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MICROMAGNETICS OF COMPOSITE PATTERNED MEDIA

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Introduction

Magnetic recording currently is the major data storage technology. Conventional magnetic media implement continuous magnetic layers consisting of microscopic grains. Such media have constraints of thermal instability due to the superparamagnetic effect, which occurs when the magnetic grains become too small. The superparamagnetic effect may set the fundamental limit of about 0.5Tbit/in^{2}on achievable densities of storage. Overcoming this constraint is one of the key challenges in the modern hard drive industry.

One of the most promising solutions to overcome the superparamagetic effect is to use patterned magnetic media, which comprise arrays of physically separated magnetic elements with perpendicular anisotropy [1-4]. Patterned media allow eliminating any transition noise and are intended to support area densities of storage of more than 1Tbit/in^2. Further improvements can be achieved by using composite structures, where every medium element is composed of two or more layers with different anisotropy that are ferromagnetically coupled through their common interfaces [5-9]. Such media allow switching hard layers with very high anisotropy, thus enhancing the thermal stability.

The goal of this work is to pursue a thorough study of reversal mechanisms in individual and arrayed elements of composite patterned media for a variety of reasonable magnetic and geometric parameters and to assess effects of these parameters on magnetic recording, including the investigation of the sensitivity of reversal field to timing errors and synchronization margins. The analysis is based on accurate micromagnetic simulations that make no assumptions on the medium parameters.

Structure configurations and method of analysis

The reversal mechanisms are modeled by the Landau-Lifshitz equation [10]:

$$\frac{d\mathbf{m}}{dt} = -\gamma H_K \mathbf{m}\times\mathbf{H}_{\text{eff}} - \alpha\gamma H_K\left(\mathbf{m}\times\left(\mathbf{m}\times\mathbf{H}_{\text{eff}}\right)\right) \tag{1}$$

where $\mathbf{m}=\mathbf{M}/M_s$ is the magnetization $\mathbf{M}$ normalized by the saturation magnetization M_s , t is time, γ is the gyromagnetic ratio, and α is the damping coefficient. The first and second terms in the right hand side of Eq. (1) represent gyromagnetic precession and torque components. The effective field $\mathbf{H}_{\text{eff}}$ is normalized by the element crystalline anisotropy H_k and is given by

$$\mathbf{H}_{eff} = (\mathbf{k} \cdot \mathbf{m})\mathbf{k} + \frac{\mathbf{H}_{ext}}{H_k} + 2\frac{M_s}{H_k} l_{ex}^2 \nabla^2 \mathbf{m} + \frac{M_s}{H_k} \nabla \int \frac{\nabla \cdot \mathbf{m}}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r}' \tag{2}$$

where the first, second, third, and fourth terms represent the normalized perpendicular uniaxial anisotropy field, external (reversal) field, exchange field, and magnetostatic field, respectively. In addition, $l_{ex} = A^{1/2}/M_s$ is the exchange length with A the exchange constant.

For numerical implementation, the patterned medium elements are discretized into small cells. The magnetostatic field $\mathbf{H}_{stat}$ is determined by allowing for non-uniform magnetization in each cell. All differential operators are evaluated using the second order finite difference scheme. The computation of the magnetostatic field can be accelerated by non-uniform grid algorithms [11, 12]. The techniques developed were used to study basic reversal mechanisms occurring in composite patterned media with perpendicular anisotropy under uniform and non-uniform reversal fields.

Simulation results

To demonstrate properties of composite patterned media, consider a configuration comprising an array of dual layer magnetic dots, recording head, and soft underlayer (SUL) (Fig. 1(a)). In the horizontal cross-section, the dots are square and have size w. In the vertical dimension, every dot is composed of two layers of identical thickness $t_h = t_s = w/2$. The bottom and top layers are magnetically hard (high K_h) and soft ($K_s = 0$), respectively (Fig. 1(b)). The two layers are coupled through their common interface with an exchange energy per surface area J_s.

