Digests of
The 26th Magnetic Recording Conference
TMRC 2015

University of Minnesota
Minneapolis, MN
August 17 - 19, 2015

Sponsored by the IEEE Magnetic Society
and

co-sponsored by:
Center for Materials for Information Technology, University of Alabama
Center for Micromagnetics and Information Technologies, University of Minnesota
Center for Magnetic Recording Research, University of California, San Diego
Center for Magnetic Nanotechnology, Stanford University
Data Storage Systems Center, Carnegie Mellon University
Computer Mechanics Laboratory, University of California, Berkeley

Financial Support from:
Seagate Technology
Western Digital
Hoya
Center for Micromagnetics and Information Technologies, UMN
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The 26th Magnetic Recording Conference will focus on magnetic recording technologies that enable storage densities above 1 Tbit/in². A total of 38 invited papers of the highest quality will be presented orally at the conference and will be published in the IEEE Transactions on Magnetics.

**Topics to be presented include:**

- Perpendicular Magnetic Recording at More Than 1Tbit/in² (Readers, Writers, Servo, Tribology, Signal Processing)
- Shingled and Two-Dimensional Magnetic Recording
- Heat Assisted Magnetic Recording
- Bit Patterned Magnetic Recording
- Alternate Recording Technologies (MAMR, Tape, Spintronics, MRAM, STT-RAM)
- Fundamentals (Metrology, Tooling, Materials, Recording Physics)

**TMRC 2015 Organization**

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Welcome to TMRC 2015

Welcome to the 26th Magnetic Recording Conference (TMRC 2015). TMRC is an annual forum organized under the auspices of the IEEE Magnetics Society, with the invited presentations published in a special issue of the IEEE Transactions on Magnetics. This year’s conference is taking place on August 17-19th and is hosted on the campus of the University of Minnesota in Minneapolis.

The magnetic recording technology and industry continues to progress at an astonishing rate. Never have we seen such rapid growth in information creation, consumption, analysis and storage. The Cloud continues to rapidly expand and in the process drive major market changes. The Internet of Things promises to push this trend further with tens of billions of new networked devices. By the end of the decade, the projected information created could reach over 40 Zettabytes and information storage demand over 10 Zettabytes. Unlike in the late 1990’s when HDD areal density (AD) grew faster than demand, today perpendicular magnetic recording is reaching its asymptote. Meanwhile solid state storage is proving to be a competitor in some applications and a partner in many others. Multiple new Hard Disk Drive (HDD) recording technologies are being pursued to extend Perpendicular Magnetic Recording (PMR) technology and enable the next growth curve to many Terabytes/in2 AD. These technologies include Shingled Magnetic Recording (SMR) and He-filled drives which are already in released products. Technologies in development include Two-Dimensional Magnetic Recording (TDMR) with until recently unheard of multiple readers, assisted-write technologies such as Heat Assisted Magnetic Recording (HAMR), perhaps Microwave Assisted Magnetic Recording (MAMR) and longer-term Bit Patterned Magnetic Recording (BPMR), Heated Dot Magnetic Recording (HDMR) and more. It is hard to remember a time of greater opportunity, or greater challenge. To gauge our progress, we will continue the tradition of surveying you and your co-participants on what and when these technologies will be available for sale.

In this environment it is more important than ever for the HDD industry to pursue a common roadmap. The TMRC is a key forum to chart our progress and will not disappoint. This year’s 3-day conference is packed with no parallel sessions and an uncommon focus on technical depth and timely dialogue. We’re pleased to offer 39 invited lectures from some of the world’s leading researchers in the field, covering most of the current state-of-the-art developments in the area of advanced magnetic recording. The program features dedicated sessions on HAMR heads, media and system; a session on signal processing for TDMR, a session exploring spintronics for advanced reader and MAMR; and a session on alternative storage including BPM and All Optical Switching. These 6 oral sessions are complemented by 2 sessions with over 30 contributed posters and traditional Bierstube. Capping the event will be notable banquet and keynote speaker.

Events such as the TMRC are an important opportunity for the industry to come together and share important technical progress. This would not be possible without the many volunteers that create and coordinate the conference. Please join me in recognizing the committee of many dedicated individuals that make this year’s TMRC possible. This is a strong international, inter-disciplinary group that well demonstrates the hard work and strong execution that is the cornerstone of the HDD industry. Lastly we would like to thank the University of Minnesota MINT Center for generously hosting again this year.

On behalf of The Magnetic Recording Conference Committee, Welcome!

Mark Kief
General Chair
TMRC 2015 | Corporate Sponsors

TMRC 2015 could not have happened without the generous support of our sponsors

Seagate Technology,
Western Digital,
Hoya
Transportation:
There are light rail stations at both terminals of MSP airport and the East Bank Station (blue symbol) is a few 100 feet from Keller Hall (oral presentations will take place in room 3-210). You must transfer from the blue line to the green line in downtown Minneapolis, cost is about $2.00, and time required is about 40 minutes.

Taxi is about $50 and requires about 20 minutes if there is no traffic.

Private cars may pay to park at Washington Street Ramp, which is across the street from Keller Hall. Ramp may fill later in the day, so late arrivals may need to park at more distant ramps. Rate is $3/hr and $12/day.

Driving to UMN from MSP International Airport:
1) Take MN-5E from Glumack Drive then keep right and take MN-55W; 2) Keep left and take MN-62W, use the right 2 lanes to take I35W N exit; 3) Continue on I35W N and take exit 18 to University Ave SE. 4) Continue on University Ave SE to Church St SE, Pillsbury Dr SE, Beacon St SE and then Union St SE, you can park in Washington Street Ramp.
The Magnetic Recording Conference (TMRC) 2015 Program

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Map showing the locations of Keller Hall and McNamara Alumni Center on the University of Minnesota campus.
Dr. William Cain
VP Advanced Technology, Western Digital Technologies
Irvine, CA

“Navigating Market and Technology Transitions”
Monday, 17th August, 8:30 AM – 11:45 AM        Location:  3-210 Keller Hall

(A1).  8:30 AM:  HAMR Drive Integration Features and Challenges
Phillip Haralson, Harold Ruan, Galvin Chia, Pradeep Thayamballi, Kent Anderson,
William Cain, Shafa Dahandeh, James Alexander, Curtis Macchioni, Gerardo Bertero- Western Digital, Fremont, CA.

(A2).  9:00 AM:  Radius and Skew Effects in a HAMR Hard Disk Drives
Michael A. Cordle, Drew M. Mader, Steven D. Granz, Alfredo S. Chu, Pu-Ling Lu, Frank Martens,
Ying Qi, Tim Rausch, and Jason W. Riddering, - Seagate Technology, Shakopee, MN.

(A3).  9:30 AM:  Characterization of Laser induced Protrusion in HAMR by the Burnish Method
Zhenyi Zhang, Kowang Liu, Eric Jin, Moris Dovek - Headway Technologies, Milpitas, CA;  James Kiely - Seagate Technology,
Bloomington, MN; Osamu Nakada - TDK, Nagano, Japan;  Pak Kin Wong, Vincent Man Fat Chiah, Xiao Ming Liu - SAE Magnetics, Hong Kong, China.

10:00 – 10:15 AM: Break

(A4).  10:15 AM:  A Novel Lubricant Transfer and Deposition Phenomenon at the HAMR Head-Disk Interface
Yang Yang, Paul M. Jones, Michael Stirniman, Fujian Huang, Florin Zavaliche, Xiaoping Yan, Xinwei Li, Hongbo Wang, James D. Kiely,
John L. Brand, Huan Tang - Seagate Technology, Fremont CA and Bloomington, MN.

(A5).  10:45 AM:  Decoding magnetic and structural characterization results for L10 FePt-X granular films
O. Mryasov, A. Kalitsov, O. Krupin, Y. Zhang, A. Chernyshov, M. Chapline, Th. Le, H. Ho, B. Ozdol, R. Zhang, H. Yuan, T. Seki, S. Myers,
S. Pirzada, M. Alex, P.Dorsey, G. Bertero.- Western Digital, San Jose, CA.

(A6).  11:15 AM:  Predicted Areal Density Gain for HAMR on Bit Patterned and Granular Media
Randy Victora, Pin-Wei Huang, Yipeng Jiao, Sumei Wang, and Yao Wang - University of Minnesota, Minneapolis, MN.
Monday, 17th August, 1:15 PM – 5:00 PM  
Location: 3-210 Keller Hall


(B1). 1:15 PM: Microstructure control and thermal management of L10 FePt granular media for heat assisted magnetic recording


(B2). 1:45 PM: Structural Optimization of FePt-C nanogranular films for HAMR recording


(B3). 2:15 PM: The relevance of structure information at the atomic level for a better understanding of granular FePt media

S. Wicht - IWF Dresden, Germany; S.H. Wee, O. Hellwig, D. Weller – HGST, San Rosa, CA; and B. Rellinghaus - IWF Dresden, Germany.

2:45 – 3:00 PM: Break

(B4). 3:00 PM: Femtosecond Magneto-optics of FePt nanocrystals for HAMR media

J.-Y. Bigot, J. Kim, M. Vomir, O. Kovalenko - University Strasbourg, France; O. Mosendez, S. Jain, and D. Weller – HGST, San Jose, CA

(B5). 3:30 PM: Temperature dependence of magnetic properties of HAMR media

M. Chapline, C. Papusoi, A. Ajan, P. Dorsey, M. Desai, and R. Acharya - Western Digital, San Jose, CA

(B6). 4:00 PM: FePt based HAMR media with a function layer for better thermal control

JiangFeng Hu, Kiat Min Cher, Binni Varghese, Baoxi Xu, Chee Beng Lim, Jianzhong Shi, Yunjie Chen, Kaidong Ye, Jing Zhang, Chengwu An, and Wen Huei Tsai - Data Storage Institute, Singapore

(B7). 4:30 PM: Influence of thermal fluctuation on areal density in heat assisted recording

C. Vogler and D. Suess - TU Wien, Vienna, Austria

Monday, 17th August, 5:15 PM – 7:00 PM  
Location: Johnson Great Room, McNamara Alumni Center

Session P1: Posters (Invited Aug. 17 & Contributed. Bierstube)

(C1). 8:30 AM: Writer and Reader Head to Media Spacing Sensitivity assessment for HAMR
Chris Rea, Mourad Benakli, Pradeep Subedi, Riyan Mendonsa, James Kiely, Weibin Chen, Hua Zhou, Stephanie Hernandez, Kaizhong Gao, Mike Seigler, and Edward Gage - Seagate Technology, Bloomington and Shakopee, MN.

(C2). 9:00 AM: Nano-thermal consideration for heat assisted magnetic recording (HAMR)
Michael Morelli, Rabee Ikkawi, Hyoujune Lee, Brad Johnson, Marc Finot, Matthew Gibbons - Western Digital, Fremont, CA.

(C3). 9:30 AM: Characterization of plasmonic near field transducers for heat-assisted magnetic recording
Xianfan Xu, Nan Zhou, and Yan Li, Purdue University, IN.

10:00 – 10:15 AM: Break

(C4). 10:15 AM: Nanoscale characterization of HAMR heads using polymer imprint thermal mapping
Anika Kinkhabwala, Matteo Staffaroni, Oz Suzer, Stanley Burgos, and Barry Stipe – HGST, San Jose, CA.

(C5). 10:45 AM: Efficient integrated light delivery system design for HAMR maximal optical coupling for transducer and nanowaveguide
Vivek Krishnamurthy, Doris Ng, Kim Peng Lim, Qian Wang - Data Storage Institute, Singapore.

(C6). 11:15 AM: Novel transducer and coupling arrangement for a heat-assisted magnetic recording
Jacek Gosciniaik, Brian Corbett - Tyndall National Institute, UK and Marcus Mooney, Mark Gubbins - Seagate Technology, Londonderry, UK.
Tuesday, 18th August, 1:15 PM – 5:00 PM  
Location: 3-210 Keller Hall

Session D: Reader & MAMR (Co-Chairs: Qunwen Leng – Western Digital, Takeo Akihiko – Toshiba)

(D1). 1:15 PM: Effects of spacer materials in Heusler-alloy-based CPP-GMR devices for read sensors


(D2). 1:45 PM: CPP-GMR effect using Ag-Mg ordered alloy spacer layer and Heusler alloy Co2(Fe,Mn)Si electrodes

Takahide Kubota, Hiroyuki Narisawa, and Koki Takanashi - Tohoku University, Sendai, Japan.

(D3). 2:15 PM: Recent progress in CPP-GMR readers for > 1 TB/in²


2:45 – 3:00 PM: Break

(D4). 3:00 PM: Microwave-assisted magnetization reversal in CoCrPt-based granular films using a linearly polarized microwave field with a width of several tens of nanoseconds

Yukio Nozaki - Keio University, Yokohama and Shinya Kasai - National Institute for Material Science, Tsukuba, Japan.

(D5). 3:30 PM: Perspectives of Microwave Assisted Magnetic Recording at 2 Tb/in²

Tiejun Zhou, Mingsheng Zhang, Shikun He, Chung Hong Jing, Kelvin Cher, Melvin Low, Yi Yang and Z.M. Yuan - Data Storage Institute, Singapore.

(D6). 4:00 PM: Advantages of MAMR Read-Write Performance

Ikuya Tagawa, Masato Shiimoto, Masato Matsubara, Shuya Nosaki, Jun Aoyama and Yosuke Urakami - HGST

(D7). 4:30 PM: Optimizing Modeled ECC Media Structures for MAMR

Terry Olson, Byron Lengsfield, G. J. Parker - HGST, San Jose CA; Masato Shiimoto, Mikito Sugiyama - HGST Odawara, Japan; and Lei Xu, - HGST, San Jose, CA.

Tuesday, 18th August, 5:15 PM – 7:00 PM  
Location: Memorial Hall, McNamara Alumni Center

Session P2: Posters (Invited Aug. 18 and 19 & Contributed. Bierstube)

Tuesday, 18th August, 7:00 PM – 9:00 PM  
Location: Memorial Hall, McNamara Alumni Center

Banquet and Keynote Speaker: William Cain – VP Technology, WD
Wednesday, 19th August, 8:30 AM – 11:45 AM  
Location: 3-210 Keller Hall

Session E: Bit Patterned Media & Alternative Technologies (Co-Chairs: Gerardo Bertero – Western Digital, Ganping Ju – Seagate Technology)

(E1). 8:30 AM: Advances in Fabrication and Recording Performance of Bit Patterned Media
Phillip L. Steiner, Bruce Buch, David M. Chung, Belkacem B. Derras, Michael Feldbaum, Yautzong Hsu, Yukiko Kubota, David S. Kuo, Kim Y. Lee, Ning Li, Puskal Pokharel, Alexei H. Sacks, Kyaw Sinmaung, Antonia Tsukatos, Raman C. Venkataramani, Barmeshwar Vikramaditya, Koichi Wago, Shuaigang Xiao, Ruoxi Yang, XiaoMin Yang, and Zhaoning Yu, Seagate Technology Fremont, CA and Shakopee, MN.

