damping parameter

A ferrimagnetic material has two sublattice magnetizations M_{s1} and corresponding angular momentums $A_{s1} = M_{s1}/|\gamma_1|$. The net magnetization is $M_s = |M_{s1} - M_{s2}|$, and the net angular momentum is $A_s = |A_{s1} - A_{s2}|$. Both the gyromagnetic ratio $|\gamma_i|$ and the g-factor g_i are the ratio of the magnetization to the angular momentum; that is, $|\gamma_i| = M_{si}/A_{si} = g_i(\mu_B/\hbar)$, where μ_B is the Bohr magneton. Therefore, when the

Fig. 2 Configurations of magnetizations and angular momenta at (a) magnetization compensation temperature T_M and (b) angular momentum compensation temperature T_A for the case of $g_1 \neq g_2$.

Fig. 3 Temperature dependence of net magnetization M_s , net angular momentum A_s , effective Gilbert damping parameter α_{eff} , and reversal time τ of magnetization in ferrimagnetic material for the case of $g_1 = g_2 = 2$. The material of $g_1 = g_2$ is hypothetical.

g-factor g_1 of the first sublattice is different from the g-factor g_2 of the second sublattice, the magnetization compensation temperature T_M does not agree with the angular momentum compensation temperature T_A . Although $M_s = 0$ at T_M , A_s has a non-zero value in such a case (Fig. 2 (a)). Similarly, although $A_s = 0$ at T_A , M_s has a non-zero value (Fig. 2 (b)).

We have proposed that the effective Gilbert damping parameter α_{eff} in ferrimagnetic material is inversely proportional to A_s ; that is, $\alpha_{\text{eff}} = A_0/A_s$ ²⁾, where A_0 is defined as $\lambda_1/|\gamma_1|^2 + \lambda_2/|\gamma_2|^2$ using the Landau-Lifshitz damping parameter λ_i , and A_0 is assumed to be constant. This assumption was confirmed by an experiment conducted by C. D. Stanciu *et al.*³⁾. It is also well known that the effective gyromagnetic ratio γ_{eff} is expressed as $\gamma_{\text{eff}} = M_s/A_s$. Our calculations in this paper are made under the above assumptions.

Fig. 4 Temperature dependence of M_s , A_s , α_{eff} , and τ of magnetization in ferrimagnetic material for the case of $g_1 = 1.85$ and $g_2 = 2$. The g-factors $g_1 = 1.85$ and $g_2 = 2$ correspond the alloy of Gd-Tb-Fe-Co.

Fig. 5 Minimum reversal time as a function of the g-factor g_1 .

3.2 Case of g-factor $g_1 = g_2$

Substituting α_{eff} for α and γ_{eff} for $|\gamma|$ in Eq. (1), we obtain the magnetization reversal time τ for ferrimagnetic materials as

$$\tau = \frac{1 + \alpha_{\text{eff}}^2}{\alpha_{\text{eff}}} \frac{1}{\gamma_{\text{eff}}} \frac{1}{H_{\text{ext}}}. \quad (3)$$

Since M_s is proportional to A_s in the case of $g_1 = g_2$, γ_{eff} becomes constant and T_M agrees with T_A . Hence, τ reaches a minimum when $\alpha_{\text{eff}} = 1$.

The damping parameter α has often been assumed to be a constant. This assumption, however, gives rise to the inconsistency that the magnetization M_s can be reversed even when $M_s = 0$ at T_M from Eq. (3). In our assumption, α_{eff} is inversely proportional to M_s when $g_1 = g_2$. Therefore, τ is expressed as follows:

$$\tau \propto \frac{M_s^2 + \text{const.}}{M_s}. \quad (4)$$

From Eq. (4), we obtain a consistent interpretation that $\tau \rightarrow \infty$ when $M_s = 0$.

A simulation was carried out by the ordinary mean field method using ferrimagnetic material of a rare earth-3d transition metal such as Gd-Fe or Gd-Co.

Strictly speaking, although g_1 and g_2 of Gd-Fe or Gd-Co are almost identical, they are not completely in agreement because the experimental g-factor of Gd-Fe or Gd-Co shows temperature dependence. Therefore the material of $g_1 = g_2$ is hypothetical. The calculation parameters were $A_0 = 5.69 \times 10^{-7} \text{ erg} \cdot \text{s}/\text{cm}^3$ [2], $H_{\text{ext}} = 100 \text{ Oe}$, and a Curie temperature of 600 K. The reversal time was found to considerably vary with the temperature, as shown in Fig. 3. It can be seen that τ is divergent at T_M . The damping parameter α_{eff} becomes $\alpha_{\text{eff}} = 1$ near the point at which $T_M = T_A$. The minimum reversal time τ_{min} is 1.14 ns, which can be compared with the value of 14.2 ns in ferromagnetic material. The reversal time in ferrimagnetic material is expected to be one order faster than that in ferromagnetic material.

