Capped bit patterned media for high density magnetic recording

Shaojing Li¹², Boris Livshitz¹², H. Neal Bertram²³, Akihiro Inomata⁴, Eric E. Fullerton¹², and Vitaliy Lomakin¹²

¹Department of Electrical and Computer Engineering, University of California, San Diego, CA
²Center for Magnetic Recording Research, University of California, San Diego, CA
³Hitachi San Jose Research Center, Hitachi GST, San Jose, CA
⁴Storage and Intelligent Systems Laboratories, Fujitsu Laboratories Ltd., Japan

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Abstract

A capped composite patterned medium design is described which comprises an array of hard elements exchange coupled to a continuous cap layer. The role of the cap layer is to lower the write field of the individual hard element and introduce ferromagnetic exchange interactions between hard elements to compensate the magnetostatic interactions. Modeling results show significantly reduction in the reversal field distributions caused by the magnetization states in the array which is important to prevent bit-errors and increase achievable recording densities.
1. Introduction

Bit patterned media (BPM) comprised of lithographically-defined arrays of separated magnetic islands, are envisioned to overcome magnetic recording density limitations due to transitional noise and the superparamagnetic effect$^{1,2}$. BPM can comprise arrays of simple homogeneous elements or exchange-coupled (composite) elements to achieve reduced reversal fields$^{3-7}$. A potential problem of BPM based on separated elements is that the magnetostatic interactions between the BPM elements can lead to significant distributions of the reversal field caused by distributions of the magnetization states of the neighboring array elements. These distributions lead to bit-errors and can significantly limit the BPM recording densities$^8$.

In this paper, we propose a new capped BPM (CBPM) configuration that consists of an array of hard elements and a continuous soft layer, referred to as a “capping layer”, which is placed on top or at the bottom of the array and is ferromagnetically coupled to the array’s elements through their common interfaces. The motivation to introduce this structure is that, similar to coupled continuous-granular (CGC) perpendicular recording media$^9$, the soft layer provides a mechanism for the coupling between the hard elements through the exchange field. Since the exchange and magnetostatic fields have opposite signs, conditions can be found that lead to compensating the effects due to these two types of coupling. As a result, the distributions of the recorded states in the introduced capped BPM array do not lead to significant distributions of the switching field.

2. Structure configuration

The proposed CBPM comprises hard elements that are arranged into an array coupled from the bottom or the top to a continuous soft layer with a surface energy $sJ$ through the common interfaces. The hard elements have a vertical uniaxial anisotropy of energy density $hK$, length $a_x$, width $a_y$, and thickness $ht$. The capping layer has thickness $st$ and is assumed to be perfectly soft. All materials have a damping constant $\alpha$, saturation magnetization $sM$, and exchange length $AAMw = \frac{\alpha}{M_s}$ with $A$ the exchange constant. The spacing between the hard elements in the CBPM array is $B$.

An external field $H_{ext} = -H_a \text{erf}(2t/\tau)(\hat{z}\cos\varphi + \hat{x}\sin\varphi)$ is applied under an angle $\varphi$ to the vertical axis uniformly through the height of the soft and hard parts but only to the area determined by a hard element. For a field $H_a > H_r$ with reversal field $H_r$, the magnetization in the element under the field switches from the initial $\hat{z}$ to the $-\hat{z}$ state. To characterize effects of the interactions between the hard elements, we compare the reversal field for two scenarios. In the first (parallel) scenario all the elements have the same magnetization state, whereas in the second (opposite) scenario the elements neighboring the middle element have an opposite magnetization state. These scenarios lead to different reversal fields, hence reversal field distribution$^{10}$. Reducing such reversal field distribution compared to conventional...
homogenous and composite BMP is the main goal of this work. For the chosen uniform applied field, both CBPM configurations, i.e. the one with the capping layer on the top and bottom, have the same reversal field.

The reversal fields of the CBPM structure are studied by numerically solving the Landau-Lifshitz-Gilbert equation\(^{11-14}\) with discretization chosen to obtain convergence. In all simulations, \(M_s = 1250\text{emu/cm}^3\), \(\tau = 0.1\text{ns}\), \(H_K = 2K_s/M_s = 60\text{kOe}\), and \(\phi = 45^\circ\). The damping constant varies in the range between \(\alpha = 1\) and \(\alpha = 0.1\), which with a chosen field rise time \(\tau\) corresponds to damping and precessional reversal regime, respectively\(^{11,12}\).