(E2). 9:00 AM: Directed self-assembly of high-chi block copolymer for nano fabrication of bit patterned media via solvent annealing
Shisheng Xiong – University of Chicago, IL; Lei Wan, Yves-Andre Chapuis, Lei Wan, He Gao, Ricardo Ruiz – HGST, San Jose, CA; and Paul F. Nealey - University of Chicago, IL.

(E3). 9:30 AM: All-optical magnetic switching: From fundamentals to nanoscale all-optical recording
Y. Tsema, J. Becker, M. Savoini, D. Afanasiev- Radboud University, the Netherlands; A. Tsukamoto - Nihon University, Chiba, Japan; O. Mosendz, D. Weller – HGST, San Jose, CA; S. El Moussaoui, F. Nolting- ; Swiss Light Source, Villigen, Switzerland; J.C. Maan, P.C.M. Christianen, A. Kirilyuk, A. Kimel and Th. Rasing - Radboud University, the Netherlands.

10:00 – 10:15 AM: Break

(E4). 10:15 AM: All-optical control of magnetization in various metallic magnetic systems
Rajasekhar Medapalli - University of California San Diego, CA; Y. K. Takahashi - National Institute for Materials Science, Tsukuba, Japan; Y. Quessab, D. K. Kim, C.H. Lambert - University of California San Diego, CA; O. Hellwig – HGST, San Jose, CA; S. Mangin - University of California San Diego, CA; K. Hono - National Institute for Materials Science, Tsukuba, Japan; Y. Fainman, and Eric Fullerton - University of California San Diego, CA.

(E5). 10:45 AM: Consideration on Voltage Writing in Magnetic Recording Media with Magnetoelectric Effect
M. Sahashi, T. Nozaki, Y. Shiokawa, M. Al-Mahdawi,, S.P. Pati - Tohoku University, Sendai, Japan; T. Shibata, S. Yonemura- TDK Corporation, Japan; and K. Mibu, Nagoya Institute of Technology, Japan.

(E6). 11:15 AM: Characterizing the advanced recording technology assets with hyper-scale applications
Yoichiro Tanaka – Toshiba, Tokyo, Japan.
Wednesday, 19th August, 1:15 PM – 5:00 PM Location: 3-210 Keller Hall

Session F: Channels (Co-Chairs: Roger Wood – HGST, Shafa Dahandeh – Western Digital)

(F1). 1:15 PM: Areal-Density gains and Technology Roadmap for Two-Dimensional Magnetic Recording
Shafa Dahandeh - Western Digital, Irvine, CA; M. Fatih Erden - Seagate Technology, Shakopee, MN; and Roger Wood- HGST, San Jose, CA.

(F2). 1:45 PM: Comparison of two-reader and three-reader TDMR systems
Nedeljko Varnica, Rathnakumar Radhakrishnan, Shashi Kiran Chillaappagari - Marvell Semiconductor, Santa Clara, CA, Mehrdad Khatami - University of Arizona, AZ; and Mats Oberg - Marvell Semiconductor, Santa Clara, CA.

(F3). 2:15 PM: Cross-track Distribution of LDPC Codewords for Areal-Density Gain
Niranjay Ravindr, Sharat Batra, Joseph Blomer, Rick Galbraith, Jana Jarrell, Roger Wood, - HGST, Rochester, MN and San Jose, CA

2:45 – 3:00 PM: Break

(F4). 3:00 PM: TMR Sensitive Equalization for Electronic Servoing in Array Reader based Hard Disk Drives
Yu Zheng, George Mathew, Travis Oenning, Rich Rauschmayer, and Bruce Wilson - Avago Technologies, Mendota Heights, MN and Longmont, CA.

(F5). 3:30 PM: Optimization of Bit Geometry and Multi-Reader Geometry for TDMR
J. Barry - GA Tech, B. Vasic, M. Khatami, M. Bahrami – University of Arizona, AZ; Y. Nakamura, Y. Okamoto – Ehime University, Japan; Y. Kanai – Niigata Institute of Technology, Japan.

(F6). 4:00 PM: Dynamic Grain State Estimation for High-Density TDMR: Progress and Future Directions
Xueliang Sun, Benjamin Belzer, and Krishnamoorthy Sivakumar - Washington State University, WA.

(F7). 4:30 PM: Relaxing media requirements by using multi-island two-dimensional magnetic recording (TDMR) on bit patterned media (BPM)
Yao Wang, B.V.K. Vijaya Kumar – Carnegie Melon University, Pittsburgh, PA; M. Fatih Erden, Philip L. Steiner - Seagate Technology, Shakopee, MN and Fremont, CA.

Wednesday, 19th August, 5:00 PM – 5:15 PM Location: 3-210 Keller Hall

Closing Remarks.
HAMR Drive Integration Features and Challenges

Phillip Haralson, Harold Ruan, Galvin Chia, Pradeep Thayamballi, Kent Anderson, William Cain, Shafa Dahandeh, James Alexander, Curtis Macchioni, Gerardo Bertero
Western Digital, Irvine, CA 92612, USA

I. INTRODUCTION

Since commercialization, Perpendicular Magnetic Recording (PMR) has allowed us to increase the areal density by almost 10 times from \( \sim 100 \text{Gb/in}^2 \) to \( \sim 1 \text{Tb/in}^2 \). However, due to thermal instabilities, we are rapidly approaching the limits of those areal density gains. To overcome these physical limits, a new recording technology is needed. Heat Assisted Magnetic Recording (HAMR) is expected to be the next technology enabler for continued areal density growth, potentially exceeding \( 5 \text{Tb/in}^2 \) [1].

HAMR utilizes a near field transducer to focus the energy from a laser below the diffraction limit, thereby heating a localized region of the media to at or above the Curie temperature. The high temperatures involved, introduce several challenges that need to be addressed before HAMR can be commercialized. In this paper, we discuss some of those challenges and how they relate to both spacing control and laser power control. Both of these challenges however can be addressed through a combination of firmware and hardware features within a HAMR disk drive.

II. HAMR Challenges

The high temperatures involved in HAMR recording introduce several additional challenges compared to PMR. One such challenge involves spacing control or protrusion management. In perpendicular magnetic recording (PMR), there are typically 2 types of protrusion, both with similar time constants that need to be managed: Write Pole Tip Protrusion (WPTP) caused by the write coil, and Dynamic Fly Height (DFH) heater protrusion from 1 or more resistive heater elements. In HAMR recording, in addition to the legacy protrusions, the drive must also manage the Laser Pole Tip Protrusion (LPTP), Scattered Light Pole Tip Protrusion (SPTP), and Optical Pole Tip Protrusion (OPTP). Each of these have differing time constants that range on the order of microseconds to 10’s of milliseconds and all must be successfully managed to maintain write-ability.

Another critical challenge in HAMR recording is maintaining consistent write performance and therefore a constant laser output. Solid state laser diodes are typically biased using a constant current biasing scheme. However when using a constant current bias, the output of the laser is not constant due not only to changes in environmental conditions, but also due to properties of the laser itself including self heating and mode hopping.

III. Addressing HAMR Challenges

The additional protrusions introduced in HAMR recording (LPTP, SPTP, and OPTP) can be addressed through a combination of hardware and firmware features during drive integration. In this paper, we’ll discuss some of the features necessary to correct for these additional protrusions, specifically as they relate to the DFH heater controls and laser current overshoot. Figure 1 demonstrates the gradual ramp in signal amplitude when the protrusion management features are disabled, and the resulting improvement in signal quality when proper protrusion management is enabled.
In addition to protrusion management, to guarantee consistent write performance, laser output power must also be carefully managed. Laser output power, when biased with a constant current source, changes based on die temperature. The die temperature is influenced both by the ambient temperature and the self heating from the laser itself. In this paper, we’ll also discuss several potential methods for measuring this variation and methods that can mitigate it through both firmware and hardware features. Figure 2 shows an example of the change in laser output, as measured by a photodiode, due to the laser self heating when biased using a constant current source.

ACKNOWLEDGEMENTS
To all of our colleagues that helped us within Western Digital.

REFERENCES
RADIUS AND SKEW EFFECTS IN A HAMR HARD DISK DRIVE

Michael A. Cordle¹, Drew M. Mader¹, Steven D. Granz¹, Alfredo S. Chu¹, Pu-Ling Lu¹, Frank Martens¹, Ying Qi¹, Tim Rausch¹, and Jason W. Riddering¹
1) Seagate Technology, Shakopee, MN 55379 USA,

I. INTRODUCTION

As areal densities in conventional Perpendicular Magnetic Recording (PMR) approach the physical limits of magnetic thermal stability, Heat Assisted Magnetic Recording (HAMR) has been identified as a likely successor to enable continued areal density growth beyond 1Tb/in². In the past decade, many of the principles of HAMR recording have been explored in detail, however current research has primarily been limited to a spinstand environment and relatively minimal focus has been given to integrating HAMR into Hard Disk Drives (HDD). As HAMR continues to make progress towards production, understanding the unique effects and limitations of the HDD environment will be crucial to the success of HAMR. Two such elements are the geometric effects of radius and skew angle. In this talk, we will discuss these effects on HAMR recording in the drive environment and present experimental results to provide a comparison to PMR.

II. EXPERIMENTAL DETAILS

Fully integrated heads and typical HAMR media were assembled into drives after first being screened on a spinstand, similar to [1]. The laser diode current was calibrated by minimizing the triple-track bit error rate (BER) at a fixed track pitch. The Adjacent Track Interference (ATI) was measured by writing three adjacent tracks with the center track being repeatedly re-written and the BER on the inner diameter (ID) and the outer diameter (OD) tracks being periodically re-measured, similar to [1]. Areal Density Capability (ADC) was determined by finding the laser power that yielded an aspect ratio at the highest areal density as described in [2].

III. RESULTS

The experimental data in Figure 1 shows the calibrated laser diode current as a function of disk radius, normalized to the mid-diameter (MD) of the disk. This demonstrates an overall trend that a higher laser current is required as the radius increases. Figure 2 shows a comparison of ATI behavior between HAMR and PMR at extreme skew angles. The lower left and right graphs of Figure 2 compare the performance loss on the adjacent tracks when a center track was repeatedly written at both the inner diameter (ID) and outer diameter (OD) locations of the disk among a population of PMR and HAMR drives respectively. Figure 3 shows maximum ADC measured at different radii, both normalized to the MD of the disk. This talk will cover the effects that disk radius and skew angle have on laser diode current, write current, ATI, and ADC and subsequently compare these relationships to PMR.

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Figure 1: Calibrated laser power vs. disk radius

Figure 2: The radial aspect of hard disk drives affects HAMR and PMR in differing fashions with respect to performance

Figure 3: Areal density capability vs. disk radius
CHARACTERIZATION OF LASER INDUCED PROTRUSION IN HAMR BY THE BURNISH METHOD

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I. INTRODUCTION

The slider flying height affected by laser induced protrusion significantly impacts the Heat-Assisted Magnetic Recording (HAMR) [1] heads' performance and lifetime [2]. Nonetheless, the pointy local protrusion amount is hard to accurately measure by touch down sensors. Based on previous indirect thermal-mechanical studies with different sensors and techniques [3], a new methodology is implemented to measure the laser induced protrusion by burnishing the head during writing with laser on and utilizing atomic force microscopy (AFM) scans. This burnish method requires the air bearing surface (ABS) to physically contact the rotating disk but without excessive overdrive, which relies on precise settings of touch down sensors and detection methods. The repeatability of this method is validated. The result shows the local protrusion induced by the laser in the range of 2nm ~ 5nm. Accordingly, detailed studies about touch down sensor's sensitivity and protrusion amount as a function of laser power have been conducted. In addition, the impact of varying degrees of stiffness of the air bearing surface is discussed.

II. METHODOLOGY

Figure 1 shows a brief test procedure of this burnish test methodology. Before the test, a fresh head’s air bearing surface (ABS) topography is scanned and recorded by large area (20µmx20 µm) atomic force microscopy (AFM). This scan should cover both reader and writer areas. The fresh head’s topography will be used as a reference to measure the protrusion amount after the burnish test. As shown in Figure 1, step 1 is to conduct touch down using a motor jitter sensor to measure and record the touch down heater power; in step 2, saturated laser power will be selected based on laser current sweep procedure with roughly 8nm laser-off clearance; step 3 is to stress the head during the writing procedure. In this step, touch down power from step 1 and laser power from step 2 will be utilized to physically burnish the protruded portion by the rotating disk for 4 minutes. After all these steps, a second AFM scan for the same area will be conducted in order to measure the worn space, which indicates the protruded amount during the writing procedure with the selected laser power.

III. RESULTS

Figure 2 shows the AFM scan results after the burnish test. The curves indicate the height difference along the scanned position for both the fresh and the burnished heads’ surfaces. Head disk interface (HDI) touch down sensor position is selected as a height reference to measure the worn space. As shown in Figure 2, position B has higher temperature and larger protrusion. Reference position A is far from the transducer and
has smaller protrusion. The height difference change between the fresh head and the burnished head is induced by the laser during write mode. By measuring the change in the height difference, we conclude the local protrusion amount to be around 4.1nm. The repeatability of the method is further validated. Protrusion variation within one kind of head design is small.

