Layered Magnetization Reversal by Multi-Head Writing in Three-Dimensional Magnetic Recording

Yugen Jian[1,2], *Graduate Student Member, IEEE*, Ke Luo[1], Jincai Chen[1,3,4], and Xuanyao Fong[2], *Member, IEEE*
[1]Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology,
Wuhan 430074, China, jcchen@hust.edu.cn
[2]Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117583, Singapore
[3]School of Computer of Science and Technology, Huazhong University of Science and Technology, Wuhan 430074, China
[4]Key Laboratory of Information Storage System, Engineering Research Center of Data Storage Systems and Technology,
Ministry of Education of China, Wuhan 430074, China

Three-dimensional magnetic recording (3DMR) is a highly promising approach to achieving ultra-large data storage capacity in hard disk drives. One of the greatest challenges for 3DMR lies in performing sequential and correct writing of bits into the multi-layer recording medium. In this work, we propose a multi-head writing architecture with graded heat-assisted recording, and validate it in a dual-layer 3DMR system with FePt-based thin films via micromagnetic simulation. Our results reveal the layered magnetization reversal mechanism of the medium, ultimately attaining appreciable medium signal-to-noise ratio (SNR) for each layer. In particular, an optimal head-to-head distance is identified as the one that maximizes the medium SNR, which can support 3DMR scaling to more recording layers.

***Index Terms*—Heat-assisted magnetic recording (HAMR), three-dimensional magnetic recording (3DMR).**

I. INTRODUCTION

MASS-CAPACITY hard disk drives (HDDs) continue to be one sustainable and reliable choice to meet the escalating demand for large-scale data storage. Three-dimensional magnetic recording (3DMR), which utilizes more than one layer of recording medium, has been considered a very promising approach capable of surpassing the capacities of existing HDD products [1]. The implementation of 3DMR is facing a number of challenges [2] and the most critical of these is how to write bits sequentially and correctly to the multi-layer recording medium. In this work, we propose a multi-head writing architecture that features graded heat-assisted recording for 3DMR. Through micromagnetic modeling and simulation, we examined the architecture in a system with dual-layer FePt-based thin films. The magnetization reversal dynamics of top- and bottom-layer grains during the multi-head writing process were elucidated. Discussions on the performance of our proposed architecture were conducted, with the results demonstrating its superiority for the future realization of robust 3DMR.

II. MULTI-HEAD HEAT-ASSISTED RECORDING

To enable independent writing on either recording layer in 3DMR, it is imperative that they possess distinct anisotropy fields and can be magnetized under different physical conditions. Heat-assisted magnetic recording (HAMR) with graded temperatures has been reported as a feasible way to realize 3DMR [3]. Adjusting the laser's focal depth and power to match the position and Curie temperature of each recording layer thus allows for separated writing in 3DMR.

Here we propose a multi-head writing architecture for 3DMR, leveraging multi-pass writing with graded HAMR to sequentially write data into the multi-layer recording medium. Fig. 1(a) gives a schematic diagram of the architecture. Overall, the multi-head writing process begins from the bottom layer and progresses upward, layer by layer, as the medium moves. Each head corresponds to the respective layer, i.e., head i operates on layer i at the i-th pass writing $(i = 1, 2, \cdots, N)$. Writing temperature T_{wi} and writing field $\vec{H}_{wi}$ produced by head i are determined by the structural position and physical properties of layer i, and will be either preset or controlled by the write current.

The writing fields can be independent from one another, while the writing temperatures need to satisfy the conditions:

$$\begin{cases} T_{w1} > T_{w2} > \cdots > T_{wN} \\ T_{wi} = T_{Ci} + \delta T_i \quad (i = 1, 2, \cdots, N) \end{cases} \tag{1}$$

T_{wi} and T_{Ci} are the writing and Curie temperatures of head/layer i, respectively. δT_i is a small positive value that represents T_{wi} is slightly higher than T_{Ci}. It is essential to hold such a temperature gradient to ensure that data previously written remains unaffected in the onward process.

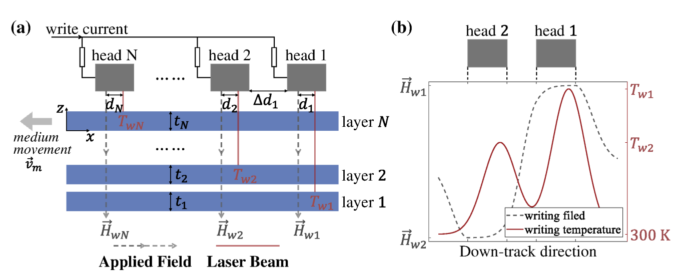

Fig. 1. (a) Schematic diagram of the multi-head writing architecture with graded heat-assisted recording for 3DMR. (b) Examples of down-track profiles of writing temperature T_w (red solid line) and writing field $\vec{H}_w$ (gray dashed line) produced by head 1 and head 2.

