Antiferromagnetically coupled capped bit patterned media: Writability, switching field distributions, and readback regulation

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We report on the enhanced performance of a novel antiferromagnetically coupled capped bit patterned media design in terms of three major aspects relevant to magnetic recording: writability, switching field distributions (SFDs), and readback response. The media consists of a two-dimensional array of patterned dots antiferromagnetically coupled from above to a continuous capping layer. The dots may be homogeneous nanoparticles or exchange-coupled composite elements (ECC) with improved writability. Lateral and vertical exchange (LVE) is introduced in the system through the coupling with the capping layer. This provides important magnetostatic and exchange interactions needed to compensate the dipolar contribution to SFDs. Additionally, the interplay of AF coupling and LVE results in a self-regulated readback response distinguished by ample signal strength and diminished magnetostatic interference from neighboring bits.

The current state of the art in hard disk drive (HDD) technology is perpendicular magnetic recording (PMR), with an estimated areal density limit of about 1Tb/in² (1). To achieve areal densities beyond 1Tb/in² the size of the bits must be reduced without jeopardizing thermal stability or writability. This will be difficult to realize on continuous polycrystalline media used in PMR due to problems of transitional noise and the superparamagnetic effect (2) (3). To overcome these difficulties, a new approach to information storage is being developed, known as bit patterned media (BPM), where data is stored magnetically on predefined single-domain islands (4) (5) (6) (7) (8). Superior areal densities are achieved through the elimination of transitional noise and the deferral of superparamagnetism.

While BPM will extend the accessible areal densities of magnetic storage, it will face similar challenges as PMR as device geometry is reduced to smaller dimensions. The problem of writability reemerges at very high areal densities, where, in order to reciprocate for reduced bit sizes and maintain thermal stability, the anisotropy must be increased to such values that the switching fields may no longer be within the range of conventional write heads. Furthermore, high proximity of patterned bits at ultra-high densities implies exacerbated dipolar interactions resulting in a significant broadening of switching field distributions (SFDs). The capacity to resolve the magnetization of the recorded bits also diminishes, as inter-bit spacing shrinks, and magnetostatic interference from neighboring bits increases. Heightened writability requirements, enlarged SFDs, and a diluted readback jeopardize information integrity, hindering the climb to exceptional areal densities (2) (9) (10) (11).

To address these challenges we present a novel model of BPM characterized by improved writability, reduced switching field distributions (SFDs), and a self-regulated readback response. The design consists of a two-dimensional array of patterned particles antiferromagnetically coupled from above to a continuous low-anisotropy film (Fig. 1), called the capping layer (12). The particles may be homogeneous, or exchange-coupled composite (ECC) elements consisting of a magnetically hard and soft section (13) (14) (15) (16). We employ the latter due to their improved writability and diminished sensitivity to distributions in anisotropy energy and easy-axis direction (17). Lateral and vertical exchange (LVE) is established through the coupling of the bits with the continuous capping layer. This provides the important exchange interactions necessary for the SFD reduction (12) (18) and readback regulation mechanisms. Antiferromagnetic coupling is introduced to assist LVE in mediating readback response, but also to actuate a secondary mechanism of SFD reduction operating at longer range via magnetostatic...
interactions. This is important in ultra-high density media with closely packed bits where even the second nearest neighbors (and beyond) can have a substantial influence on SFDs. We show that the recording and readback performance of the proposed media is superior to the performance of a number of recently reported and other possible BPM designs (8) (14) (12) (19).

To investigate the switching field behavior and readback response of AFC capped composite BPM (AFC CCBPM), we employ micromagnetic simulations based on the Landau-Lifshitz-Gilbert equation, taking into account all energy terms via the effective field, and ensuring good convergence through proper discretization (12) (20) (21) (22) (23).