REFERENCES


A Novel Lubricant Transfer and Deposition Phenomenon at the HAMR Head-Disk Interface

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I. INTRODUCTION

Heat Assisted Magnetic Recording (HAMR) emerges as the most promising next generation storage technology in recent years to further push the magnetic recording density far beyond one terabit per square inch (1 Tb/in²) [1]. In the HAMR system, the media is heated to above its Curie temperature to write the magnetic bits via a near-field transducer (NFT) in the head that plasmonically couples the light into a tiny spot in the media tens of nanometers in size. The media experiences ultra-rapid heating during the writing process and reaches a peak temperature in excess of 500°C. Self-heating of the NFT as a result of a large amount of the light energy being dissipated in the NFT itself and the nearby light delivery structures, along with back-heating from the hot spot in the media, may cause the NFT to heat up to a rather high temperature, albeit below that of the media. The uniqueness of these transient thermal stress poses significant challenge to HAMR head-disk interface (HDI) reliability. The lubricant film, along with the carbon overcoat, which protects the magnetic storage layer from environmental, thermal and tribological degradations, have to be able to withstand the repeated thermal stress and maintain functional. The cumulative effect of the high temperature transients on the distribution of lubricant on the media surface are probed through a HAMR multi-sector write test by varying the test conditions such as the number of write cycles, laser-on durations, the head flying height (FH), laser output, etc.

II. EXPERIMENT

The HAMR multi-sector write test were performed on a spinstand, with the disk spinning at 10,000 RPM. A schematic of the test is shown in Fig. 1, in which a narrow, 1.5-μm wide radial band was exposed to the repeated HAMR write stress. The black arcs in the figure represent write sectors (laser-on) and blank parts between them represent servo sectors (laser-off). The laser on/off duration was synchronized relative to the spindle index during every disk revolution and can be changed according to test needs. The fly height (FH) of the head was adjusted by means of thermal FH control and included compensation for laser induced thermal protrusion. After the tests, the media and the heads were analyzed by using various techniques, including an Optical Surface Analyzer (OSA), Atomic Force Microscope (AFM), and Time-of-Flight Secondary Ion Mass Spectrometer (TOF-SIMS), to characterize the changes to the media as a result of the HAMR stress tests.

III. RESULTS AND DISCUSSION

After performing 1000 cycles of multi-sector writes on a piece of HAMR media at a fixed FH, the media surface was analyzed with an OSA and found to exhibit periodic dark features that coincided with the times when the laser was turned off (see Fig. 2). These dark features were found to be media lubricant and had a height ~3.3Å based on TOF-SIMS analysis and AFM (see Fig.2d), and therefore represent lubricant accumulation. Brighter regions between the dark features indicate that lubricant depletion takes place in sync
with the laser-on during HAMR writing (see Fig. 2). The exact timing of the lubricant accumulation was determined to be at the instant when the laser was turned off, namely at the end of each sectorized write. Our study showed that the lubricant accumulation phenomenon is driven by temperature changes in the head and media.

By changing the laser on/off duration, we found that the lubricant deposition process was confined to a short time window after the laser was turned off. Besides, the dependence of the amount of lubricant accumulation on write cycles, FH and laser output was explored and an equilibrium model of thermal displacement due to evaporative and condensation processes is used to discuss the effect of head-media temperature changes on the lubricant transfer and deposition. Possible solutions to eliminate or minimize lubricant accumulation to boost HAMR HDI reliability are discussed.

REFERENCES


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Fig. 1 Schematic of the multi-sector laser-on/laser-off HAMR write test. The number of write cycles, the laser on/off durations, FH and the laser output are varied for the four zones to probe the effects of these parameters on the media lubricant redistribution.

Fig. 2 (a)-(c): OSA images of tested media samples with (a)100, (b)500 and (c)1000 cycles of multi-sector writes. (d) AFM image of one dark feature on the media sample with 1000 write cycles.
DECODING MAGNETIC AND STRUCTURAL CHARACTERIZATION RESULTS FOR L10 FEPT-X GRANULAR FILMS

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I. INTRODUCTION
The SNR, bit-to-bit transition jitter, reliability, magnetic and structural characterization of heat assisted magnetic recording (HAMR) media are currently some of the most active R&D areas. The key magnetic performance characteristics include Curie point (Tc) and its grain-to-grain distribution (σTc), magnetic anisotropy constant (K) and some structural characteristics that greatly influence the magnetic characteristics, such as grain size (D) and distribution (σ D), chemical order parameter (η), and texture (fraction of grossly misoriented grains) of L10 FePt-X films. In this work we focus on understanding of the magnetic characterization results for granular L10 FePt-X films [1] using multi-scale simulations [2] and microstructure analysis of FePt-X grains Transmission Electron Microscopy (TEM).

II. RESULTS AND DISCUSSION
Recently proposed magneto-optical techniques for Tc and σTc characterization of FePt-X granular films [1] revealed important grain volume/ diameter dependence of Tc and σT. As an effort to understand the measured trends we extended previously proposed model of magnetic interactions [2] to a more realistic case where the effect of reduced chemical order parameter η and modified grain surface interactions was considered. The atomic resolution High Angle Annular Dark Field (HAADF) imaging associated with Scanning Transmission Electron Microscopy (STEM) technique indicated that the chemical order parameter of FePt-X nanograins changed with grain volume (e.g., η about 80% was found in these nano-granular structures). Model development accommodated composition variations across grain boundaries as revealed by TEM, and the constrained Monte-Carlo (cMC) algorithm for calculations of anisotropy Hk and its temperature dependence. We use static susceptibility cusp to identify dependence of Tc on the average grain size of FePt. σTc was determined with the assumption that the σD is only weakly dependent on the average grain size. This model has been applied to HAMR recording simulations with realistic temperature and field profiles. Spin dynamics simulations [2] were performed for these field profiles modulated according to high frequency single tone pattern. Calculated magnetization response was used to determine mean value of the temperature for transition formation which we call freezing temperature, (Tf). Calculated Tf is shown in Fig. 2 as function of grain diameter D. In Fig. 2 we compare results of computationally intensive and accurate atomistic stochastic simulations [2] with relatively simple master equation theory for an ensemble of grains. Some of the critical parameters entering simple relaxation rate theory have been carefully calculated within atomistic simulations approach. As it can be seen in Fig. 2, good agreement between the two different length scale descriptions achieved with M(T), K(T), energy barrier and attempt frequency parameters determined from more accurate atomistic theory with atomic scale interaction parameters [2]. We further apply this parameterized master equation model for analysis of thermal erase and Alternating Current-Magneto-Optical Kerr Effect (AC-MOKE) experiments to extract Tc and σTc. Finally, we used high resolution TEM/STEM characterization results to determine characteristic FePt grain defects. We incorporated the TEM results into our atomistic model [2] to determine the impact of defects on the magnetic anisotropy. We find that anti-site defects reduce significantly anisotropy constant in general agreement with magnetic characterization results for FePt-X granular films.

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Figure 1. Curie point (Tc, circles) and its grain-to-grain distribution (σTc, squares) as function of average grain diameter (D, nm) calculated using Monte-Carlo (MC) method with model of magnetic interactions [2] tailored to take into account of the reduced order parameter and interface effects characteristic for FePt-X media grain as follows from TEM.

Figure 2. Freezing temperature (Tf, see text for explanation) calculated as a function of grain diameter (D, nm) using atomistic scale stochastic spin dynamics (open circle) and master equation simulations (filled circle) of HAMR recording process with realistic temperature and field profiles.
PREDICTED AREAL DENSITY GAIN FOR HAMR ON BIT PATTERNED AND GRANULAR MEDIA

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I. INTRODUCTION AND METHODS

Heat assisted magnetic recording (HAMR) is a potential technique to extend magnetic recording into the multiple-terabit/in² range. Over the last 5 years, we have performed extensive simulations of HAMR on both granular and bit-patterned media. For this purpose, we represent [1] the behavior of granular media near the Curie temperature with renormalized blocks of spins of order 1 nm³. The change in magnetization of these blocks can then be evaluated using the Landau-Lifshitz-Gilbert equation. The behavior of bit patterned media is typically evaluated [2] using an atomistic approach. Optical spots are calculated using a finite difference time domain technique and heat flow is evaluated using the usual Fourier differential equation.

In order to provide a good basis for comparison, we have also evaluated the performance of alternate technologies including shingled recording of both granular and bit patterned media. For comparative purposes the discussion will be based on user areal density, as opposed to the channel density that will, in some cases, be much higher.

II. RESULTS

Our research [2, 3] has shown that HAMR on a composite granular media can yield jitter close to the grain size limit \((\sigma=D^{3/2}/(12*\text{read width})^{1/2})\) provided that switching temperature variation between grains is tightly controlled. These results assumed a relatively narrow read width equal to 60% of the heat spot full-width half maximum. Areal density is proportional to the \((\sigma*\text{track pitch})^{-1}\). The form of the expression suggests that areal density will be maximized by low Bit Aspect Ratio (BAR). Table I shows maximum channel areal density consistent with current levels of transition noise, as a function of grain pitch, BAR, and track pitch. Assuming that a BAR of 3:1 is mechanically obtainable and that the tracks can be sufficiently squeezed so that read width is 40% of track pitch, then a grain pitch of 5nm yields jitter of 1.1 nm and track pitch of 20 nm. The channel density will be about 4.8 Tbits/in² and the user density will be about 4 Tbits/in². These values could be improved by lower BAR, smaller grains, and more sophisticated read-back. They illustrate the great importance of reducing grain size.

The combination of HAMR with Bit Patterned Media has sometimes been proposed as the ultimate recording technology. We find that likely user areal density, while significantly exceeding HAMR on granular media, is ultimately limited by insufficient temperature gradients to avoid adjacent track erasure.
at very high recording densities. Assuming a 50 nm wide peg on a Lollypop head, we find [2] that a written BER below $10^{-3}$ is obtainable at 5 Tbits/in² in the presence of 3% standard deviation of Curie temperature between dots. We have previously shown that read-back should pose little difficulty within a TDMR approach. We have simulated higher densities such as 6.7 Tbits/in², but the BER becomes sufficiently high to prevent useful contributions to user density even with a 24 nm wide peg. For a reduced Curie temperature distribution, the maximum user density that we have obtained is 5.8 Tbits/in² for a bit size of 8nm x 14nm. This is unlikely to be significantly exceeded unless substantial progress can be made regarding spot size and thermal insulation between the media islands. Alternatively, shingled recording using HAMR is also expected to substantially improve attainable areal densities.

We have demonstrated [4] successful reading of an ideally written pattern at more than 10 Tbits/in² user density for 5.5 nm grain pitch media using TDMR techniques and a rotated read head, albeit at a very low magnetic fly height of 3 nm. Even at more accessible fly heights, read-back is unlikely to be the leading difficulty. Micromagnetic writing at a magnetic fly height of 5 nm yields 2.5 Tbits/in² user density using a 9 nm grain pitch media consisting of a hard ECC media. These results were all obtained near a BAR of 1:1 that will place significant demands on the mechanical systems. Performance will decline sharply at higher BAR, e.g. 2:1 BAR reduces user density to 2.0 Tbits/in².

Shingled, non-HAMR writing of BPM offers another possibility for high density recording. A very encouraging result is found [6] for shingled writing of BPM: 8.1 Tbits/in² at BER of $10^{-3}$ and a magnetic fly height of 5 nm. One major benefit to shingled recording is the reduced requirement for ATE, a density limiting problem for BPM. It can be seen that our highest predicted user densities to date are obtained for shingled recording on BPM.

REFERENCES


<table>
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<th>Grain Pitch (nm)</th>
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Table I Variation of channel density and jitter [7].

Fig. 1 Switching probability (dashed) and distribution (solid) for areal density of 5.8Tb/in² [7].
I. INTRODUCTION

Heat assisted magnetic recording (HAMR) is one of the most promising candidates for next generation hard disk drive (HDD) applications to enable increase in magnetic areal density beyond 1.5 Tb/in² [1,2]. HAMR technology provides a viable solution to the fundamental constraint of thermal stability versus writability by locally heating up the recording medium during the writing process. The reduced media coercivity at elevated temperatures provides not only writability for high anisotropy media, and therefore smaller thermally stable grains, but also enables much higher effective writing-field gradients than conventional perpendicular recording, since the effective writing-field gradient is defined by the product of thermal gradient (dT/dx) and slope of temperature dependence of the anisotropy field (dHk/dT).

Several magnetic materials such as $L_10$ FePt, CoPt, FePd, and MnAl offer high magnetic anisotropy and have been identified as possible candidates for HAMR media [3]. However, in order to induce the ordering required to achieve high anisotropy, a high processing temperature is required, making it extremely challenging to obtain media with sub 6nm grain size. With its high magnetocrystalline anisotropy ($K_u \approx 7 \times 10^7$ erg/cc) and strong chemical stability, $L_10$-FePt is seen as a likely choice for recording medium in HAMR. Additionally, the strong temperature gradient of anisotropy field near the Curie temperature $T_c$, leads to sharp magnetization transitions based on thermal rather than magnetic field gradients. $L_10$-FePt also has a moderate $T_c$ of 750K in comparison to other high $K_u$ alloys, which is favorable for overcoat and lubricant properties and subsequently corrosion resistance and tribology performance during the high temperature recording process.

While there has been considerable progress in HAMR technology through areal density demonstrations and drive level reliability improvements, significant effort is required to understand and overcome limitations in order to accelerate the transition from a technology demonstration to a commercial product. In this work, we will discuss some of the key challenges specific to the microstructure and thermal design of FePt based HAMR media, and highlight recent progress achieved in overcoming these issues.

II. MICROSTRUCTURE AND THERMAL DESIGN OF HAMR MEDIA

Typical HAMR media stack as shown in Fig. 1 consists of an adhesion layer, heat sink to optimize the thermal response of the media, seed layer/interlayer to control the microstructure and magnetic properties, FePt-X granular recording layer, and a thermally stable overcoat. We have demonstrated substantial improvement in realizing a well segregated microstructure with high aspect ratio grains and reduced grain size and distributions [4,5]. This has been achieved by evaluating several segregant materials for FePt while focusing on segregant properties namely thermal and chemical stability, solubility in FePt, surface energy and thermal conductivity. We will present our findings on how segregant properties affect microstructure and...
recording performance of FePt based HAMR media. Another critical factor which needs to be considered is the existence of $L1_0$-FePt grains with in-plane ordering or grains consisting of multi-variants. Such grains limit the areal density capability of HAMR media. We will discuss some of the possible approaches to minimize the impact of such grains through the development of better seed layer structures for FePt. An additional challenge for HAMR is media roughness due to its strong impact on head-media spacing (HMS) and head lifetime. We will highlight our progress in reducing surface roughness over different generations of HAMR media.