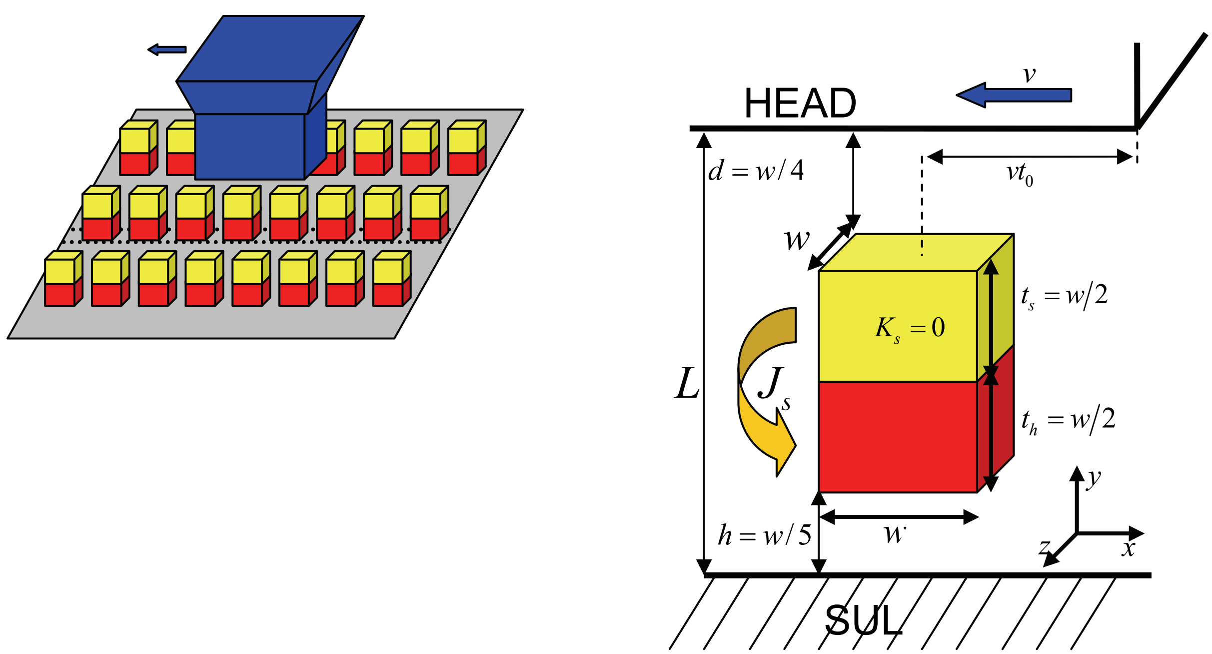

Fig. 1: (a) Dual layer patterned medium. (b) Dual layer dot near an SUL under a moving recording head

First, consider a model where $\mathbf{H}_{\text{ext}} = H_{\text{ext}}(x)\,\hat{\mathbf{y}}$ is applied to a single dot. The field is applied uniformly across the width (*z* dimension in Fig. 1(b)) and through the height (*y* dimension) of the dot, but only over varying percentages of the length (*x*) direction. Figure 2(a) plots the normalized reversal field H_r / H_k versus normalized exchange coupling per area $J_s/(2K_h t_h)$. Two phenomena are observed. First, for all curves, there exists an optimal value of $J_s / (K_h t_h) \approx 0.32$ leading to the minimal reversal field, which agrees qualitatively with approximate results of recent analytical works [8, 9]. Second, the reversal fields for smaller percentages of the dot coverage increased only by a relatively small amount. The weak increase is associated with highly non-uniform reversal mechanism [4]. It is worthwhile mentioning that all (scaled) results in Fig. 2(a) remain valid for *any* value of the damping constant α ranging from very small (e.g. $a = 0.01$) to very large (e.g. $a = 1$).