The simulated structure is a five-by-five array of identical, equally spaced, ECC elements antiferromagnetically coupled to a continuous capping layer [Fig. 1]. Material parameters and media geometry, shown in the caption of Fig. 1, corresponds to an areal density of 4Tb/in² and a thermal stability $KV = 61 k_B T$ of the hard elements (at 400 K). In all the simulations the recording field is applied uniformly over a region of space defined by the central ECC element and the fraction of capping layer beneath it. The dependence of the switching field on the magnetization states of surrounding bits is determined in order to characterize SFDs.

Figure 2a shows the behavior of the switching field of the central element, $H_{SW}$, with respect to the number $Z$ of neighboring elements oriented upwards, ranging from $Z = 1$, when only one nearest neighbor is oriented upwards, to $Z = 8 + 16 = 24$, when all first and second nearest neighbor are pointing up. Though the same $Z$ may be obtained by different combinations of magnetization states of neighboring bits, for simplicity we only present switching fields computed for select configurations. The triangular (blue) and square (green) plot markers correspond to data obtained when the initial magnetization of the central bit was directed upwards and downwards, respectively. The range spanned by the data points (shaded pink) indicates the width of the SFD. All data points are within 4% of the mean switching field, which indicates a narrow SFD width.

Same numerical calculations were performed for other reported and possible BPM designs (listed in the caption to Fig. 2b) for equal areal density, and the same material parameters (when applicable) (footnote, optimize cbpm). Due to concerns involving planarization and write-field gradients (24) (25), the net thickness of the pillars (homogenous or composite) was chosen to be 10 nm for all designs, except for the tri-layer composite structure, with thickness $4 \text{ nm} + 6 \text{ nm} + 4 \text{ nm} = 14 \text{ nm}$. Performance in terms of switching fields and SFDs for the different models is summarized in the chart of Fig. 2b.

Composite BPM is seen (Fig. 2b) to be remarkably successful at reducing switching fields in comparison to homogeneous BPM, but suffers from a large SFD due to an increased net moment. AFC composite BPM, on the other hand, noticeably lowers SFDs, but has the disadvantage of heightened switching fields resulting from AF coupling. The apparent trade-off between the two quantities is partially resolved for the case of capped BPM, and tri-layer composite BPM with ferromagnetic coupling at one interface and reduced antiferromagnetic coupling at the other, the disadvantage of the latter being excessive necessary tallness of patterned elements. It is only with AFC CCBPM that the trade-off between switching fields and SFDs is eliminated and a simultaneous and significant reduction in both quantities is achieved. Improved performance can be accredited to the wide range of tuning parameters afforded by the multilayer structure, which enable independent reductions in SFDs and switching field strengths through proper optimization of AF coupling and LVE exchange in the system.

The reciprocity principle (26) has been used to calculate the readback response for AFC CCBPM and other BPM designs. The read head was modeled as a finite width MR sensor and infinitely wide shields, following the procedure outlined in Ref. (27) and (28). Head width was chosen to be $W = 15 \text{ nm}$, with a thickness of the MR sensor $t = 3 \text{ nm}$, and a gap between sensor and shield $g = 15 \text{ nm}$. The pattern of magnetization states used in the reciprocity calculation is displayed in the diagram of Fig. 3a. Such a pattern has been selected to emphasize the magnetostatic interference (or screening) effects neighboring bits can have on the central element during readback,
when the dimensions of the head, due to technological limitations, do not ideally conform to the media geometry. The plots in Fig. 3b and 3c indicate the signal strength obtained when the read head flies at a height of $h = 5$ nm over the media along the path defined by the red line in Fig. 3a. For ECC BPM the screening effects are very pronounced (Fig. 3b), due to the large net moment of the highly proximal composite elements. A more robust signal results from AFC CCBPM, where interference effects are compensated by the AF coupled capping layer, leading to a more consistent waveform (Fig. 3c). Comparing the peak-to-trough amplitude between the two models we note the up and down magnetization states are three times more distinguishable for the case of AFC CCBPM then for ECC BPM, in this comparison.

