Analysis of recording in patterned media (PM) with geometry and material fluctuation

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Abstract

Unlike continuous media recording, patterned media (PM) require strict synchronization of the signal misregistration time and the element positions. Here, we propose a scheme that relies on full micromagnetic simulations of the single PM element and allows for the characterization of synchronized PM recording and proper writing probability for different media parameters fluctuations (e.g. anisotropy field and element separation). To elucidate the limits of recording and PM density improvements we introduce the model of idealized recording head. Various PM designs (homogeneous and composite) have been shown to support high areal density scenarios of up to 6.5 Tb/in\textsuperscript{2}. 
Following the ongoing effort for achieving of ultra-high recording densities, patterned media (PM) are envisioned\(^1,^2\). The superparamagnetic effect, writing field bounds and signal-noise ratio (SNR) are principal physical limitations of the recording density\(^3\). It can be overcome by using PM elements of high anisotropy in conjunction with various assisted methods as inclusion of coupled soft layer, heat or microwave energy-assisted schemes \(^4^-^8\). In addition, such fabrication problem as statistical fluctuations of PM element’s parameters, e.g. geometry, anisotropy, and element position, also limits the PM density. Unlike for continuous media recording, PM require strict synchronization of the element position with recording signal. Due to this fact, effects of medium parameter fluctuations can be critical.

In this work, first, we formulate writing window (WW) concept of synchronized PM recording. Next, we study limitations on PM densities due to fluctuations of PM element parameters. In addition, we find density bounds for idealized head taking in account fluctuations. Finally, based on different fluctuation rates we estimate maximally achievable areal density for wide class of PM designs.

In our work we study individual PM bit reversal in one track approach assuming small magnetostatic influence of adjacent bits. That approach does not involve repeatable and expensive simulations of highly spatial PM geometry and it is valid for bit-to-bit spacing greater than half bit size \(^9\). The reversal field deviation produced by adjacent elements is bounded by 5-10\% and could be taken into account by introducing an additional coercivity fluctuation. Taking it in mind consider a recording system comprising two elements of a PM, a soft under layer (SUL), and a recording head moving leftward with a velocity \(v\) as shown in Fig. 1. As an example in this letter, the PM are represented by
exchanged coupled dual-layer elements with parameters in Fig. 1. The head field is expressed by \( \mathbf{H}_a = H_a \mathbf{h}(x-vt, y) f(t) \), where \( H_a \) is the head field magnitude, \( \mathbf{h}(x, y) \) is the spatial shielded head field distribution, \( f(t) = \text{erf} \left( \frac{2(t-t_0)}{\tau} \right) \) is the head time dependence with rise time \( \tau \) and the misregistration time \( t_0 \) w.r.t. the center of the left element. It is assumed that the left element is to be switched whereas the right element has already been written and should not be switched. Our goal is to characterize the influence of the elements parameter fluctuations on the PM recording. Here, we consider fluctuations of the element anisotropy field \( H_K \), which is assumed to have a Gaussian distribution with the mean value \( H_{K0} \) and deviation \( \sigma_K H_{K0} \). The magnetization behavior is modeled numerically by solving the Landau-Lifshitz equation\(^{10} \). The considered two elements allow estimating writing probabilities in the case of realistic PM and clearly explain the obtained results without a need to execute an excessive number of simulations.

Figure 2(a) shows reversal curves, which represent the reversal field \( H_0 \), viz. the value of \( H_a \) allowing for reversal, as a function of misregistration time \( t_0 \) for the two elements (the left and right curve corresponds to the left and right element, respectively). Each curve separates the region where reversal of the corresponding element is possible (left to the curve) and impossible (right to the curve). The area between the curves defines the range of \( H_a \) and \( t_0 \) that permits reversal of the left element but not of the right element.

The observation of two reversal curves and given applied field allows formulating idea of the “writing window” (WW). Actually it is dependence of probability of correct writing vs. misregistration time. WW for chosen level of head field is a result of the \( H_a \) level’s crossing with two reversal curves \( (H_{r1}^{(1)} \text{ and } H_{r1}^{(2)}) \) corresponding to two adjacent
elements. Another interpretation of WW is pulse function due to product of two step functions with regards to those reversal curves.

Choosing value of applied head field we have to keep in mind that minimal as possible level is a best choice. The reason for that preference is nested in fact that recording process for writing head is a sequence of fast switching pulses of different polarity with some rise time. To reach higher level takes more time; hence, it leads to higher rise time and slower recording. On the other hand, setting this level to value close to the low reversal curve causes high sensitivity to PM parameters’ fluctuation and extremely high error probability.