3. Recording and reversal field distributions

To characterize reversal properties of the proposed CBPM structures, we considered a linear array of three hard elements coupled to a continuous capping layer. We first compare the dependence of the reversal field \(H_r\) vs. the element spacing \(B - w\) for three different types of BPM in the damping regime (obtained for large \(1/\alpha = 1\)). Figures 1(a) and (b) show the reversal curves for homogeneous and dual-layer composite BPM arrays\(^{10-12}\). As expected, due to magnetostatic interactions, the reversal fields are smaller for the parallel arrangement and the gap between the reversal fields in the two scenarios decreases with increasing element separation. This gap can be significant for smaller separations between the elements and restrict the achievable recording densities due to the resulting reversal field distributions and inability to provide a proper writing window\(^{15}\). For example for \((B - w)/w = 1\), the relative gap given by \(2|H_{r1} - H_{r2}|/(H_{r1} + H_{r2})\) is 1.6% and 3.3% for the BPM arrays comprising homogenous and composite elements. If newly proposed “ledge” composite media is used, this distribution is even more significant.\(^{13,16,17}\) The increased gap in the composite case is due to a stronger influence of the magnetostatic field on the soft section of the composite elements combined with the lower coercive field of the composite structure.

The reversal field behavior is very different for the capped structure. From Fig. 1(c), it is evident that for the chosen parameters \(H_r\) is larger for the antiparallel configuration for small enough separation between the elements. This behavior, which is opposite to that obtained in Figs. 1(a) and (b), is a manifestation of the exchange field interactions between the hard elements through the cap layer. The exchange field tends to align nearby spins in the same direction and transfers this influence to the hard elements via their ferromagnetically coupled common interfaces. This exchange influence is strong for small inter-element separations but reduces rapidly for larger separations. Since the magnetostatic and exchange interactions have opposite effects to the reversal field, a balancing point can be found where there is no distribution of the reversal field is present. For the parameters in Fig. 1(c), this is achieved for \((B - w)/w = 1\). For larger
separations, some distribution is present, however this distribution is much smaller than that obtained for disconnected (homogeneous and composite) arrays.

The behavior of the reversal curves, the balancing point, and the distributions of the reversal field can be optimized by carefully choosing the structure parameters. Fig. 2(a) shows the reversal curves of the CBPM for different thicknesses of the capping layer. It evident that thicker capping layers lead to lower reversal fields\textsuperscript{13}. However, for the compensation phenomenon, the thickness of cap layer is less important. All curves are similar with balance points obtained near \((B - w)/w = 1\).

The balancing point and reversal curve behavior can be tuned by changing the strength of the exchange interactions between the hard elements in the array, which is closely related to the coupling strength between soft cap layer and hard element. Figure 2(b) shows the reversal field as a function of the elements’ spacing for three different normalized coupling strength \(j_s = 0.15\), \(j_s = 0.3\) and \(j_s = 0.45\), which are defined via \(j_s = J_s / (2K_s t_s)\) and corresponds to \(J_s = 5.6 \times 10^8 t_s\), \(J_s = 11.25 \times 10^8 t_s\) and \(J_s = 22.5 \times 10^8 t_s\), respectively. All other parameters are as in Fig. 2(a). The “optimal” exchange coupling for the given parameters is found to be \(j_s = 0.15\) as it leads to an almost flat reversal field behavior over the entire \(1 < (B - w)/w < 2\) range with the balancing point at \((B - w)/w = 0.9\).

We have also considered the influence of a finite anisotropy in the soft capping layer. The obtained behavior was similar with some quantitative differences in terms of the optimal choice of the balancing point. In addition, we studied the CBPM in the regime of precessional reversal, which is obtained for under sufficiently short (but practical for the composite elements) rise times\textsuperscript{11,12}. Similar compensation phenomena were obtained apart from an additional reduction of the reversal field associated with precessional mechanisms\textsuperscript{11,12}. Again, quantitatively, the balance point was somewhat different for the same structure parameters but it can be tuned. The curve behavior may have some additional features including slight dips in the parallel reversal scenario. The thickness of cap layer was found to have somewhat more significant effects. For all consider CBPM, one can tune the structure parameters, including \(J_s, t_s\) and the anisotropy of the capping layer, to find optimal balance between he magnetostatic and exchange interactions.

