Precessional magnetization reversal in composite patterned media: Dependence on applied field parameters

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Precessional reversal in composite patterned media elements has been studied for various applied field parameters. The decrease of the percentage of the elements covered by the applied field leads to a rapid increase of the reversal field and decrease of the critical rise time required for precessional reversal. For weak and strong applied fields, the reversal time respectively was found to decrease and increase with an increase of the applied field strength and decrease of the rise time. For certain (large) values of the applied field strength and pulse duration bands of non-reversal can be obtained. This behavior is associated with multiple precessional oscillations between two equilibrium states. Such oscillations can be eliminated by properly choosing the field pulse duration and element damping constant.

\textit{Index Terms—} Landau-Lifshitz equation, perpendicular magnetic recording, patterned media, precessional magnetization reversal.

I. INTRODUCTION

Patterned media (PM) are envisioned for ultra-high recording densities in the Tb/in\textsuperscript{2} range \cite{1, 2}. The performance of PM is constrained by the problems of thermostability, writeability and single-noise ratio \cite{3}. Microwave-assisted \cite{4} and heat-assisted \cite{5} schemes can solve the writability and thermostability problems by allowing for low writing fields for media with high anisotropy. However, these schemes may be complicated to use. Exchange coupled composite PM media designs were suggested to reduce the writing field without loss of thermostability \cite{6, 7}.

Recently we showed that reversal in composite media can occur in damping as well as precessional regimes \cite{8, 9}. Under precessional reversal, the system can by-pass the energy barrier as long as the energy maximum is below the energy before the external field is applied, which results in a reduced reversal field \cite{10, 11}. PR is obtained under the following three conditions: the external field is applied at an angle to the element’s easy axis, the rise time is small, and the material damping constant is small \cite{8, 11, 12}. For composite elements, PR is characterized by several important properties including a significant reduction of the reversal field, a modified angular dependence, and substantially increased critical rise time, viz. the maximal rise time required for PR to occur. The properties of PR in such media can be controlled by tuning the structure parameters, e.g. interlayer coupling and soft layer thickness \cite{8, 9, 13}. Phenomena of PR are anticipated to become especially important for ultra-high density and speed recording requiring GHz switching rates and sub-nanosecond signal rise times.

In this paper, we thoroughly study PR dynamics in composite media for various applied field parameters including effects of spatially non-uniformity of the external field, as well as the magnitude pulse duration of the external field. We access conditions on the external field parameters that allow achieving fast and reliable PR in composite PM.

The outline of the paper is as follows. Section II presents the structure under investigation and describes the numerical approach used to generate the results. Section III studies PR dependence on various parameters of applied field. Finally, Sec. IV summarizes the findings in the paper.

II. PROBLEM FORMULATION

We consider exchange coupled dual-layer elements comprising layers of identical size $w, w, t_h$ (insert in Fig. 1). The bottom (hard) layers is characterized by perpendicular uniaxial anisotropy with energy $K_x$ and the top (soft) layer is completely soft with $K_s = 0$. The layers are coupled with surface energy $J_{er}$. Both layers have a damping constant $\alpha$, saturation magnetization $M_s$, and exchange length $l_{ex} = A/2M_s$ (with $A$ the exchange constant). A magnetic field $H_{sat} = -H_w f(t/\tau)\psi(r)(\Delta \sin \varphi + \gamma \cos \varphi)$ is applied to reverse the magnetization from the top to bottom equilibrium state. Here, $\varphi$ is the field angle, $H_w$ is the field magnitude, $f(t/\tau)$ is the field time dependence with the field rise time $\tau$, and $\psi(r)$ is the field spatial dependence. Specific time and spatial dependences $f(t/\tau)$ and $\psi(r)$ are defined in Secs. III and IV. The reversal behavior under such non-uniformly applied fields is related to that in the case of writing head with a sharp gradient of the field distribution.

In all simulations, the structure parameters were chosen as $w = 10 \text{ nm}, t_h = 5 \text{ nm}$, $M_s = 500 \text{ emu/cc}$, $K_x = 3.75 \times 10^6 \text{ erg/cm}, H_w = 2K_x/M_s = 15 \text{ Koe}$, and $\varphi = 45^\circ$. The exchange constant was assumed to be $A = 1.875 \times 10^{-8} \text{ erg/cm}$ corresponding to the exchange length of $10 \text{ nm}$. The value of the coupling energy was chosen as $J_c/(2K_x t_h) = 0.3$ to result in a low reversal field. Elements with the chosen parameters can be used to construct PM with density above $1 \text{Tbit/in}^2$.