3.3 Case of g-factor $g_1 \neq g_2$

In the case of $g_1 \neq g_2$, substituting $\alpha_{\text{eff}} = A_0/A_s$ for α and $\gamma_{\text{eff}} = M_s/A_s$ for $|\gamma|$ in Eq. (1), τ is expressed as

$$\tau = \frac{1 + \alpha_{\text{eff}}^2}{\alpha_{\text{eff}}} \frac{1}{\gamma_{\text{eff}}} \frac{1}{H_{\text{ext}}} = \frac{A_s^2 + A_0^2}{A_0} \frac{1}{M_s H_{\text{ext}}}. \quad (5)$$

Since the magnetization M_s is proportional to A_s in ferromagnetic material, M_s and A_s cannot be controlled independently. In ferrimagnetic material, on the other hand, when $g_1 \neq g_2$, a state in which M_s is large and A_s is small can be realized. The term $M_s H_{\text{ext}}$ is the energy of magnetization reversal in Eq. (5), and A_s is the cause of precession. It is interpreted from Eq. (5) that the precession caused by A_s makes the reversal time long. A large $M_s H_{\text{ext}}$ and small A_s consequently bring about a short reversal time of magnetization. Furthermore, from Eq. (5) it is also seen that a small A_0 makes the reversal time short under the condition of $A_s = 0$. The term A_0 may thus be regarded as a type of friction.

In addition, we can also obtain the same interpretation that $\tau \rightarrow \infty$ when $M_s = 0$ from Eq. (5).

When $g_1 = 1.85$ and $g_2 = 2$, τ_{min} is only 0.14 ns around T_A due to the large M_s and small A_s , as shown in Fig. 4, compared with the value of 1.14 ns for the case of $g_1 = g_2$. The g-factors $g_1 = 1.85$ and $g_2 = 2$ correspond to the alloy of Gd-Tb-Fe-Co since g_1 of Gd is 2 and g_1 of Tb 3/2.

Figure 5 shows the minimum reversal time τ_{min} as a function of the g-factor g_1 . When g_1 decreases from $g_1 = 2$, τ_{min} decreases rapidly. To decrease g_1 , the use of low g-factor element, such as Tb, Dy, Ho, may be effective.

4. Discussion

Even if $g_1 = g_2$, the reversal time in ferrimagnetic material is one order faster than that in ferromagnetic material. From the relationships of $\alpha = A_0/A_s$ and

$|\gamma| = M_s/A_s$, we obtain $A_0 = \alpha M_s/|\gamma|$. In this paper, we assumed $\alpha = 0.04$ and $|\gamma| = 1.76 \times 10^7 \text{ 1}/(\text{Oe} \cdot \text{s})$ for ferromagnetic material. We can estimate the value of A_0 in ferromagnetic material by the further assumption of $M_s = 500 \text{ emu}/\text{cm}^3$; that is, $A_0 = 11.4 \times 10^{-7} \text{ erg} \cdot \text{s}/\text{cm}^3$, which is only double the value of $A_0 = 5.69 \times 10^{-7} \text{ erg} \cdot \text{s}/\text{cm}^3$ in ferrimagnetic material. On the other hand, $(1 + \alpha^2)/\alpha$ is 25 for $\alpha = 0.04$ in ferromagnetic material. In ferrimagnetic material, α_{eff} can be adjusted so that $\alpha_{\text{eff}} = 1$, and $(1 + \alpha_{\text{eff}}^2)/\alpha_{\text{eff}}$ is only 2 when $\alpha_{\text{eff}} = 1$. Hence, the main reason for the slow reversal time of ferromagnetic material is the state of underdamping of $\alpha = 0.04$.

Furthermore, if $g_1 \neq g_2$, the reversal time becomes much faster than that in the case of $g_1 = g_2$ because a large net magnetization and small net angular momentum can be realized. Since M_s is proportional to A_s in the case of both ferromagnetic and ferrimagnetic materials when $g_1 = g_2$, some precession is essential to reserve the energy $M_s H_{\text{ext}}$ of magnetization reversal. On the other hand, in the case of ferrimagnetic material when $g_1 \neq g_2$, precession is completely unnecessary. In other words, the precession caused by the net angular momentum makes the reversal time long. However, the magnetization can be reversed without the net angular momentum when $g_1 \neq g_2$. Thus, high-speed magnetization reversal is possible.

Although the exchange mode is not taken into consideration, the role of the magnetization and the angular momentum in the magnetization reversal time for ferrimagnetic material becomes clear in this calculation.

5. Conclusion

The magnetization reversal time in ferromagnetic material was calculated. Considering the limitation on the head field and thermal stability determined by magnetic anisotropy, the reversal time may be comparable with the writing time for high-density recording.

One possible means of avoiding this problem may be the employment of ferrimagnetic materials. When the g-factor of the first sublattice is different from that of the second sublattice, a large net magnetization and small net angular momentum can be realized. This state is effective for high-speed reversal of magnetization. A one or two order faster reversal time can be estimated for ferrimagnetic material in comparison with ferromagnetic material.

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References

- 1) N. Inaba, Y. Uesaka, A. Nakamura, M. Futamoto, Y. Sugita, and S. Narishige: *IEEE Trans. Magn.*, **33**, 2989 (1997).

- 2) T. Kobayashi, H. Hayashi, Y. Fujiwara, and S. Shiomi: *IEEE Trans. Magn.*, **41**, 2848 (2005).
- 3) C. D. Stanciu, A. V. Kimel, F. Hansteen, A. Tsukamoto, A. Itoh, A. Kirilyuk, and Th. Rasing: *Phys. Rev. B* **73**, 220402(R) (2006).

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