Thermal design for HAMR media necessitates the combination of one or more layers with careful consideration given to thermal and optical properties of the heat sink material. The objective of the thermal design is to obtain high thermal gradients in the cross track and down track directions ($\text{Jitter} \propto 1/(dT/dx)$), without increasing $\sigma_{Hk}$ or $\sigma_{Tc}$. Moreover, this should not be achieved at the expense of thicker heat sink (higher laser power requirement for the head) as shown in Fig. 2. We will discuss methods to tailor the thermal design of HAMR media to maximize SNR at reduced laser power in order to provide a pathway for high areal density and improved reliability.

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Fig. 1 Cross sectional TEM image of a typical HAMR media.

Fig. 2 wsSNR, laser current, and thermal gradient as a function of heat sink thickness for HAMR media.
STRUCTURE OPTIMIZATION OF FePt-C NANOGRANULAR FILMS FOR HAMR MEDIA

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INTRODUCTION

In 2008, Perumal et al. demonstrated the [001]-textured FePt-C granular film structure with well-isolated \( L1_0 \)-FePt grains of \(~6\) nm with a narrow size distribution on thermally oxidized Si substrates [1]. Since then, FePt-C granular films have been considered as the most promising candidate for heat assisted magnetic recording (HAMR) media [2,3]. However, the FePt-C films have the vital problem of the difficulty in growing columnar grains. Because of the strong driving force for the phase separation between FePt and C, the FePt-C system can form well-separated in-plane granular structure, while a second layer appears when the nominal thickness of the FePt-C layer exceeds 6 nm [1]. The remaining issues for the FePt-C system are: 1) how to grow \( L1_0 \)-FePt grains columnarly, 2) how to reduce the average grain size to achieve the pitch distance of 6 nm, and 3) how to remove the in-plane component of magnetization.

Columnar grain growth appears to be possible in FePt-C films by modifying the composition of segregant and sputtering conditions as reported in recent reports from industrial laboratories [4,5]. However, no details on the materials and processing conditions for achieving the columnar grain structure have been revealed. Although the process is totally different from the industrial one, Varaprasad et al. reported a way to achieve the columnar growth of FePt grain by using a concentration graded co-sputtering method [6]. However, a systematic approach is indispensable to understand the underlying mechanism for the columnar growth of FePt grains in the FePt-C system. As to the reduction of the grain size, we need to understand the detailed growth process of the columnar media structure from the nucleation and growth stage to the coarsening stage on heated substrates. For the reduction of in-plane magnetic component, Wang et al. employed TEM based orientation mapping and concluded that the angular distribution is originated from the misoriented MgO seed layer [7], suggesting that the in-plane component may be reduced by improving the [001]-texture of the MgO seed layer. On the other hand, Wicht et al. reported that FePt grains are nucleated at step edges of the MgO seed layer having slight misalignment from the cube-to-cube orientation relationship [8]. However, recent investigations on the FePt(Ag)-C granular films deposited on single crystalline MgO(001) substrates have shown the in-plane component can be suppressed almost completely [6,7], suggesting the correlation with the angular distribution in the MgO seed layer and the presence of grain boundaries. More recent work using grain-to-grain convergent beam electron analysis by Ho et al. [9] pointed out the FePt grains crossing MgO grain boundaries have multi-valiant \( L1_0 \) structure. In this presentation, we address several issues to be overcome for obtaining the ideal nanogranular structure as HAMR media, including the methods to reduce the grain size below 5 nm with narrow size distribution, suppression of the easy axis distribution, and the growth of columnar structure of FePt grains on glass substrates through suitable underlayer structure by investigating the model FePt-C system grown on both single crystal MgO (001) substrate and polycrystalline MgO seed layer.

EXPERIMENTAL

In order to investigate the intrinsic microstructure feature of the FePt-C system without additional factor arising from the microstructure of the MgO underlayer, we employed single crystalline MgO (001) substrates. FePt-C films were deposited by co-sputtering Fe, Pt and C targets at the substrate temperature, \( T_s \), of 600°C under 0.48 Pa.
Ar with a deposition rate of 0.15 nm/s. FePt-C layer was deposited by changing carbon concentrations during deposition, i.e., MgO (001) / [FePt-xC (2nm) / FePt-yC (2nm) / FePt-xC (2nm) / FePt-yC (2nm)] where x, y and z are carbon volume percentage varied from 0 to 35%. During the sputtering, C target was continuously sputtered and we manually changed the target power for changing C concentration. Each layer was 2 nm, e.g., three layer sequence for total thickness of 6 nm, five layer sequence for 10 nm thickness. The film microstructures were examined by in-plane and cross-sectional transmission electron microscopy (TEM) using FEI Tecnai 20. The magnetic properties were measured using a superconducting quantum interference device vibrating sample magnetometer (SQUID-VSM) with an applied magnetic field of up to ±7 T.

RESULTS

Fig. 1 shows the in-plane and cross-sectional TEM images of FePt-30vol.%C with the nominal thickness of 10 nm, which was deposited by the compositionally graded process. The in-plane TEM image shows a uniform microstructure with the average grain size of 7.8 nm and the cross sectional TEM image shows the aspect ratio of 1.5. Note that the film thickness of 10 nm is thicker than the critical thickness of the single layer formation of 6 nm in the FePt-C system. The perpendicular $H_c$ is 40 kOe with good squareness required for recording media. In the in-plane magnetization curve, straight line and negligibly small hysteresis are evident, indicating that the FePt grains are strongly [001] oriented in the perpendicular direction. Comparisons with the microstructure of co-sputtered 10-nm-thick film suggested that the suppression of the migration of C to the surface by the gradual change of C concentration to y and z during deposition was effective to suppress the formation of the 2nd FM layer. However, if the C is kept low z while the thickening of FePt continues, the FePt grains impinge each other due to the lack of segregant. Based on these model studies, we discuss how to optimize the nanogranular structure and magnetic properties suitable for HAMR media.

INTRODUCTION

High capacity data storage at ultimate densities is critical for the steadily increasing amount of digital information. Recently, Seagate demonstrated an areal storage density AD = 1.4 Tb/in² using heat assisted magnetic recording (HAMR) [1]. For this technology, granular chemically ordered L10 FePt media with magneto-crystalline anisotropy of about 5 MJ/m³ are used [2]. To improve the potential of these media, accurate control and thorough understanding of details of the media microstructure down to the atomic level are mandatory. The current work highlights detailed atomic scale characterization of both the granular FePt layers and the interface between FePt and the underlying seed crystals. A first study is focusing on granular FePt-C films grown on highly textured polycrystalline MgO seed layers. Here, the lattice mismatch of 9.6% between the MgO lattice constant and the a-axis of L10-ordered FePt induces a preferred growth of the tetragonal unit cell with the [001] magnetic easy axis perpendicular to the film plane. Nevertheless, the use of MgO provokes some drawbacks such as a relative misalignment between the local FePt grains and the underlying MgO seed crystals [3]. To better understand this misalignment, the MgO seed layer surfaces are modified by Ar⁺ ion irradiation prior to the deposition of FePt, thereby modifying the quality of the FePt-MgO interface. The influence of this treatment on the structure and magnetic performance of granular FePt is investigated. In a second study, the influence of the lattice mismatch between the substrate and the FePt layer on the structure of the magnetic film is examined in detail. Therefore, FePt films are deposited onto different single crystal substrates with a variety of lattice mismatches $\Delta a/a$: MgO (9.6%), MgAl₂O₄ (MAO) (4.9%), SrTiO₃ (STO) (1.4%), and (La,Sr)(Al,Ta)O₃ (LSAT) (0.4%). The quality of the FePt-substrate interfaces is evaluated by statistical characterization of the dislocations emerging at these interfaces.

METHODS

In case of the Ar⁺ ion irradiated samples, atomic force microscopy (AFM), X-Ray diffraction (XRD) and aberration-corrected high-resolution transmission electron microscopy (HRTEM) in cross section and plan view geometries are used to explore the properties of the MgO seed layer, the granular FePt layer, and the interface between them. The results are then correlated with the magnetic properties as obtained from perpendicular and longitudinal vibrating sample magnetometry (VSM) in fields up to 14 T. The second study largely focuses on the evaluation of cross-sectional HRTEM images and the measurement of the lattice parameters using XRD.

RESULTS AND DISCUSSION

The AFM results of bare, uncovered MgO layers right after the Ar⁺ irradiation reveal a smoothening of the seed layer surfaces with increasing irradiation times [4] that goes along with an improved out of plane (oop) texture of the FePt granular media (at least for a moderate treatment of up to 4 s) as determined from the FePt (001) and (002) reflexes in the XRD patterns. Longer irradiation times, however, result in a decrease of these super structure peaks and the emergence of additional FePt (110) and (111) peaks. HRTEM analyses in cross-sectional geometry reveal that this modification of the texture is accompanied

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by a change of the grain morphology. Whereas for the untreated reference sample mainly spheroidal grain morphologies occur, this changes to columnar and island-like shapes upon increasing the irradiation times to 4 s or longer. Furthermore, the amount of randomly oriented second layer particles as well as the degree of coalescence of primarily deposited grains, are enhanced. The latter strongly affects the magnetic performance of the media, which is observable in magnetic measurements along the easy (EA) and the hard axis (HA) directions of the granular films, respectively. For the EA curves, the proceeding coalescence results in a reduction of the coercivity from 5.0 T to 2.6 T, since the grain boundary regions form the magnetically weakest parts of the coalesced particles, which induces magnetization reversal [5]. On the other hand, the contacts of regions with different easy axes orientations inside the sintered grains strongly degrade the magnetic texture of the film, which becomes evident from an enhanced HA remanence.

In contrast to the work of Dong et al. [6], the analysis of the pure (segregant-free) FePt films deposited on single crystal substrates reveals the presence of discontinuous FePt films with island sizes larger than some 100 nm for all lattice mismatches. Along with this mismatch the density of dislocations at the FePt-substrate interface decreases from MgO over MAO and STO to LSAT (see Fig 1). Especially the amount of misfit dislocations (additional lattice planes within the FePt islands), which are needed to reduce lattice strains within the FePt, strongly decreases. For the FePt film on STO this leads to the appearance of a strained state with a reduced c/a-ratio as compared to that of perfectly ordered bulk FePt. In contrast to the dislocations, the fraction of FePt islands that exhibit a partial or complete in plane orientation of the easy magnetic c-axis increases by decreasing the lattice mismatch.

![Fig 1: a) Cross-sectional TEM sample of FePt deposited on a single crystal MgO substrate including the position markings of step dislocations. b) Summarized data of the dislocation analysis revealing that a reduction of the lattice mismatch results in a reduced amount of step dislocations at the interface while the fraction of in plane oriented material is enhanced.](image)

FEMTOSECOND MAGNETO-OPTICS OF FEPT NANOCRYSTALS FOR HAMR MEDIA

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I. INTRODUCTION

With nano-materials useful for Heat Assisted Magnetic Recording (HAMR), inducing the pre-heating with femtosecond laser pulses allows reaching very large electron temperatures beyond the Curie point without over heating the lattice. This is the temporal regime that corresponds to Femtomagnetism during which the interaction of light with photons is primordial to modify the magnetic properties of the material. In that context we have been investigating the properties of L₁₀ FePt nanoparticles which are particularly interesting for HAMR as they can be designed to have a very large anisotropy, with corresponding coercive fields larger than 5 Tesla at room temperature. The very large energy reached after the femtosecond optical excitation allows demagnetizing the nanocrystals as well as reducing their coercive field without over-heating them as the total energy deposited in the short times is moderate and compatible with the coming generation of miniaturized high repetition rate femtosecond fiber laser technology. The present contribution aims first at studying in a systematic way the dynamics of the L₁₀ FePt nanoparticles and second at giving some insights of the effect of doping them with noble metal “impurities” on the magneto-optical response. The absolute values given in our measurements can be considered as a benchmark for future practical use. All our experimental studies can well be described by a modified Landau-Lifschitz-Gilbert dynamical behavior in which we consider that the modulus of the magnetization is a time dependent quantity via a three temperatures model corresponding to the charges, the spins and the lattice.

II. EXPERIMENTAL DETAILS

1) Samples elaboration and characterization.

The studied samples are FePt magnetic nanoparticles. As previously reported, the chemical ordering of L₁₀ FePt nanoparticles on a glass substrate with an MgO seed layer has been made [1-3]. The high temperature growth of the FePt films, in the presence of carbon for segregation, results in isolated single domain spherical nanoparticles. The nanoparticles are in the tetragonal L₁₀ phase with their c-axis perpendicular to the film and have high coercive magnetic properties at room temperature. They have a typical diameter of ~10 nm, a large magnetization of ≈ 900 emu/cc and a coercive field H_c = 4.1 Tesla which warrants a high thermal stability with respect to superparamagnetic fluctuations. Figure 1a) shows the temperature variation of the coercive field from 150 K up to 400 K obtained from hysteresis curves M(H) measured with a SQUID apparatus. These static characterizations allow us calibrating the variation of temperature induced by the laser when performing the time dependent pump-probe experiments.

More recently we have studied Cu doped FePt nanoparticles presenting the particularity of a reduced coercive field due to a lower magneto-crystalline anisotropy induced by the alloying with copper. We briefly comment on these doped nanoparticles in the results section.

2) Time resolved measurements with femtosecond optical pulses

The time resolved experiments consist in performing pump and probe Kerr magneto-optical measurements [4-5] with pump pulses (400 nm, 100 fs) and probe pulses (800 nm, 48 fs). The spot diameters of the pump and probe beams, focused on the sample surface, are respectively ~200 µm and ~50 µm. The Kerr rotation (θ) and ellipticity (η) of the probe beam at normal incidence (φ=0°) or at φ=45° from the sample surface are determined as a function of the pump and probe delay τ, using a polarization bridge and a differential synchronous detection [6]. The samples are placed in a superconducting magnet where the field is along the incident probe direction and can be swept from ±10 Tesla. In addition, the change of reflectivity R(τ) is also measured for each configuration. The quantities plotted in the following are the differential ones: ΔS/S(τ,H)=[S(τ,H)-S₀]/S₀ (with S=θ, η or R), either for a fixed time delay τ=τ₀ as a function of the field H, or for a fixed field H₀ as a function of the time delay τ. S₀ corresponds to the static value for each measured quantity.

Figure 1b) shows the schematic of this magneto-optical experimental set-up which requires the sophisticated combination of high static magnetic field to saturate the nanocrystals as well as the pump probe design with a polarization conservation between the linearly polarized incident beam intensity Iₒ and the analyzed reflected beam Iₒ that has an aspect ratio (Iₒ/Iₒ) smaller than 10⁻³ in an environment where the Vervet constant

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of the cryostat windows have to be compensated for when sweeping the static magnetic field.