Magnetization reversal from up to down equilibrium state occurs when $H_{sat}$ is above a certain reversal field $H_r$. For the same structure, the reversal field is different depending on $\tau$. For $\tau$ smaller or larger the critical rise time $\tau_{crit}$, reversal occurs in the precessional and damping regime associated with precessional and damping reversal field $H_{dr}$.
and \( H_m \) (\( H_m < H_a \)), respectively [8, 9]. The critical rise time \( \tau_{\text{crit}} \) is defined as the rise time that leads to the reversal field \( H_r = H_m + 0.2(H_a - H_m) \). Reversal occurs over a reversal time \( t_r \), defined as the time required for magnetization to reverse and remain in the reversed state after the applied field is turned off.

Magnetization reversal was studied by numerically solving the Landau-Lifshitz-Gilbert equation, which includes the precessional and damping terms calculated based on the effective magnetic field comprising the Zeeman, anisotropy, exchange, and magnetostatic components [14]. The element was discretized into cubic cells of size assuring numerical accuracy. All differential operators were evaluated using second-order finite-differences. The magnetostatic field was evaluated based on superposition. The exchange coupling between the soft and hard layers was modeled by replacing the normal component of the exchange length at the discretization cells on the interface by \( \Delta_e = (J_\Delta)^2/M_s \), where \( \Delta \) is the linear size of the discretization cell.

III. EFFECTS OF NON-UNIFORM FIELDS

This section studies reversal fields in the PR regime under non-uniform external magnetic fields. The field is applied uniformly across the width (\( z \) coordinate) and through the height (\( y \) coordinate) of the element but only over a varying part of the element along the length direction (\( x \) coordinate). The field spatial dependence is given by \( \psi(r) = 1 \) for \( x < x_i \) and \( \psi(r) = \exp(-(x-x_i)/(0.25w)) \) for \( x > x_i \). The time dependence is \( \psi(t) = 1 - 2\exp(-2t/\tau) \).

Figure 1(a) shows \( H_r \) vs. \( x_i/w \) for three rise times 20, 45 and 200 ps. It is found that for all cases \( H_r \) increases with a decrease of \( x_i/w \). However, the rate of this increase is smaller than the rate of the decrease of \( x_i/w \). The reduced increase rate is associated with non-uniform reversal modes in the horizontal direction, which is similar to what was shown in the damping reversal. It is further found that \( H_r \) is substantially smaller for smaller rise times. For example, considering a fully covered element, \( H_r = 0.21H_x \) for \( \tau = 20 \text{ ps} \) (solid curve), whereas \( H_r = 0.28H_x \) for \( \tau = 200 \text{ ps} \) (dashed curve). The reversal field reduction for small \( \tau \) is due to the phenomenon of PR.

As explained in Sec II, PR is possible only for rise times \( \tau < \tau_{\text{crit}} \). Figure 1(b) depicts \( \tau_{\text{crit}} \) vs. \( x_i/w \) for the elements in Fig. 1(a). For full coverage (\( x_i = w \)), \( \tau_{\text{crit}} = 58 \text{ ps} \), which is about 6 times larger than \( \tau_{\text{crit}} \) for a homogeneous element identical to the hard layer section (estimated by \( 2\pi/(yH_x) \) as \( \sim 10 \text{ ps} \)). The increase of \( \tau_{\text{crit}} \) for composite elements is important for ultra-high density recording when large \( H_k \) is required to render thermal stability. Indeed, in this case, \( \tau_{\text{crit}} \) required for homogeneous elements are too small to be generated by a recording head. On the other hand, the increased \( \tau_{\text{crit}} \) for composite elements can be practical. The values of \( \tau_{\text{crit}} \) can be even larger for other structure parameters (e.g. for higher thickness of the soft layer or different interlayer strength; see also “ledge” designs in [13]).

From Fig. 1(b), \( \tau_{\text{crit}} \) substantially decreases with a decrease of \( x_i/w \). This behavior suggests a way to control the reversal mechanism by carefully choosing the rise time. This is demonstrated by the dotted curve in Fig. 1(a), which shows \( H_r \) for \( \tau = 45 \text{ ps} \). From Fig. 1(b), such \( \tau_{\text{crit}} \) allows for PR for full coverage (\( x_i = w \)) but does not allow for PR for a partial coverage (\( x_i < w \)). As a result, \( H_r \) is low when the entire element is under the applied field, whereas it is substantially higher and almost equals the damping reversal field when only a small part of the element is under the applied field. The obtained rapid reversal field increase can reduce time margin errors in magnetic recording applications.