The leading fluctuation producing recording error is related to hard layer’s anisotropy coefficient $K_h = M_s H_k / 2$. Assuming constant saturation magnetization we have the equivalent problem of anisotropy field fluctuation with Gaussian distribution of anisotropy field $H_k$ about $H_{k0}$ with normalized deviation $\sigma_k$:

$$F(H_k, H_{k0}, \sigma_h) = \frac{1}{\sqrt{2\pi} H_{k0}^2 \sigma_k^2} \exp \left( -\left( \frac{H_k - H_{k0}}{\sqrt{2} H_{k0} \sigma_k} \right)^2 \right).$$  \hspace{2cm} (1)

Note, that our operative figure (Fig. 2(a)) is plotted for reversal fields normalized by $H_k$. Hence, anisotropy fluctuation could be explained by curves’ shifting along vertical axis up or down. The writing probability is expressed by next:

$$P_{\text{switch}}^H = \frac{1}{2} \text{erfc} \left( \frac{H_r^{(1)}(t_0) - H_a}{\sqrt{2} H_r^{(1)} \sigma_r} \right) \times \frac{1}{2} \text{erfc} \left( \frac{H_a - H_r^{(2)}(t_0)}{\sqrt{2} H_r^{(2)} \sigma_r} \right),$$  \hspace{2cm} (2)
where $\sigma_r$ is normalized deviation of reversal field due to anisotropy field fluctuation. It could be estimated by

$$\frac{dH_k}{dH_k} \frac{H_{K0}}{H_{r0}} \sigma_k$$

and achieves about $\sigma_k$ for homogeneous and dual-layer element cases. Note, that according (2) probability curves are very sensitive to the level of applied field then applied field is close to the minimal reversal field.

Figure 2(b) shows the writing probability obtained from the results in Figure 2(a) for different $\sigma_k$. As $\sigma_k$ increases the curves are modified from pulse to bell shape. The resulted probability curves depend significantly also on $H_a$ and PM spacing $L$. To have sufficiently wider WWs and lower errors, is required to increase $H_a$ and $L$, which is an important limitation of PM density and writability. Therefore, fluctuations of the PM parameters may crucially limit the PM density. Optimal parameters/PM designs should be found.

To characterize quality of PM recording we introduce WW width $D$, where level of switching probability is slightly less when 1, e.g. 0.99 (it corresponds to bit-error rate BER=0.01). WW width corresponds to the interval of normalized misregistration times where switching probability exceeds that level. WW width is helpful in fluctuation analysis. As it clear from numerous studies $^{3,11}$ PM position fluctuation is not critical for recording up to relevant PM spacing (half element’s width). Hence, the anisotropy fluctuation is crucial in PM recording analysis.

First, in Figure 3(a) we analyze WW width vs. normalized applied field for different anisotropy fluctuation rates with the spacing of $w$. All curves reveal similar behavior: initially, they show zero probability until critical applied field; after that, they increase fast to the high value; finally, they grow slowly or saturate. Lower anisotropy fluctuation
corresponds to smaller critical applied field, sharper increase and higher saturation level. Obviously, only head field exceeding critical applied field provides recording with required switching probability for given spacing. According this figure it is impossible to obtain required recording for \( H_s = 0.45H_i \) and \( \sigma_k = 0.15 \). Hence, possibility of higher spacing should be verified.

Figure 3(b) depicts the dependence of WW width at BER=0.01 vs. the PM spacing for \( H_s = 0.45H_i \) and for different \( \sigma_k \). It is evident, that higher fluctuation corresponds to lower window widths. Note, that for a given \( \sigma_k \), there is a minimal allowed distance (i.e. maximal recording density) which is allowed, i.e. the density is limited by the fluctuation rate.

Obviously, a proper PM recording in the presence of fluctuations is highly sensitive to writing head field distribution. To clarify limits of the recording with fluctuation we will investigate WW and WW width for the case of idealized recording head. The recording field distribution is expressed by pulse function below the idealized head. The applied field angle is set to 45° and 30° to obtain minimal reversal field in regimes of damping or fast precessional switching in homogeneous and composite element respectively12,13.