III. RESULTS

Figure 2 shows the time dependent signals ∆R/R, ∆θ/θ for φ = 0 (figns. 2(a)). In fig. 2(a) the field is set at saturation (H=7 T), while for fig. 2(b) it is either 7 T or 9 T. They correspond respectively to the charges dynamics (reflectivity) and magnetization dynamics (Kerr rotation). The density of energy of the pump is E_{pump} = 0.1 mJ/cm^2. The ultrafast demagnetization, corresponds to the heating of the spins which occurs in ~200 fs for this laser energy density. It is followed by a re-magnetization that involves two mechanisms. First, the spins-lattice equilibrium process with a building time T_{spin-lat} = 2.6 ps for E_{pump} = 0.1 mJ/cm^2. Its dependency on the density of laser energy can be deduced by a three temperatures model [7]. The second step of the remagnetization is the thermal relaxation to the environment (mainly in the heat sink underneath the FePt nanoparticles) which occurs with a longer relaxation time T_{rel} = 75 ps, measured with a longer delay setting, which does not vary with the laser density of energy E_{pump}. In contrast, both the demagnetization and spins-lattice equilibrium time depend on the density of excitation. Note that the charge-lattice relaxation time is shorter (T_{el-lat} = 1.43 ps). This is due to the smaller electronic specific heat associated to the charges as compared to the one of the spins when the temperature approaches the Curie point.

In another set of measurements, we kept the pump-probe delay τ0 fixed, recording the change of Kerr rotation ∆θ/θ(τ0,H) as a function of H for different laser energy densities E_{pump}. The field is swept continuously at a slow rate of 1 Tesla/min from -7 T to +7 T, back and forth. Two quantities are then determined, the change of magnetization at saturation ∆M_s/M_s(τ0, E_{pump}) and the coercive field H_c(E_{pump}). Figure 3a) shows two hysteresis curves for τ0 = 200 fs and E_{pump} = 0.02 and 0.25 mJ/cm^2. Note that the hysteresis curves have opposite signs as compared to the static one in figure 1a) because of the convention of the differential signals ∆S/S(τ,H) (signal with pump minus the static value). It shows that both M_s and H_c are reduced due to the pump heating. Figures 3b) and 3c) show the reduction of these two quantities as a function of the laser energy density. Interestingly the curve H_c(E_{pump}) is highly nonlinear with a threshold of ~0.2 mJ/cm^2 beyond which the coercivity almost completely disappears. We attribute this behavior to a variation of the FePt nanoparticle anisotropy constant K_u as a function of temperature. The variation of M_s(E_{pump}) is first linear and then saturates, a behavior which corresponds to approaching the Curie point as the laser heating is larger. Such full demagnetization, occurring during the first 500 fs, has been reported in thin films of CoPt [8] as well as CoPt submicron dots [9]. Note that in this time scale the temperature of the spins is not in equilibrium with the lattice. For longer delays τ0, we checked that the variation of M_s with E_{pump} is linear, showing that the reduction of the magnetization is driven at long times by the excess of energy which is not yet dumped into the heat sink.

In conclusion, the approach that we are proposing here is to use ultrashort optical pulses to provide the necessary energy both for the preheating process required in HAMR and also on a time scale that defeats any expectations so far in the product line of magnetic discs. Our motivation is to bridge the gap between the research field of Femtomagnetism, initiated in 1996 in nickel thin films [4-5], with the current and future recording needs. The two essential questions to answer then are: how fast can one manipulate the writing process with such nano-crystals? Which energy is required to do so? With those requirements in mind we forecast that subsequent developments will be used in a near future by improving the material elaboration, especially by a tailoring of the magneto-crystalline anisotropy [10] via an appropriate doping of the native FePt nano-crystals with noble metal ions, as well as by making progresses to realize affordable miniature femtosecond lasers technology, a technology that has considerably improved the past 10 years.

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TEMPERATURE DEPENDENCE OF MAGNETIC PROPERTIES FOR HAMR MEDIA

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I. INTRODUCTION

Heat Assisted Magnetic Recording (HAMR) is expected to significantly increase the areal density beyond that of conventional magnetic recording. In this technology, the effective writing field gradient depends on the thermal gradient generated by the laser heating spot as well as the temperature dependence of the media anisotropy field. Thus, understanding the temperature dependence of the media magnetic properties is important for developing suitable materials for HAMR media. Here we focus on characterizing the media magnetic properties that are expected to have the greatest impact on the HAMR recording performance. Analytical models together with AC susceptibility measurements versus temperature and frequency were used to characterize the distribution and temperature dependence of the anisotropy energy (K) as well as the distribution of Curie temperatures (Tc). Vibrating sample magnetometer (VSM) and Polar Kerr (PK) measurements were used to characterize the media magnetization versus temperature and field. Most notably, from these measurements we determined the temperature dependence of the saturation magnetization, Ms(T), and used first order reversal curve (FORC) analysis to evaluate the temperature dependence of the grain coercive field and interaction distributions.

II. EXPERIMENTAL DETAILS

Granular FePt:X samples were fabricated by DC magnetron sputtering on glass substrates. The complex magnetic susceptibility was measured versus temperature (300-750K) for frequencies in the range from 100 Hz to 50k Hz. A small AC field was applied perpendicular to the sample plane using a Helmholtz coil. The change in magnetization induced by the AC field was measured using a Magneto-Optical Kerr effect detection scheme. The real and imaginary parts of the susceptibility were determined using a differential lock-in amplifier. Measurements of the magnetization versus field and temperature were measured using a VSM and PK magnetometer. The grain size distributions were evaluated using TEM.

III. RESULTS

AC susceptibility measurements have been widely used to characterize the magnetic properties of ensembles of superparamagnetic particles. A theory of susceptibility for non-interacting Stoner–Wohlfarth particles was put forward by Neel [1] and later extended to account for thermal perturbations by Shliomis & Stepanov [2] and for weak interactions between particles by Shcherbakov & Fabian [3]. These equations can be adapted to interpret susceptibility measurements of HAMR media since the HAMR magnetic grains are typically well isolated by the segregate and their interactions at high temperatures are small. Figure 1 shows measurements of the HAMR media susceptibility versus temperature as a function of the AC field frequency. The ref. 2-3 models were modified to account for variations in the grain volume, K and Tc and then used to fit the measured real and imaginary parts of the susceptibility as a function of temperature and frequency. From these fits, we obtained estimates for the variance and mean values for K and Tc as well as temperature dependence of K. The extracted value for the scaling parameter γ, K(T) ∼ M^γ(T), agrees well with theoretical expectations while the magnitude of K agrees with estimates from hard axis loops. In addition, the extracted Tc distribution agrees well with VSM measurements of Ms(T). We have also used the FORC methodology of Papusoi et al. [4] to evaluate the temperature dependence of the distributions of grain coercivities and interactions for HAMR media. Using PK measurements we explored temperatures up to ~575 K. Figure 2 shows a FORC diagram measured at ~575 K for a HAMR media sample.
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Figure 1. Example of measured susceptibility versus temperature for several AC field frequencies. Susceptibility normalized to the imaginary peak for each temperature scan.

Figure 2. Example of FORC diagram for HAMR sample obtained at ~575 K.
**FEPT BASED HAMR MEDIA WITH A FUNCTION LAYER FOR BETTER THERMAL CONTROL**

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I. INTRODUCTION

The increase of the demands on storage capacity requires the areal density of the magnetic recording media keep increasing. The new recording technology such as heat assisted magnetic recording (HAMR) was proposed to replace the current perpendicular magnetic recording (PMR) technology [1]. HAMR technology provides a technical solution to the fundament constraint of the thermal stability (utilization of the high magnetic anisotropy material) and the writability (limited writing field can be generated by the write head) by locally heating up the recording medium during the writing process. By utilizing the near field optical transducer (NFT), the laser beam is concentrated to nanosize to locally heat the recording medium [2] above its Curie temperature in the writing process. The most critical challenge for HAMR technology is the reliability issue due to the deterioration of the NFT under high temperature working condition. How to reduce the requirement of the laser power while at the same time to heat up the FePt based recording media to the desired temperature for writing is the key.

II. EXPERIMENTAL DETAILS & RESULTS

All the samples in the present study were fabricated by using Intevac 200 Lean (Gen II) sputtering machine. We have developed a function layer acting as a thermal switching layer to retard the heat flow during the media heating process and it converts to be a better thermal conductor to allow the heat flow along the perpendicular direction once the media reaches certain temperature. The requirement to the NFT regarding to the output power could be reduced. The function layer enables a better thermal control of the FePt based HAMR media, to allow utilization smaller laser power to heat up the recording media during the writing process. The developed function layer in current work has a temperature dependent thermal conductivity and it also has the proper crystalline structure to induce the growth of the (001) textured FePt film. The function layer can partially replace the MgO without deteriorating the magnetic properties of the FePt based recording media. Compared to the HAMR media with MgO underlayer alone, the simulation results demonstrated a higher peak temperature of recording media after introduction of the thermal function layer under same input power to NFT. Thus, smaller laser power could be used and the reliability of NFT could be improved. The function layer was prepared using dc magnetron sputtering process and the deposition rate is much higher than that of MgO, which is very critical from the viewpoint of mass production. In our previous work, we have developed the HAMR media with Cu based heat sink layer via decomposition of the copper nitride layer [3]. Although the texture of the MgO underlayer and the FePt based recording layer could be developed, the surface roughness of the full stack HAMR media stack increased due to the formed bumps on MgO surface resulting from the released N₂ (decomposition of copper nitride) under high temperature condition. The developed thermal function layer in current work could absorb the released N₂ from the copper nitride layer, thus the surface morphology of the full stack media could be improved.

Fig. 1 shows the typical time domain thermal measurement results for samples with different layer structures. There are two parts in the measured curve: the first part is caused by electron temperature rise which takes place within a few of ps; the second part is caused by lattice temperature rise. Based on lattice temperature decay, the medium cooling time is defined as the time at which the lattice temperature reaches 1/e of the maximal lattice temperature. If we compare the results for FePt-C films with 6 nm MgO layer with the sample with 3 nm thermal function layer and 3 nm MgO layer, the cooling rate is the same about 80 ps. When the function layer thickness increased from 3 nm to 6 nm, the cooling rate dramatically increased from 80 ps to 160 ps. The function layer has a much smaller thermal conductivity compare to that of the MgO at room temperature. For FePt based HAMR media with the function layer developed in current work, the small thermal conductivity at the initial heating stage will enable to use a relatively smaller laser power to heat up the FePt HAMR media to desired temperature during the writing process. We can tune the thermal properties of the HAMR media via varying the thickness of the thermal functional layer, which is critical from application viewpoint. Figure 2 shows the corresponding hysteresis loops of the samples discussed in Fig. 1. It can be seen that the introduction of the function layer does not deteriorate the magnetic properties of the FePt-C composite film too much.

The talk will give the details of the development of the function layer and some of the advantages such as

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the surface morphology improvement of the full stack HAMR media with Cu based heat sink layer. Simulation results will also be given to illustrate the effect of the function layer on thermal performance of the recording media, such as thermal spot size and the thermal gradient.

![Graph showing time domain thermal measurements of FePt-C based HAMR media](image)

**FIG. 1** Time domain thermal measurements of FePt-C based HAMR media of (a) NiTa/heat sink/MgO 6nm/FePt-C; (b) NiTa/heat sink/function layer 3nm/MgO 3nm/FePt-C; and (c) NiTa/heat sink/function layer 6nm/MgO 3nm/FePt-C

![Graph showing hysteresis loops of FePt-C based HAMR media](image)

**FIG. 2** Hysteresis loops of FePt-C based HAMR media with different layouts

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INFLUENCE OF THERMAL FLUCTUATIONS ON AREAL DENSITY IN HEAT ASSISTED MAGNETIC RECORDING

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I. INTRODUCTION

Heat assisted recording is believed as the most promising candidate for future high density magnetic recording. Within this work we investigate the potential of heat assisted recording based on micromagnetic simulation at finite temperature. In particular the study elucidate the question how confined bit transitions can be written when the ambient temperature during recording is close to the Curie temperature. As a consequence highly thermally exited state are present leading to thermally induced transition noise and DC noise. As pointed out in Ref [1] a dilemma between small thermally written in errors [2] and sharp bit transition occurs in HAMR. We want to address this central question and investigate the potential in areal density of different HAMR techniques, where continuous or pulsed heat spots are applied to a bit patterned recording medium. Moreover, the effect of shingled as well as conventional (centered) recording is analyzed. To correctly describe the magnetization dynamics during high temperatures in a reasonable amount of computation time a coarse grained Landau-Lifshitz-Bloch (LLB) model is used. The switching behavior of monolayer as well as composite structures with graded Curie temperature under different external conditions is examined by means of this model.

III. RESULTS

LLB simulation of single islands of a BPM are performed under the action of the write field and heat spot. In pulsed laser spot recording (PLSR) a short temperature pulse is applied which is assumed to be significant shorter than the field pulse. In constant laser spot recording (CLSR) a continuous laser heating is assumed and magnetic field pulses are applied. For both recording techniques the bit error rate (BER) is calculated as function of the spacing in x and y direction of the magnetic islands (center to center distance). The islands have a diameter of \( d=5 \text{ nm} \) and a height of \( h=10\text{ nm} \). The total BER of bit \( B \) is the product of the joint probability to successfully write the bit \( B \), but not the previous bit \( D \) on-track and not the adjacent bits \( A \)i off-track, \[ \text{BER} = P_B (1-P_B) \prod_{i=0}^{n-1} (1-P_A) \]. The exponent \( n \) denotes the number of write processes for which all adjacent bits have to retain their state. In the case of shingled writing \( n=1 \), whereas in the case of centered recording \( n=1000 \).

Fig. 1 shows the BER for different grain spacing for a) shingled and b) conventional recording for a graded Curie temperature medium consisting of a hard magnet with low \( T_C \) and soft magnet with high \( T_C \). The write field amplitude is 0.8 T. On the left a map of the number of possible head positions for different grain spacing \((l_x \text{ and } l_y)\) under the constraint of a BER < 10^{-3} is shown. The purple area shows island spacing (which directly leads to areal density) where within a head position error of 2.5 nm x 2.5 nm the BER < 10^{-3}. In these simulation no distributions in \( T_C \) or other material properties are assumed. The limitation in the areal density is purely due the stochastic process at finite temperature, which introduces switching temperature distributions. For the case of centered recording an areal density of about 3 Tb/inch² is achieved and for shingled recording about 5 Tb/inch².