4. Readback process

In addition to altering the writing process the introduction of the capping layer is also expected to affect the readback signal. The readback signal was calculated using reciprocity and approximate expressions for the head field\textsuperscript{18}. We find pronounced differences for CBPM with the capping layer on the top and at the bottom of the hard element array and for different bit separations.
Figure 3 shows the readback voltage of an interleaved bit pattern of six elements for a conventional composite (dual-layer) media, CBPM with capping layer on top, and capped media with capping layer at the bottom (“reverse cap”). For conventional composite media, the readback signal is nearly insensitive to whether the soft section on the top or bottom.

For bit spacing greater than $B > 2w$ ($B = 2w$ in Fig. 3(a)), the readback signals for all considered cases are similar with some differences at the left and right edges. For smaller spacing between the elements ($B = 1.6w$ in Fig. 3(b)), the readback signal decreases noticeably for the CBPM with the capping layer on top. This reduction of the readback signal is obtained because the magnetization states in the soft capping layer change rapidly between elements while the hard elements are at a larger distance from the read head. On the other hand, for the CBPM with the capping layer at the bottom of the array, the readback signal slightly increases with the approximately the same transition width. This is because the hard elements are close to the read head. It is noted that while leading to improvements in terms of the readback signal, the arrangement with the capping layer on the bottom may lead to a somewhat higher reversal field for non-uniform applied (head) fields with the field decreases in the vertical dimension. Optimal medium parameters should be found as a trade-off between read-and write-field requirements. It is also noted that the differences in the readback signal are due to effects of the magnetization distribution in the capping layer. Due to the high anisotropy, the magnetization distribution in the hard elements was mostly uniform in all considered cases.

Finally, it should be mentioned that the capping layer does not directly introduce transitional noise as in conventional granular media since it is assumed to be made of perfectly soft continuous material. However, noise can be introduced by distributions of the hard elements’ position, material properties, and shape as in conventional BPM.

5. Summary

We introduced a CBPM configuration that comprises an array of hard elements coupled to a continuous soft layer. The reversal field of the CBPM can be at the level similar to conventional composite elements, which is substantially lower than that for homogenous element. At the same time, the cap layer provides a mechanism of inter-element exchange coupling that can compensate the effects of magnetostatic field interactions between the array elements. Optimal structure parameters can be chosen to lead to significantly reduced reversal field distributions caused by the magnetostatic fields associated with distributions of the magnetization states in a BPM array. This can allow for lower bit-error rates and can improve the BPM performance. The readback signal is not noticeably degraded compared to conventional media.

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Fig.1: Normalized reversal field $H_r/H_s$ vs. the hard element spacing $(B-w)/w$ for three BPM structures and two magnetization configurations for each structure. The structure parameters are $\alpha = 1$, $l_e = w$, $M_s = 1250 \text{ emu/cm}^3$, $H_k = 60\text{KOE}$, $J_s = 0.6K_d t_h$, and $t_h = w/2$. 
Fig. 2: (a) Normalized reversal field $H_r/H_k$ vs. the hard element spacing $(B-w)/w$ for different cap layer thicknesses for $t_a = w/2$, in damping regime. (b) Normalized reversal field $H_r/H_k$ vs. hard element spacing $(B-w)/w$ for different normalized coupling surface energies $j_s = J_s/(2K_a t_a)$; for all three cases $t_h = t_s$. 
Fig. 3: The readback signal of an interleaved bit pattern from a double shielded reading head (shown in inset), for three different material structures: conventional patterned media, the “cap” media and the “inverse cap” media. The spacing between the elements in (a) is the same of the hard element width; (b) 60% of the hard element width. The parameters of the read head defined in the inset are \(d = t_h, t = 0.4t_h, g = 1.5t_h\).