IV. EFFECTS OF EXTERNAL FIELD STRENGTH AND DURATION

This section studies the reversal time associated with PR as a function of the external field strength and duration. It is assumed that the external field is spatially uniform so that \( \psi(r) = 1 \). Section IV.A considers the regime of weak and moderate external fields. Section IV. B studies the reversal time for strong reversal fields. Section IV. C studies the dynamic magnetization behavior under stronger external fields for different durations of the reversal field.

Reversal mechanism in composite elements in the precessional regime comprises the same three stages as in the damping regime [15]: nucleation and reversal propagation in the soft layer, reversal depinning at the soft-hard layer interface, and the hard layer reversal. Depending on the applied field magnitude, reversal mechanisms associated with these stages occur differently as explained next.

A. Weak and moderate external fields

First, consider the case where applied field magnitude \( H_a \) is only slightly larger than the reversal field \( H_r \). Such field is referred to as “weak” field. The field time dependence is assumed to be the same as in Sec. III. Fig. 2 shows the reversal time \( t_r \) vs. \( H_r \) for the dual-layer element with \( \tau = 0 \text{ ps} \), \( \tau = 50 \text{ ps} > \tau_{\text{crit}} \), and \( \tau = 200 \text{ ps} > \tau_{\text{crit}} \). As a comparison, results for a single layer element with \( \tau = 10 \text{ ps} \) (under PR) are also shown. All curves exhibit increased values of \( t_r \) as \( H_r \to H_a \). The increase of the reversal time for smaller \( H_a \) is mostly because of the time required for the reversal mode nucleation, propagation in the soft layer, and depinning through the interface. After these steps are completed, the reversal in the hard layer occurs rapidly.

For the dual-layer element, under moderate \( H_a \), which do not significantly exceed \( H_r \), the reversal times for \( \tau = 0 \) and \( \tau = 50 \text{ ps} \) are much smaller than those for \( \tau = 200 \text{ ps} \). Moreover, compared to the case of homogeneous elements, the reversal time for \( \tau = 0 \) and \( \tau = 50 \text{ ps} \) for the dual-layer element have an advantage of lower reversal field with a minor difference of the reversal time. The reversal time reduces mainly because the reversal is precessional for \( \tau = 0 \) and \( \tau = 50 \text{ ps} \), whereas damping reversal occurs for \( \tau = 200 \text{ ps} \). As \( H_a \) increases, the reversal time for \( \tau = 200 \text{ ps} \) is nearly a constant up to a certain level (\( H_a = 1.36H_r \approx 0.38H_a \)). However, as \( H_a \) increases (\( H_a > [1.36H_r \approx 0.38H_a] \)), the reversal mode changes from damping to precessional, and the reversal time becomes comparable to those obtained for small values of \( \tau \). This behavior occurs because, in this case, the external field reaches high values for a very short time before the field reaches its maximal value such that reversal occurs in the precessional regime.

B. Strong external fields

Now, consider the case where the applied field \( H_a \) is substantially above the reversal field \( H_r \). Such field is referred to as “strong” field. More specifically, we chose
$H_0 = 0.7H_k \approx 3.5H_p$ and studied the magnetization evolution in the hard layer in the PR regime.

Figure 3 depicts the time dependence of the normalized vertical component of magnetization of the hard layer for different damping constants. For a small $\alpha = 0.02$ several peaks in the magnetization evolution are observed. In this regime, the magnetization returns to the original (top) state multiple times. With an increase of the damping constant the number of oscillations decreases. For instance, for $\alpha = 0.1$ the magnetization returns to the initial state only once. For $\alpha = 0.2$, it does not return to the initial state at all for the chosen parameters. For stronger applied fields more oscillations are obtained. Interestingly, the number of oscillation and the reversal time increase as the rise time decreases.

The increase of the reversal time for the strong external field case is due to the time required for multiple oscillations between two equilibrium states. The frequency of these oscillations is related to the ferromagnetic resonance frequency of the element. This oscillatory behavior is more pronounced for smaller $\alpha$ and $\tau$.