The recording performance is improved for CLSR as shown in Fig. 2. Here the best recording performance is obtained by a single phase media (FePt). This is in contrast to PLSR where the best performance is obtained for a \( T_C \) graded media. Without any intrinsic distributions the obtained areal densities are about 5 Tb/inch² and 10 Tb/inch² for centered recording and shingled recording, respectively. If a 3 % distribution of \( T_C \) is assumed the densities lower to 5 Tb/inch² and 4 Tb/inch² for centered recording and shingled recording, respectively.

REFERENCES

Fig. 1: (left) Island spacing for BER < 10^{-3} for pulsed laser spot recording (PLSR). (right) The BER is color coded for different head positions \((x,y)\). In the area marked by the black contour line the BER < 10^{-3}.

Fig 2: Same as Fig 1 for continuous laser spot recording (CLSR). The island is pure FePt and not a graded \(T_c\) structure as in Fig 1.
With the recent 1.0[1] and 1.4[2] Tb/inch^2 basic technology demonstration, and drive level demonstration [3,4] heat-assisted magnetic recording (HAMR) [5] has proven to be a viable and promising technology for future magnetic data-storage products. The commercialization of HAMR presents some significant technical challenges that need to be resolved before the widespread adoption of the technology can begin. Head to media spacing (HMS) has long been a key input for recording scaling. The dependence and sensitivity for new recording technologies must be bounded in order to understand opportunities and risks.

In this paper, we compare and contrast the HAMR write and readback processes. The readback process shares similarities with the conventional Perpendicular Magnetic Recording (PMR) readback process, but is distinguished by increased curvature in HAMR recorded patterns and the increased spacing due to coatings (head and media) and media roughness [6]. Experimental and modeled reader HMS sensitivities are compared at high density recording conditions with PMR. Understanding these different characteristics enables us to better project reader HMS requirements for the HAMR system.

HAMR relies upon focused energy using near-field plasmonics technology during the write process to elevate the media temperature close to the Curie point [5]. A significant challenge in HAMR is the definition and control of the writer clearance in the presence of large protrusions [6], temporal variation of the thermal...
expansion [7], and the impact of interface materials, including lubricant, on the write process [8, 9]. We explore the influence of the NFT clearance control on the recording performance. HAMR models and measurements are compared in order to better understand the influence of optical spacing vs. clearance control. Curvature, jitter, and noise breakdown techniques are exploited in order to isolate relative contributions with the write clearance. Using this information we can bound the NFT design requirements and compare to the recording roadmap requirements [10].

Fig. 2 Measured Areal Density (AD), Linear Density (LD) and Track Density (TD) capability for a HAMR head vs. clearance, laser power re-optimized for each clearance level.

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I. Abstract

Heat Assisted Magnetic Recording (HAMR) is pushing frontier of generating <100nm thermal spots using plasmonic methods, and managing 400C generated in the nano-scale structures to achieve required lifetimes. Requirement to efficiently use optics to excite plasmons for high electric field generation and localization, the coupling of these fields from the recording head into the recording media, and the mix of electron dominated and phonon dominated dissipation mechanisms, under both ballistic and diffusive regimes, places unique constraints on HAMR engineering methods and options. This talk will outline some of these challenges, with the focus on topics which the academic community can engage.

Fig. 1 Example of elastic protrusion.

Figure 2. Grain growth in NFT material

Figure 3. Temperature measurement
CHARACTERIZATION OF PLASMONIC NEAR FIELD TRANSDUCERS FOR HEAT-ASSISTED MAGNETIC RECORDING

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I. INTRODUCTION

Heat-assisted magnetic recording (HAMR) has the potential to keep increasing the areal density in the next generation HDDs by using nanoscale optical antenna, called near field transducer (NFT) to locally and temporally heat a sub-diffraction-limited region in the recording medium. The NFTs made of plasmonic nanoscale optical antenna provide the capability of sub-wavelength light manipulation at optical frequencies. These antennas are designed using both plasmonic resonance and localized plasmons to produce an enhance field in an area far below the diffraction limit. To reduce the self-heating effect in the NFT, which could cause materials failure that lead to degradation of the overall hard drive performance, the NFT must deliver sufficient power to the recording medium with as small as possible incident laser power. In this talk, we present the design and characterization of these plasmonic antennas and the effect of optical properties on field localization, absorption and coupling efficiency. Computations of heat dissipation and the induced temperature rise in NFT are carried out to study their dependence on materials’ properties. With the recent significant interests in searching for alternative low-loss plasmonic materials in the visible and near infrared range, the possibility of using alternative plasmonic materials for delivering higher power and simultaneously reducing heating in NFT are investigated. NFT characterization using scanning near-field scanning optical microscopy (s-NSOM) will also be discussed.

II. EXPERIMENTAL DETAILS

We developed scattering near field scanning optical microscopy (s-NSOM) to characterize NFTs. In s-NSOM, a metallic or dielectric tip is used to scatter the optical near field around nanostructures. The scattered field is detected in the far field with a resolution beyond the diffraction limit, which is generally dominated by the Z component (the out-of-plane component, E_z). An accurate interpretation of the field distribution produced by nanostructures will require a characterization of both the in-plane and out of plane components. Thus it is beneficial to explore the method for the detection of in-plane component with s-NSOM. The optical field distribution in the space above the nanostructures is also critical. With these considerations, the method of mapping three-dimensional (3D) distribution of optical near field was developed, providing a full 3D characterization of the complex vector fields around the designed NFT structures.

III. RESULTS

Figure 1 shows the amplitude and phase distributions of the E_z field, together with an illustration of the scanning process for the 3D mapping. The sample is a bowtie antenna aperture made in gold film. As shown in Fig. 1(a), at each XY position in the horizontal plane, a sweep of the piezo stage is performed, producing several line curves with relations between the measured quantities and the Z movement of the piezo stage. From these curves, the optical field at this location can be obtained. By repeating the same process through every point in the XY plane, a 3D field distribution is constructed. In Fig. 1, the optical field distribution has been overlapped with the measured topography (back shading), illustrating the height relation between the structure and the measured field. Figure 1(b) clearly indicates the concentration of E_z field near the edges of the aperture gap. It also reveals that the fields are tightly bounded to the structure surface and following the curvatures of the edges. Because of the existence of curvatures of the fabricated antenna, the hot spots spread over the corner, leading to an increase in the size. The characteristic 180° phase shift between the spots is also clearly resolved in Fig. 1(c). The dimensions of the model used in the simulation are from AFM topography measurement. The calculated amplitude and phase distributions are shown in Fig. 3(c) and (d), which generally confirm the validity of the experiment results.

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Figure 1. (a) Illustration of the scanning process for 3D mapping. Overlapped image of sample surface and measured optical (b) amplitude and (c) phase of $E_z$ in $XZ$ plane across the gap of the bowtie aperture, and the corresponding simulation results of (d) amplitude and (e) phase.
Nanoscale Characterization of HAMR Heads Using Polymer Imprint Thermal Mapping
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I. INTRODUCTION
A number of systems require high-resolution, non-perturbative thermal mapping. This need is especially apparent for Heat-Assisted Magnetic Recording (HAMR), a technology developed to increase the areal density for magnetic storage. In HAMR, plasmonic antennas are used to heat magnetic media by hundreds of degrees in a nanoscale region. Understanding the antenna’s temperature is critical, but the available methods for high-resolution thermal mapping are dominated by experimental artifacts [1-3]. In order to measure the temperature distributions of a plasmonic antenna without major perturbation, a new technique, Polymer Imprint Thermal Mapping (PITM), was developed, which relies on the thermal response of a thin polymer film to report temperature. The polymer crosslinks permanently upon heating, so the thermally induced height change of the polymer film is directly correlated to the sample temperature. It is experimentally shown that PITM creates thermal maps that are far superior to conventional Scanning Thermal Microscopy (SThM). In addition, modeled thermal distributions show remarkable agreement with the measured PITM thermal maps.

II. RESULTS
Scanning Joule Expansion Microscopy (SJEM) [4] uses changes in a polymer film to detect temperature. In SJEM, the sample is coated with a thin polymer film that is heated with a pulsed source, such as a pulsed laser. With each heating pulse, the polymer expands and contracts; this periodic height change can be measured with AFM by locking in to the frequency of the pulsed heat source. PITM is similar to SJEM, but with one critical improvement: PITM uses a polymer that deforms permanently under heating. As depicted in Figure 1, there are 3 steps to PITM. Figure 1a shows the first step, wherein a reference topography image is measured using AFM. Next (Figure 1b), the antenna is laser heated in pulsed mode for a set amount of exposure time, which is 3 minutes for all experiments in this paper. It is important that the AFM tip is retracted for this thermal annealing step, so that the only perturbation is the presence of a thin, transparent polymer layer during heating. Figure 1c shows the last step, measurement of the permanent deformation of the polymer with a final AFM topography image. By analyzing the change in the polymer’s thickness, the temperature of the polymer during thermal annealing step is measured. Oven annealing experiments can be used to calibrate the polymer response.

PITM was performed on two E-antenna geometries (Figure 2a,b). These two geometries differ in their heat sink (HS) design. Thermal annealing was again accomplished through an integrated laser aligned to the entrance of the waveguide. Since the laser is integrated with the waveguide, it is difficult to know precisely how much light reaches the plasmonic antenna. The laser power was therefore chosen such that both antennas magnetically wrote HAMR media similarly, so the waveguide entrance for E-antenna 1 and E-antenna 2 were excited with 12mW and 22mW of 830nm light respectively. The difference in laser power needed for writing is mainly attributed to alignment of the laser to the waveguide. E-antenna 1 (Figure 2a) has a much broader temperature profile than E-antenna 2 (Figure 2b). This difference is attributed to the difference in the thermal shunt designs for the two antennas and is in excellent agreement with the optical and thermal modeling results (Figure 2c,d).

PITM, a novel thermal mapping technique, has been demonstrated to be both minimally perturbative to the plasmonic antenna, as well as immune to artifacts from direct optical absorption. Direct comparison between mapping using SThM and PITM for the E-antenna shows that PITM creates nanoscale thermal maps that much better reproduce modeled predictions. This technique is ideally suited to measuring any thermal map where a significant amount of light is present, such as plasmonic antennas, or where the presence of an AFM tip during he ANIKA KINKHABWALA
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II be given in the full paper.

vES

**FIGURES**

Fig. 1 a) Schematic of polymer (V3D3) coated E-antenna. The first step of PITM is to measure a reference AFM topography image. b) Next, the E-antenna is heated by light, imprinting the temperature profile into the polymer film. c) A final AFM topography image is taken to measure the imprinted polymer film.

Fig. 2 a) PITM temperature map of E-antenna 1 geometry (poor thermal shunt design). b) PITM temperature map of E-antenna 2 (better thermal shunt design). c) Modeled HOC temperature distribution for E-antenna geometry 1. d) Modeled temperature distribution of E-antenna geometry 2.
EFFICIENT INTEGRATED LIGHT DELIVERY SYSTEM DESIGN FOR HAMR: MAXIMAL OPTICAL COUPLING FOR TRANSDUCER AND NANOWAVEGUIDE

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I. INTRODUCTION

Improving the efficiency of light-delivery system that consists of laser, waveguide and near-field plasmonic transducer (NFT) would reduce the power requirement of the laser diode for heat-assisted magnetic recording (HAMR) technology. The overall efficiency of light delivery system is determined by waveguide-to-media coupling via NFT and laser-to-waveguide coupling. For improving the efficiency of waveguide-to-media coupling via NFT, we present a novel design strategy to account for all structural and material parameters for a simple taper-based NFT, and show that the structural optimization together with material-dependent impedance matching between the feeding-waveguide and the media, and improved dielectric-to-plasmonic mode-conversion in transducer maximizes the efficiency of optical energy coupling into the media to >10% over a spot-size of 50nmx50nm. This design strategy is different from previous works, where different NFT structures are considered, and structural optimizations are carried out for a fixed set of materials [1]. For improving the efficiency of laser-to-waveguide coupling, a graded refractive index (GRIN) layers-based cladding, shown in Fig. 1(a) is designed to collimate the light beam with a sub-wavelength spot-size from the laser diode. This integrated GRIN lens has an aberration-free design and a high numerical aperture, which enables a coupling efficiency of ~90%. The experimental realization of this integrated GRIN multilayer can be based on tuning the material composition during deposition.

II. DESIGN PHYSICS AND RESULTS

Waveguide-to-media coupling: NFT is designed by structurally optimizing the transducer for different feeding waveguide materials as shown in Fig. 2(a). Then the transducer efficiency, defined as the ratio of the power absorbed over a volume of 50nmx50nmx10nm in the media to the incident optical power is calculated. A maximum efficiency of ~11.5% is achieved at ~950nm wavelength when silicon feeding-waveguide is used and ~3.5% at ~930nm wavelength when TiO2 feeding-waveguide is used. However, in a longer wavelength regime of 1200nm-1400nm, maximum efficiency is ~8% at ~1250nm wavelength. For the considered structure, the high index waveguide yields high efficiency because the transducer behaves as a resonator between waveguide and the media. So, as shown in Fig. 2(b), the peak efficiency of the considered transducer reaches its global maxima when feeding waveguide refractive index is closer to that of silicon. This is because of: 1) improved wave impulse matching between high-index silicon feeding waveguide and high-index recording media that reduces reflection loss by ~5x compared to that of TiO2 waveguide, and 2) improvement in mode conversion efficiency by ~5x compared to that of TiO2 waveguide that is facilitated by a strong intermediate mode formed in the layer between metal and waveguide, when high-index silicon waveguide is used [2]. Hence, apart from structural optimization, improved impedance matching and mode-conversion efficiency enables us to maximize the transducer efficiency to its global maxima. So, a right feeding-material along with structurally optimized dimensions could enable any other transducer structures such as the C-aperture, Lollipop, butterfly etc., to operate at its global maxima of waveguide-to-media coupling efficiency.