Next, consider a structure that, in addition to the dual layer magnetic dots, incorporates a semi-infinite head moving leftward with a velocity v (Fig. 1(b)). The head field is given by $\mathbf{H}_{\text{r}} = H_{r0}\psi(x - vt, y)\, f(t)$, where H_{r0} is the head (reversal) field magnitude, $\psi(x,y)$ represents the spatial distribution of the head field [13], $f(t) = (1\text{-}erfc[(t - t_0)/\tau])$ is the function describing the head time dependence with rise time τ and switching time t_0 (i.e. the instant of time when the head switches its field to become positive; $t_0 = 0$ corresponds to the head corner located at the dot center). Figure 2(b) depicts the reversal field vs. normalized time $\Delta_{t0} = vt_0/w$ for different normalized rise times $\Delta_r = vt_0/w$ and different damping constants α. Large positive Δ_{t0} correspond to the dot being in the uniform vertical head field so that the reversal is achieved for low H_{r0}. Negative values of Δ_{t0} correspond to the head's corner being shifted left to the dot so that the reversal can be achieved only for high values of H_{r0}. It is further evident that larger values of τ lead to higher H_{r0} as the dot is exposed to a larger field for a shorter time. It is worthwhile mentioning that for small τ, there is a significant difference in the reversal field in the high damping (α = 1) and low damping (α = 0.01) regimes, whereas in the case of large τ the difference is minor. The reason for the difference is ultra-fast precessional switching occurring when applied fields have tilted components, the damping parameter is low, and the applied field rise time is short [14]. Note that every curve in Fig. 2(b) is a border between the values of H_{r0} and t_0 that allow reversal (the region to the right of the curve) and does not allow the reversal (the region to the left of the curve). These results are important for phase margin assessments for patterned media.

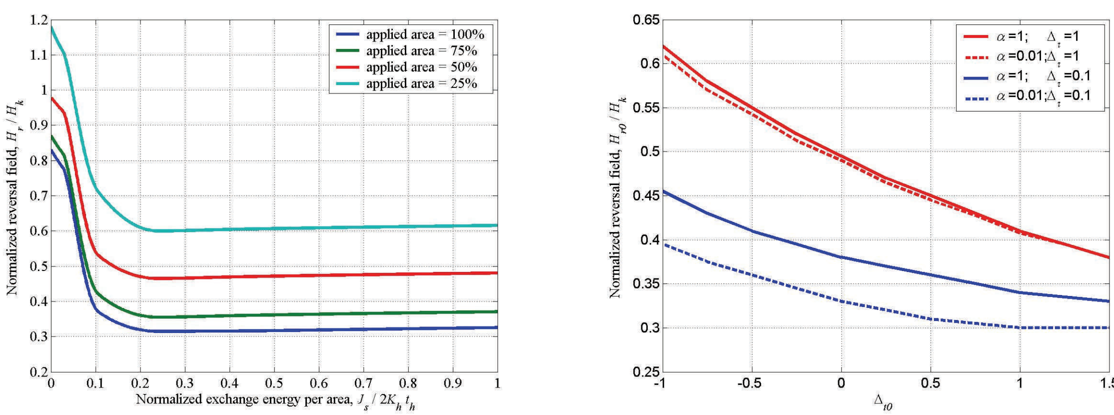

Fig. 2: (a) Normalized reversal field vs. normalized exchange surface coupling for non-uniform reversal fields applied for different area percentages of the composite dot. (b) Normalized reversal field vs. normalized starting time for different switching rise times. In all simulations, the structure parameters were $M_s = 500$ emu/cc, $H_k = 15$kOe, $l_{ex} = w$, and $v/w = 10^9$ s^{-1}.

Summary

Magnetization reversal mechanisms in dual (soft and hard) layer elements with parameters suitable for patterned media recording at more than 1Tbit/in^2 have been studied under uniform and non-uniform fields by means of accurate micromagnetic simulations based on the Landau-Lifshitz equation. Optimal ferromagnetic coupling between the soft and hard layers was found that lead to small reversal fields even for very large anisotropy in the hard layer. Under non-uniform fields, only a slight increase of the applied field was required for reversal. In addition, results for timing margins and head fields allowing reversal of the dual layer elements were obtained for a moving semi-infinite head for reasonable medium and head parameters. The effects identified have important consequences in magnetic recording for both down track and cross track phenomena.

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