We have developed a micromagnetic model to simulate the multi-head writing process by solving the Landau-Lifshitz-Bloch (LLB) equation on MARS [4]. The writing temperature of each head follows a Gaussian distribution, and the writing field is considered constant within the head area, while the stray field outside the head is Gaussian distributed (as shown in Fig. 1(b)). For the recording medium, FePt-based thin film with Voronoi grains and nonmagnetic grain boundaries is modeled. In our following examination, we primarily focus on the case of $N = 2$, i.e., dual-layer 3DMR with dual-head writing. Key parameters and settings will be provided in the future full manuscript.

III. Layered Magnetization Reversal Dynamics

To investigate the dynamical process of layered magnetization reversal in 3DMR, the dual-head writing of consecutive transitions (square-wave binary sequence for both heads) on the dual-layer medium was simulated. The temporal evolution of layered magnetization reversal during the multi-head writing process can be divided into four stages, as shown in Fig. 2:

1) The medium was firstly heated to the higher writing temperature, of which $T_{w1} > T_{C1} > T_{C2}$, and the coercivity of both the top and bottom layers was rapidly reduced. The grains transitioned from ferromagnetic to paramagnetic ($m_z \to 0$) as the temperature rose.
2) As the head moved forward, the grains regained their ferromagnetic state while cooling, and the magnetization was reversed under the effect of the writing field. At this point, the bits corresponding to the top and bottom layers switched from "1" to "0".
3) The second-pass writing began, and the medium was heated to the lower writing temperature, of which $T_{C1} > T_{w2} > T_{C2}$. Consequently, only the magnetization of the top-layer grain would be erased. The coercivity and magnetization of the bottom-layer grain decreased as the temperature rose but did not meet the writable condition, thus the bottom-layer grain would remain in the state achieved after the first-pass writing.
4) Finally, the magnetization of the top-layer grain was reversed by the writing field, while the bottom-layer grain remained unaffected and returned to its previous state. The medium would reach equilibrium at room temperature, with data "1" and "0" separately stored in the corresponding bits of the top and bottom layers.

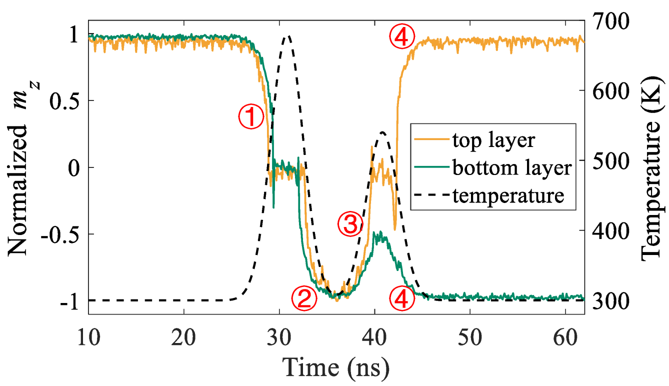

Fig. 2. Temporal evolution of the magnetization reversal of grains from the top (yellow line) and bottom (green line) layers during the multi-head writing process, which is discussed in stages ①-④. The dashed line represents the variation of the grain's temperature over time.

IV. Medium Signal-to-Noise Ratio

In the multi-head writing architecture, the distance between adjacent heads Δd emerges as an additional factor that impacts the performance of 3DMR system. Hence, we repeated the writing simulations with varying Δd, and calculated the medium signal-to-noise ratio (SNR) in each configuration.

The results of medium SNRs are shown in Fig. 3 with very interesting trends. To begin with, as the head-to-head distance Δd grows from zero, the medium SNR will gradually improve for both layers. When Δd continues to increase, the medium SNR experiences a slight decline before leveling off, which is more pronounced for the bottom layer. This suggests the existence of an optimal distance Δd_{opt}, at which the medium SNR reaches its maximum, opening up the potential for expanding to more recording layers and a larger multi-head array in 3DMR.

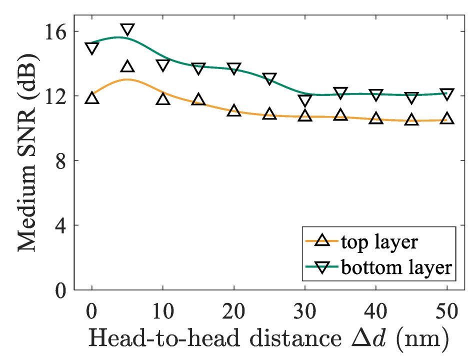

Fig. 3. The medium SNR versus the head-to-head distance Δd for the top (yellow lines) and bottom (green lines) layers.

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