From Fig. 3, one can conclude that there may be a situation where after several oscillations the magnetization remains in the original (top) state so that no reversal will occur. To characterize such oscillatory behavior, consider a pulsed applied field with a finite duration $t_{\text{pulse}}$. The time dependence is chosen as $f(t/\tau) = 1-2\exp(-2t/\tau)$ for $0 < t \leq t_{\text{pulse}}$ and $f(t/\tau) = 2\exp(-2t/\tau)+\exp(-(2t-t_{\text{pulse}})/\tau)$ for $t > t_{\text{pulse}}$. Figure 4 depicts the phase diagram presenting the reversal time as a gray scale map vs. the external field strength and pulse duration for a low dissipative case with $\alpha = 0.01$ and $\tau = 0$. The white scale corresponds to no-reversal case. The darker scale represents a faster reversal. It is evident that for strong applied fields multiple bands of alternative reversal and non-reversal regimes are obtained. This behavior is due to multiple oscillations between the equilibrium states as described in connection with Fig. 3. Under special conditions the final magnetization state is not in the reversed (bottom) position but rather in the original (top) position so that no reversal is obtained. Clearly, the number of oscillations in Fig. 3 and the number of bands in Fig. 4 depends on the rise time and damping constant. For example, for small $\alpha$ the damping in the system is small and many oscillations are possible. Even though such “ringing” reversal time behavior occurs only for rather strong fields, it still may lead to potential problems if media comprising composite elements are used in the PR regime for recording. For a given external field, two approaches can be used to eliminate these oscillations thus reducing the reversal time.

One possible approach is to increase the rise time $\tau$. Figure 5(a) presents the phase diagram for the same structure as Fig. 4 but for a larger rise time $\tau = 40\text{ps}$. It is found that the number of non-reversal ranges is reduces significantly and the reversal time is smaller. This behavior is because for a larger $\tau$ the PR mechanisms are less pronounced thus leading to the reduction of the number of oscillations. However, for the chosen $\tau$ the PR mechanisms are still well pronounced to lead to a substantial reduction of the reversal field compared to the reversal field in the damping regime.

Another way to reduce the number of precessional oscillations is to use materials with a larger damping constant. In Fig. 5(b), the damping constant is chosen as $\alpha = 0.1$. Such damping constant leads to only one narrow “tail” for a large external field $H_0 > 0.6H_p$. This behavior is due to the significantly increased damping in the system. It should be mentioned, however, that even for such a large damping the reversal field is significantly smaller than that obtained in the regime of damping reversal. It is also curious that the reversal time can be smaller for larger $\alpha$ and $\tau$. Similar behavior also was observed in a recent work [16].

V. CONCLUSION

PR in dual-layer PM elements was studied for various applied field. It was shown that PR in such elements takes place with substantially reduced reversal fields and remarkably increased critical rise times. For non-uniform applied fields, PR properties depend significantly on the percentage of the coverage of the element by the external field. For weak external fields, the reversal time decreases with an increase of the external field and decrease of the damping constant and rise time. On the other hand, for strong external fields the reversal time can increase with an increase of the external field, rise time, and damping constant. This behavior is associated with multiple magnetization oscillations between the two equilibrium states in the PR regime. These oscillations can be further eliminated by properly choosing the rise time and damping constant. The presented structures and phenomena can be used for high-density magnetic recording.

REFERENCES


Fig. 1. Normalized reversal field (a) and critical rise time (b) as a function of applied field coverage for $\varphi = 45^\circ$ and $\alpha = 0.1$.

Fig. 2. Reversal time as a function of $H_a$ under the angle $\varphi = 45^\circ$ and $\alpha = 0.1$ for the dual layer element with $\tau = 0$, $\tau = 50$ ps, and $\tau = 200$ ps as well as single layer element with $\tau = 10$ ps. Note that reversal is only possible for $H_a > H_r$.

Fig. 3. Normalized z-component of magnetization of hard layer vs. time. The external field of magnitude $H_z = 0.7H_r$ is applied at the angle $\varphi = 45^\circ$ and $\tau = 0$.

Fig. 4. Reversal time as a gray scale map vs. applied field amplitude and pulse duration for $\alpha = 0.01$ and $\tau = 0$.

Fig. 5. Reversal time as a gray scale map vs. applied field amplitude and pulse duration for (a) $\alpha = 0.01$, $\tau = 40$ ps and (b) $\alpha = 0.1$, $\tau = 0$. 