The obtained reversal curve for the case of \( \alpha = 0.1; \Delta = 0.2 \) has sufficiently strong gradient: it rises from saturation level of 0.28 to 2.02 in the interval from 1 to -0.25. Based on that curve we obtain lower applied field values of proper PM recording. For instance, in the case of 15% anisotropy fluctuation it falls from 0.6 to 0.36. Thus, idealized head recording supports reduced PM spacing and higher PM density. Next, we analyze WW dependence on PM spacing for applied field and for different anisotropy fluctuation as previously. The advantage with previous head is much pronounced for the
case of 15% anisotropy fluctuation: we observe proper recording starting from $0.7L/w$. It is essential improvement in comparison with $1.3L/w$ of the previous head. Obviously, idealized head provides proper PM recording for lower applied fields too.

Next, we focus on designing a recording system that permits high PM density even for significant anisotropy fluctuation rates. Using the standard Arrhenius–Néel theory of thermostability, an energy barrier of 45 kT is found to be sufficient to withstand temperature of 400K for a 10 years. To estimate the potential of the various scenarios, anisotropy fluctuation $\sigma_x$ is set to 0.05, 0.10 and 0.15; applied field is limited by 15 kOe and critical WW width $D$ is bounded by $w/2$. The critical PM densities for four recording systems comprising all combinations of single and dual-layered PM and of two recording heads are summarized in Table I. The study assesses composite PM as more progressive when homogeneous. It is evident from comparison of data in lines 1-3 and 2-4, which results in factor 3 and 2 for relevant heads. The potential of recording head improvement is optimistically looking too. For example of 0.05 fluctuation rate, in the case of homogeneous PM it permits for density enhancement from 1.57 to 3.14 Tbi$^2$; and for dual-layer PM from 4.93 to 6.31 Tbi$^2$. All scenarios show that the PM density quickly deteriorates at higher anisotropy fluctuation rates (the test fluctuation values are 0.05 and 0.15) with factor 2.5 and 2 for real and idealized recording head respectively.

In conclusion, we proposed WW formulation based on single PM element’s reversal permitting reliable synchronized recording by various anisotropy fluctuation account. Those fluctuations are inevitably counterproductive for achieving higher PM density. Various PM optimization designs were proposed to overcome fluctuation issue. The
bounds of PM density enhancement were studied by idealized head application. The highest PM densities require composite media and idealized recording head. Reasonable margins can be obtained up to 6.31 Tb/in².
Reference

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<tr>
<th>PM recording system</th>
<th>Element parameters</th>
<th>PM density,Tb/in² for different $\sigma_x$</th>
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<tr>
<td></td>
<td>$H_s$,kOe</td>
<td>$M_s$,emu/cc</td>
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<td>Homogeneous+ real head</td>
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<tr>
<td>Dual layered + idealized head</td>
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<td>1,350</td>
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</table>

TABLE I. Various PM designs with a real or idealized recording head and soft underlayer for different rates of anisotropy fluctuation.
\( v = 10 \text{ m/s} \), \( w = 10 \text{ nm} \), \( v/w = 10^9 \)

\( \Delta_{\alpha} = v t_0 / w \), \( \tau = 0.2 \text{ ns} \)

Write head field components,

Vertical component: \( h = w / 5 \)

Horizontal component: \( d = w / 4 \)

\( \nu t_0 \)

 Coordinate in down track direction,

\( h = w / 5 \) \( L \) \( w/2 \) \( w/2 \)

\( K = 0 \) \( \alpha = 0.1 \)

\( k_s = 3.75 \times 10^4 \text{ erg/cm}^3 \)

\( M_s = 500 \text{ emu/cm}^2 \)

\( l_{sr} = w \)
Switching probability, $P_{\text{switch}}$

$\sigma_K = 0.05 \beta_k$

$\sigma_K = 0.1 \beta_k$

$\sigma_K = 0.15 \beta_k$

$\sigma_K = 0$

$H_{r_0}(\Delta_{r_0})$

$H_{r_0}(\Delta_{r_0})$

Normalized misregistration, $\Delta_{r_0}$

Normalized reversal field, $H_{r_0} / \beta_k$

Level of head field

Reversal field for dot to be recorded

Reversal field for dot recorded previously

(2) $rtH$

(1) $rtH$

(a)

(b)
Fig. 3. a) Normalized window width vs. normalized applied field for different anisotropy fluctuations and b) normalized window width vs. normalized spacing for different anisotropy fluctuations and $H_a = 0.45H_k$. 