Figure 3d emphasizes the importance of the spin configuration of the capping layer in modulating readback. For the pattern shown, the moments in the cap are antiparallel to the magnetization of the surrounding bits, but normal to that of the central bit. Consequently, the extent to which neighboring bits interfere in the readback of the central bit is substantially reduced with no detraction from the central bit’s contribution to the signal intensity. More generally, the capping layer moments will point to a larger extent out-of-plane as the number of equally oriented bits in a particular region increases (29). In the case of a random distribution of states, the magnetization of the capping layer will point entirely in-plane and not participate in readback regulation. That regulation is not necessary for this case is clear, considering that the stray fields originating form the uncorrelated bits will themselves be uncorrelated, and cancel out.

In conclusion, we have presented results showing that heterogeneous antiferromagnetically coupled bit patterned media characterized by lateral and vertical exchange has the capacity to address concerns of writability, switching field distributions, and readback simultaneously. This is accomplished through the prosperous interplay of antiferromagnetic coupling and lateral and vertical exchange, and through the availability of a wider selection of tuning parameters offered by the antiferromagnetically coupled capped composite bit patterned media structure which admits greater operational flexibility and versatility of performance, not affordable by other BPM designs. The self-regulated readback response distinctive of AFC CCBPM provides a means to improve signal shape and reduce bit errors occurring during the reading process, without relying on the current state of the art in read head technology.
FIG. 1. Illustration of the proposed AFC CCBPM design, showing a five-by-five array of ECC elements antiferromagnetically coupled to a continuous capping layer. The ECC elements, have a interbit spacing $\Delta b = 6 \text{ nm}$, pitch $w = 6 \text{ nm}$, and bit aspect ratio 1:1. Thickness, saturation magnetization, and anisotropy energy density of the three layers are: (hard layer) $t_h = 6 \text{ nm}$, $M_{S,h} = 900 \text{ emu/cm}^3$, $K_{U,h} = 15.75 \times 10^6 \text{ erg/cm}^3$ ($H_K = 35 \text{ kOe}$); (soft layer) $t_s = 4 \text{ nm}$, $M_{S,s} = 1200 \text{ emu/cm}^3$, $K_{U,s} = 0.1 K_{U,h}$; (capping layer) $t_{cap} = 4 \text{ nm}$, $M_{S,cap} = 1165 \text{ emu/cm}^3$, $K_{U,cap} = 0.36 K_{U,h}$. The interfacial exchange energy densities for the hard layer/soft layer and capping layer/hard layer interface are $J_{h/s} = 20 \text{ erg/cm}^2$ and $J_{h/cap} = -8.33 \text{ erg/cm}^2$, correspondingly. The exchange coupling constant (intrinsic) and damping constant are $A = 1.0 \times 10^{-6} \text{ erg/cm}$ and $\alpha = 1$ for all materials.
Fig. 2. Switching fields of the central bit for different magnetization patterns of surrounding bits. The horizontal axis indicates the number of surrounding bits oriented upwards. Triangular (blue) and square (green) markers correspond to data obtained when the initial magnetization of the central bit was directed upwards and downwards, respectively. The range spanned by the data, shaded in pink, indicates the width of the SFDs.
Comparison of switching fields $\langle H_{SW} \rangle / H_K$ and SFDs $\Delta H_{SW} / \langle H_{SW} \rangle$ for homogeneous BPM (HBPM), ferromagnetically coupled composite BPM (FC ECC), AFC ECC, capped BPM (CBPM), FC/AFC trilayer composite BPM (FC/AFC ECC), and AFC CCBPM. Here, $\langle H_{SW} \rangle$ indicates the mean switching field, $H_K$ represents the anisotropy field of the hard layer, and $\Delta H_{SW}$ signifies the maximum discrepancy between any two switching fields (as illustrated by the pink shading in Fig. 2a for AFC CCBPM).

FIG. 4. (a) Schematic view of a 7x7 array of patterned bits. Magnetization states are indicated by color, back representing upward orientation, and pink downward orientation. (b) Normalized readback signal $V$ obtained when the read head transverses the pattern of magnetization states along the dashed red line in Fig. 4a, for composite BPM and (c) AFC CCBPM.