Laser-to-waveguide coupling: A mode-converter is commonly required for an efficient coupling between off-chip laser diode and nanowaveguide. The waveguide-based mode-converters typically are long with length >200 μm, and grating-based coupler exhibits limited coupling efficiency and has stringent alignment requirement. An alternative approach is to use an integrated graded refractive index lens that can perform sub-wavelength focusing with a much shorter length (e.g.,<20 μm), because of high numerical aperture [3]. The GRIN lens structure, proposed in this work acts as cladding layers for the nanowaveguide but collimates the light beam on the waveguide end. This simplifies the fabrication procedure as compared to [3] since it doesnot require multi-layer etching, but retains the high coupling efficiency provided the refractive index of the bottom layer of the GRIN lens n0 is properly designed. The graded refractive index profile is designed via a computational algorithm for aberration-free focusing. As a numerical design example, Fig. 3(a) gives coupling efficiency under different refractive index n0 of the bottom-most GRIN layer, which shows that the coupling efficiency can be ~90%, if refractive index n0 >=2.4. The dependence of coupling efficiency on different number of layers in Fig. 3b shows that around 12 layers could provide ~90% efficiency. This designed GRIN lens can be realized by controlling the material composition. For example, by tuning the flow rates of Silane, Nitrogen and Nitrous oxide in inductively coupled plasma chemical vapour deposition (ICP-CVD) system, silicon-rich nitride can be transformed into silicon oxy nitride at temperatures <250°C, to vary the refractive index from ~3.0 to ~1.6 of deposited film. So, for the considered taper-based transducer and GRIN lens
structures, a high-index feeding-waveguide could enhance the transducer efficiency to >10%, as well as the GRIN lens coupling efficiency to ~90% to provide an overall light-delivery efficiency >9%.

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Fig. 1 (a) Cross-sectional side view of the center of light-delivery system with taper-based transducer and GRIN lens-based cladding layers. There is a gap of 20nm between transducer metal layer and waveguide, and 20nm gap between GRIN lens cladding and transducer metal layer. The transducer metal is 30nm thick. (b) Top view of light-delivery system in the waveguide plane. The taper length is in the range of 350nm-550nm, depending on the waveguide refractive index and operating wavelength.

Fig. 2. (a) Transducer efficiency in comparison to transducer-specific efficiency limit when high index silicon and low index TiO2 waveguides are used. (b) Peak transducer efficiency as a function of feeding-waveguide refractive index. Transducer efficiency is evaluated by normalizing the amount of optical power absorbed in the media over a volume of 50nmx50nmx10nm with respect to the optical power in the waveguide.

Fig.3a) Coupling efficiency vs the refractive index of the bottom most GRIN layer that increases to >90% when n0>2.6. Inset shows the spatial profile of focusing of beam through the GRIN lens and propagation in the nanowaveguide. b) Coupling efficiency when different number of GRIN layers is considered.
NOVEL TRANSDUCER AND COUPLING ARRANGEMENT FOR A HEAT ASSISTED MAGNETIC RECORDING

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I. INTRODUCTION

Growing research field of plasmonics associated with its two main ingredients i.e., surface plasmon polaritons (SPP) and localized surface plasmon resonances (LSPR) rely upon the high degree of concentration of electromagnetic fields in the vicinity of metal surfaces which is well beyond that allowed by the diffraction limit. Those allow to develop a new technique called the heat assisted magnetic recording (HAMR) to overcome an existing limit of conventional magnetic recording utilizing a near-field transducer (NFT) [1]. The NFT design is based on excitation of surface plasmons on a metal structure, which couple light with a sub-diffraction limited light spot and confined in the near field.

II. RESULTS

We proposed a novel “droplet” near-field transducer (NFT) and a light delivery system to the NFT for a heat assisted magnetic recording (HAMR) head using a Mach-Zehnder Interferometer (MZI) waveguide arrangement with a TE mode coupled to the planar waveguide from a single mode fiber [2]. The proposed design offers great flexibility in the coupling of light to the NFT in order to match the radiation pattern of the antenna and thus to optimize the energy transfer. Furthermore, it allows excitation of particular surface plasmon (SP) resonances of the transducer (quadrupole or higher) by controlling the coupling angle and the phase of the two beams of light (Fig. 1). The optimum phase shift between the transverse electric (TE) waveguide modes incident on either side of NFT can be achieved either statically by making one of the MZI arms longer/shorter compared to the other one, or dynamically by changing the mode effective index of the MZI waveguide arm through electro-optic or thermo-optic modulation. In addition, the proposed MZI waveguide arrangement enables easier coupling from a laser with a coupling losses from laser to MZI waveguide being below a 3 dB and the design enables an arrangement with a NFT placed either on the top of the waveguide at the termination side of the MZI or between the rib and ridge in maximum of the electric field of the waveguide which maximizes the SP resonance enhancement of the NFT. Another advantage is that the magnetic-write pole, in our design, can be easily integrated on the same chip, preferably above the center of the MZI, between both arms of the interferometer and away from the propagating mode thus avoiding blocking of the intended light path.

The proposed “droplet” NFT (Fig. 2) takes full advantage of the Mach-Zehnder Interferometer (MZI) - coupling arrangement to allow in more efficient way couple a light to a transducer [3]. Apart from it, it ensures better impedance match with a recording media and, consequently, better coupling of power to a recording media even operating at the same excited resonance mode of the antenna. And finally, this novel transducer design allow to confines a light in a spot size much smaller than present state-of-the-art lollipop transducer integrated in planar geometry.

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Fig. 1. Mach-Zehnder interferometer planar waveguide arrangement for coupling light to a near-field transducer (a) with a desirable quadrupole current distribution (b) to efficiently couple the light to the recording media for a transducer located at the output Y junction (c). Two possible transducer locations: between the rib and the ridge (d) and on the top of the ridge waveguide (e).

Fig. 2. (a) Electric field enhancement of the lollipop and droplet transducers in close proximity (0.5 nm) to an image plane. (b) Electric field distribution along the width of transducers through the center at distance of a 7 nm from transducer and normalized to the $E_0$. (c), (d) Electric field profile (logarithmic scale) through a cross-section of (c) droplet and (d) lollipop transducers.
EFFECTS OF SPACER MATERIALS IN HEUSLER-ALLOY-BASED CPP-GMR DEVICES FOR READ SENSORS

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I. INTRODUCTION

Co-based Heusler alloys have been extensively investigated as ferromagnetic (FM) layer of CPP-GMR devices because of their high spin polarization of conduction electrons. Many efforts have been done for improving the MR output of CPP-GMR by improving the spin polarization of Heusler alloy FM layers. Another possible approach for enhancing the MR output would be to select a proper material for the spacer layer. According to the Valet and Fert's model of CPP-GMR [1], the MR is comprised of the bulk and the interface components. While the bulk component results from the spin polarization of FM layers, the interface component depends on the band matching and structure of the FM/NM interfaces. In a theoretical work of selecting the spacer material, Ambrose and Mryasov [2] predicted that the materials with the L2₁ structure such as non-magnetic Heusler alloys might be advantageous over fcc metals such as Cu or Ag because of excellent band matching with the FM Heusler alloys. Based on this expectation, Nikolaev et al.[3] reported 6% MR ratio from the CPP-GMR device consisting of Co₂MnGe and Rh₂CuSn. However, the MR rapidly decreases as the spacer thickness because of the short spin diffusion length of the spacer layer. Thus, we still need to explore proper materials for obtaining high MR.

In this paper, we describe CPP-GMR devices using Co₂Fe(Ga₀.₅Ge₀.₅) (CFGG) Heusler alloy for FM layers and CsCl-type B₂ alloys, NiAl, CuZn and AgZn, for the spacer layer. For NiAl, we prepared epitaxial layers with the different crystal orientations, [100] and [110], and examined the orientation dependence of MR. The alloys CuZn and AgZn were selected as B₂ alloys without heavy or magnetic elements for eliminating strong spin and spin-orbit scattering effects in the spacer layer. We expected the enhancement of the interface component of the CPP-GMR.

II. EXPERIMENTAL

The films for pseudo-spin-valve type CPP-GMR devices with the (001) epitaxial layers were deposited by magnetron sputtering on MgO(001) single crystalline substrates. The stacking structure was sub./Cr(10)/Ag(100)/NiAl(10)/CFGG(10)/NiAl(5)/CFGG(10)/NiAl(5)/Ru(8) and sub./Cr(10)/Ag(100)/CFGG(10)/CuZn or AgZn(5)/CFGG(10)/Ag(5)/Ru(8), where the numbers indicate the thicknesses in nm. The samples were also prepared on sapphire (110) substrates with the layer structure sub./Ta(20)/W(100)/NiAl(10)/CFGG(10)/NiAl(5)/CFGG(10)/NiAl(5)/Ru(8) for attaining the epitaxial growth with the (110) orientation of CFGG and NiAl [4]. The samples were annealed at high temperatures for obtaining better structural ordering of CFGG. The structure of the samples was examined by X-ray diffraction, cross sectional TEM, nano-beam electron diffraction and EDS. MR properties were measured by conventional DC method after fabricating the pillars with the submicron sizes for measuring in the CPP configuration.

III. RESULTS AND DISCUSSION

X-ray diffraction and cross sectional TEM observations indicated the epitaxial growth of each layer up to the upper Ag layer. The spacer layer of NiAl and AgZn was in the B₂ structure. The CuZn layer showed very weak (100) reflections and the degree of the B₂ order seems low. Figure 1 summarizes the change of the resistance area product, ΔRA, obtained from the MR measurements at room temperature against the annealing temperature of the samples. The devices with the NiAl spacer show rather low values of ΔRA. This would be attributed to the loss of MR due to the short spin diffusion length in the NiAl layer. It is notable, however, that the values are similar for the two crystal orientations, (001) and (110). This is quite different from the results of the same experiments with fcc
Ag and Cu used for the spacer; $\Delta RA$ is higher in the devices with the (100) epitaxial layers of CFGG than the (110) orientation [5]. This was attributed to the large leading the structural disorder. In contrast, the combination of the Heusler alloys and the B2 alloys gives good lattice matching at the interface for any crystal orientation. Thus the MR is not affected by the crystal orientation.

The results for the CuZn spacer show larger $\Delta RA$ than the results with the Ag spacer [6] for $T_a$ lower than 400°C but it decreases for higher $T_a$. The decrease is attributed to the change of the layer structure due to interlayer atomic diffusion. In contrast, $\Delta RA$ for the AgZn spacer keeps increasing to 20.5 mΩ·μm² at $T_a$=630 °C. The resistance area $RA$ for the parallel magnetization configuration ranges from 30 to 40 mΩ·μm² for the both CuZn and the AgZn spacer. The values are somewhat larger than that for the case of the Ag spacer. ~20 mΩ·μm² in the previous report.

The TEM and EDS studies of the samples with the AgZn spacer showed that the layer structure is unchanged to $T_a$=630 °C. However, the Zn atoms have almost diffused out of the film and the spacer layer consists of Ag. The L2₁ order of the CFGG layers examined by X-ray diffraction was found to be higher than the sample prepared with the Ag spacer layer and annealed in the same condition at 630 °C. The results indicate that the L2₁ order is somehow enhanced when the Zn atoms diffuse through the CFGG layers. The enhancement of the L2₁ order would lead to the increase of spin polarization and thereby the enhancement of $\Delta RA$.

Another possible mechanism for the enhanced $\Delta RA$ for the lower annealing temperatures would be the enhancement of the interfacial component of MR by the spacer materials CuZn or AgZn. The interfacial component of $\Delta RA$ is expressed approximately by $2\gamma^2 R_{F/N}/(1-\gamma^2)$. $R_{F/N}$ is the resistance of the FM/spacer interface and $\gamma$ is the interfacial spin asymmetry factor. The increase of $RA$ by using CuZn or AgZn in place of Ag for the spacer come from the possibly increase of $R_{F/N}$. Then $\Delta RA$ would be enhanced through the above relationship.

IV. SUMMARY

CPP-GMR devices using the B2-type alloy, NiAl, CuZn and AgZn for the spacer layer were prepared and the structural and the MR properties were examined. The MR properties were shown to depend strongly on the selection of the spacer material. Enhancement of $\Delta RA$ in comparison to the Ag spacer was observed for CuZn and AgZn. These alloys are promising spacer materials to be combined with Heusler alloy magnetic layers for obtaining high MR outputs.

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Fig. 1: $\Delta RA$ plotted against the annealing temperature for the CPP-GMR devices consisting of indicated materials.
CPP-GMR effect using Ag-Mg ordered alloy spacer layer and Heusler alloy Co2(Fe,Mn)Si electrodes

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I. INTRODUCTION

Heusler alloys have attracted great interest because of the half-metallic electronic structure [1] which creates fully spin polarized current and enhances signals in various kinds of spin-dependent phenomena. One typical example is current-perpendicular-to-plane giant magnetoresistance (CPP-GMR) effect using cobalt (Co) based full Heusler alloys, such as Co2MnSi, Co2(Fe-Mn)Si, Co2Fe(Al-Si), and Co2Mn(Ga-Ge) [2–7]. The change of resistance area product (ΔRA) value was on the order of 10 mΩμm2, in the cases of CPP-GMR junctions using Co-Heusler alloy electrodes and an Ag spacer layer [6, 7]. The ΔRA value was much larger than those for the junctions using conventional 3d-transition metal electrodes (e.g. Co-Fe alloys). Regarding the investigation of spacer material for CPP-GMR junctions, several earlier experimental studies were reported, for example, Rh2CuSn [8], ZnO [9], B2 NiAl [10], and In-Zn-O [11]. These studies succeeded in enhancing the ΔRA values to some degree; however, the output is still not sufficient for practical applications, such as next-generation hard disk drives. In this work, we have investigated a new spacer material, Ag-Mg alloy to increase the ΔRA value. Ag-Mg alloys form the ordered L12 structure for the Mg composition ranged from 12 to 25 at.% [12], and it was reported that the resistivity value was higher than that of pure Ag [13]. We may expect that the increase of resistivity value causes the increase of RA, and ΔRA also increases in case that the MR ratio for Ag-Mg keeps the same as that for pure Ag.

II. EXPERIMENTAL PROCEDURE

Multilayer samples were prepared by an ultrahigh-vacuum magnetron sputtering system. The stacking structure consists of MgO(100) sub./Cr (20 nm)/Ag (40 nm)/Co2Fe0.4Mn0.6Si (CFMS) (20 nm)/Ag or Ag-Mg (5 nm)/Co2Fe0.4Mn0.6Si (7 nm)/Ag (2 nm)/Au (5 nm). All layers were deposited at room temperature and in situ post-annealing was performed after the deposition of the Cr layer and the top CFMS layer at 650°C and 500°C, respectively. The composition of the Ag-Mg layer was Ag80Mg17 at.%. The samples were patterned into pillar-type structure using electron-beam lithography and Ar ion dry etching technique. The CPP-GMR effects were measured by direct current 4-probe method at room temperature.

III. RESULTS AND DISCUSSIONS

RA values of junctions were estimated from the plots of the junction resistance in parallel magnetization configuration (R paralle) as a function of the inverse of junction area (1/A). RA values of 26 mΩμm2 and 51 mΩμm2 were obtained for the junctions using an Ag spacer and an Ag-Mg spacer. Observed (intrinsic) MR ratios were 35% (48%) and 36% (44%) for Ag and Ag-Mg, respectively. Here the intrinsic MR ratio (MR int) was defined as MR int = (R AP – R P)/(R P – R para), where R AP and R para denote the resistance in anti-parallel magnetization configuration and the parasitic resistance of the junction, respectively. Because of the large RA, the ΔRA value for Ag-Mg was 23 mΩμm2 which was larger than that for Ag, 13 mΩμm2. These results indicate that the Ag-Mg spacer layer is useful for increasing the output of CPP-GMR junctions [14].

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IV. SUMMARY

CPP-GMR junctions using Co$_2$Fe$_{0.4}$Mn$_{0.6}$Si Heusler alloy and Ag-Mg spacer was investigated. The value of $RA$ was found to be 51 mΩμm$^2$, which was higher than that of the conventional Heusler alloy CPP–GMR junctions using Ag spacer layer. Intrinsic values of MR ratio for the junctions using Ag–Mg and Ag spacer layer were 44% and 48%, which provide $\Delta RA$ values of 23 mΩμm$^2$ and 13 mΩμm$^2$, respectively. The $\Delta RA$ value increased successfully by a use of the Ag-Mg alloy as a spacer layer material.

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RECENT PROGRESS IN CPP-GMR READERS FOR > 1 TBIT/IN²

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I. INTRODUCTION

The ever-decreasing lateral sensor size, required for high-density HDDs, places severe demands on magnetoresistive sensor technology in order to maintain the substantial signal-to-noise ratios (SNR). Tunnel magnetoresistance (TMR) sensors with MgO barrier have been used for almost 10 years for the higher signal amplitude by the high TMR, despite having still-high resistance and therefore high Johnson noise. As sensor size scales are further reduced, sensor mag-noise (proportional to MR signal) becomes dominant and therefore reducing the sensor resistance in order to reduce the total sensor noise becomes a priority.

Consequently, current-perpendicular-to-the-plane giant magneto-resistive (CPP-GMR) sensors, with resistance-area products ($RA \sim 0.05 \Omega \mu m²$) about 10 times lower than state-of-the-art MgO TMR sensors, are of interest for ultra-high density (>1 Tb/in²) recording due to their intrinsically-low resistance at very small lateral dimensions.[1] Nevertheless, the optimization of CPP-GMR technology has remained a tremendous challenge due to the difficulty of obtaining large MR signals (>10%) with conventional magnetic materials in practical sensors, and the severe limitations placed on the sensor current due to spin-torque effects which can introduce additional noise and destabilize the magnetic layers.

Specific to recording sensor applications, there are a number of process limitations and geometrical constraints. First, the CPP-GMR sensor pillar must be fabricated with ultra-narrow width (~25nm for >1 Tb/in²) to achieve sufficient crosstrack resolution. Second, the sensor must be grown on an adequate magnetic shield surface, currently CMP-polished polycrystalline NiFe, which cannot be subsequently annealed to temperatures > 300-350 °C. Finally, the total thickness of the sensor stack must fit within the maximum shield-to-shield spacing (~25nm for ~1 Tbit/in²) suitable to achieve sufficient data bit resolution along the track direction. Consequently, the active magnetic free and reference layers in the spin-valve sensor must be ultrathin, typically <5nm.

II. EXPERIMENTAL DETAILS

We have investigated the use of specialized materials in multilayer spin-valve structures of NiFe shield / Underlayer (UL) / Antiferromagnet (AFM) / Pinned layer (PL) / Ru / Reference layer (RL) / Spacer / Free layer (FL) / Cap layer / NiFe shield. We utilized Co$_2$(Mn$_{1-x}$Fe$_x$)Ge Heusler alloys in the FL and RL [2], thin IrMn AFM with exchange coupling > 1 erg/cm², a AgSn alloy spacer providing smooth and thermally-stable interfaces, specialized FL multilayer structures to reduce the effect of spin-torque.

Sensors were fabricated by a combination of optical lithography and Ar ion milling at various incident angles to optimize the shape of the sensor. The FL magnetization was stabilized by adjacent biasing magnet structures. The sensor output was evaluated under both quasistatic conditions in fields +/- 600Oe, and in a spin-stand setup under standard high-density perpendicular recording conditions.

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III. RESULTS

Figure 1 shows a quasistatic sensor response as a function of sensor bias, demonstrating stable and noise-free MR transfer curves in laterally ~20 nm sensor even at voltage bias > 90mV, corresponding to significant sense currents of about $2 \times 10^8$ A/cm$^2$. A similar behavior is observed in spin-stand sensor output amplitude as a function of bias voltage, with linear amplitude increase up to ~3mV, until spin-torque-induced excitations increase significantly around ~100mV, resulting in maximum SNR. An example of stable and quiet head microtrack profile (Fig.2), demonstrating high sensor lateral resolution, shows that ultra-narrow CPP-GMR sensors with high spin-polarization Heusler alloys are well-suited to high density recording applications. For a physical sensor width of ~22 nm, a magnetic read profile width of ~28 nm is obtained with maximum SNR (350 MHz bandwidth) close to 32dB.

Recently, we developed another new materials for CPP-GMR spin valve sensors. Figure 3 shows $R_A$-MR of test devices with a AgSn spacer for comparison and with new materials. The spin-valve structure is the same as mentioned above and with Heusler alloy layers both in RL and FL. The total sensor film thickness including the UL and the capping layer is 27 nm. By using the new materials, $R_A$ was increased to up to $0.1 \, \Omega \, \mu$m$^2$, which is in the suitable $R_A$ range for 2 Tbit/in$^2$ sensors [3], and MR was enhanced up to ~26%. Therefore, the performance of CPP-GMR readers can be further improved.

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MICROWAVE-ASSISTED MAGNETIZATION REVERSAL IN CoCrPt-BASED GRANULAR FILMS USING A LINEARLY POLARIZED MICROWAVE FIELD WITH A WIDTH OF SEVERAL TENS OF NANOSECONDS

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I. INTRODUCTION

Improvement of writability in magnetic medium with a strong magnetic anisotropy is an urgent issue to increase an areal packing density beyond 1 terabit per square inch. A switching field reduction by applying a strong microwave field, i.e. microwave-assisted magnetization reversal (MAMR), is one of the promising candidates to solve the serious writability problem. From the viewpoint of practical application of MAMR to hard disk drives, both the operation frequency and the threshold amplitude of ac field impulse for successful MAMR should be quantitatively studied. In general, there are two methods to generate ac magnetic field. One is the method using a field generating layer (FGL) embedded in a spin torque oscillator [1] and another is using a near-field of a micro-fabricated coplanar waveguide (CPW). The FGL can easily produce a rotating field synchronized with a precession of magnetization so that a ferromagnetic resonance which is essential for the MAMR is efficiently excited. However, it is hard to measure the amplitude of rotating field and to check the stable oscillation of magnetization in the FGL. On the contrary, it is easy to electromagnetically evaluate the amplitude of ac field generated by the CPW. Furthermore, both the amplitude and frequency of the ac field can be widely changed although the ac field is not circularly but linearly polarized. The linearly polarized ac field consists of a linear combination of clockwise and counterclockwise rotating fields only one of which can contribute to the MAMR. Thus, the efficiency of MAMR using the CPW is reduced to half of the FGL. In this study, we utilized the CPW for the quantitative analysis of MAMR in granular ECC-like media. It is noted that the linearly-polarized ac field with an amplitude as large as 1 kOe was produced by decreasing the width of center conductor of the CPW down to 0.2 µm. We will present the experimental comparison of frequency-dependent reduction of switching field between single layered granular medium and ECC-like one.

II. EXPERIMENTAL

In our experimental setup, a magnetization reversal of a medium after applying an ac field impulse can be evaluated from the change in the ferromagnetic resonance (FMR) frequency [2]. Thus, a simple experimental setup similar to a vector network analyzer FMR spectroscopy is applicable to demonstrate the MAMR with an ac field impulse. We have performed the MAMR experiment on an exchange-coupled composite medium consisting of two CoCrPt-based granular films with different atomic compositions and with a same thickness. The two granular films were directly coupled with each other. The total thickness of granular ECC-like medium was fixed at 16 nm. The thermal stability factor $\Delta$ of the medium was set in the range from 68 to 91 which were experimentally determined from a dependence of coercive field on a sweep velocity of magnetic field in Kerr loop measurements. For the MAMR experiments, the films were patterned into a rectangle with a lateral size of 0.2 × 50 µm$^2$ followed by the fabrication of electrically shorted CPW on the rectangle. The width and length of the center conductor of the CPW were 0.2 and 50 µm, respectively. The CPW was electrically connected to both a vector network analyzer and a microwave synthesizer. The length of microwave impulse generated by the microwave synthesizer was fixed at 20 ns although the amplitude was varied in the range from 14 to 22 dBm. It is noted that the amplitude of microwave impulse was always calibrated at a given frequency by a broadband power meter.

RESULTS

while sweeping a magnetic field from 1 to -1 kOe for the
single and ECC-like media. The values of $\Delta$ and the static coercive field $H_c$ are ($\Delta=68$, $H_c=518$ mT) for the single medium and ($\Delta=76$, $H_c=592$ mT) for the ECC-like one. The FMR frequency at the remanent state of the ECC-like medium was obviously lower than the case of single medium although both $\Delta$ and $H_c$ values were smaller than those in the single one. It is noted that the Gilbert damping constant evaluated from the FMR linewidth is 1.5 times larger than the single medium. The result suggests that the precession of magnetization is not uniform along the thickness direction of the ECC-like medium. The broadening of FMR linewidth due to the nonuniformity of magnetization precession may be attributed to a moderate exchange coupling between two granular films in the ECC-like medium. Frequency-dependent reduction in $H_c$ for single and ECC-like media is compared in Fig. 2. The frequencies showing maximum reduction in $H_c$ for single and ECC-like media are 20 and 18 GHz, respectively. In the case of ECC-like medium, the frequency range appearing the $H_c$ reduction seems to be narrower than the case of single medium. These MAMR behaviors strongly depend on the strength of interlayer exchange coupling in the ECC-like medium.

IV. SUMMARY

We have experimentally demonstrated the MAMR in ECC-like medium using linearly-polarized ac magnetic field with an amplitude as large as 1 kOe. Both lowering and narrowing of MAMR frequency was observed in ECC-like medium with a total thickness of 16 nm.

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Fig. 1 FMR frequencies of single ($\Delta=68$, closed circles) and ECC-like ($\Delta=76$, open circles) media as a function of magnetic field.

Fig. 2 Frequency dependence of coercive fields for single (closed circles) and ECC-like (open circles) media.
Perspectives of Microwave Assisted Magnetic Recording at 2 Tb/in²

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I. INTRODUCTION

Heat-Assisted Magnetic Recording (HAMR) and Microwave Assisted Magnetic Recording (MAMR) are the two promising technologies that were proposed to maintain a high growth rate of recording density [1]. Compared to HAMR, MAMR is a resonance-based technology, which involves no or negligible heat during the writing process and therefore consumes less energy (greener technology). MAMR is also easier to integrate with the current recording system with slightly modifications on the head. MAMR, therefore, could be a competitive and greener technology towards energy assisted recording with recording density up to 2-3 Tb/in². The centre part of MAMR is the spin torque oscillator (STO) for the generation of localized AC magnetic field in the microwave frequency regime of 25-40 GHz for effective assisted writing on the recording media. Development of STO with low driving current, large operation window and high stability is one of the key enabling technologies that take MAMR to a new height. The STO needs to be placed between the main pole and the front shield in order to generate high enough AC magnetic field in recording media. There exists very strong alternating magnetic field between the main pole and the trailing shield (gap field), which acts on the STO and greatly affects the STO performance. Furthermore, due to very low flying height of 2-3 nm, the STO also senses the field from recording media. The media field is roughly normal to the gap field and lies in the magnetization-precession plane of the field generation layer, which disturbs magnetization precession, causing instability of STO, which is one of the key concerns for MAMR to take off. Currently, the current required to generate microwave with 25-35 GHz is too high [2], which not only leads to long term reliability concern but also results in non-uniform precession of field generation layer [2] and therefore lack of a strong dependence of frequency on current and having a strong dependence of frequency on the gap field. This makes it quite difficult to simultaneously adjust STO frequency and write field to optimize MAMR performance. Novel writing head and STO designs are needed to address those difficulties. On the other hand, from recording media point of view, it needs to have increasingly higher anistotropy energy to support higher recording density at smaller grain size. However higher anisotropy media impose a penalty of higher microwave frequency for the spin torque oscillators. Therefore MAMR media design with reduced frequency requirements at high media K_u is needed. As MAMR media reversal starts from the excitation of large angle precession of media magnetization by the AC magnetic field and magnetization switching happens through the magnetization precessional process with the presence of both DC and AC field, the magnetization damping of recording media plays a key role. It was reported to reduce the transition jitter to an acceptable level, at least one of the media layers needs to have a damping constant of more than 0.2 [2], which is much higher than the current PMR media. However, if the damping is too high, writing efficiency will be reduced and therefore high microwave power needed [2]. In principle, damping of recording media is strongly dependent on the media microstructure and media layer stacks (different magnetic layers are coupled together through exchange coupling). Understanding the damping mechanism in recording media with different microstructure and different layer stacks is critically important for the design of MAMR media with high writing efficiency (lower RF power and therefore lower requirements on spin torque oscillators, which is currently a key concern for spin torque oscillator) and narrow transition jitter. Although there are some reports on the damping in single layer media and CGC type media (from NIST) [2], due to difficulties in fabricating industry-grade recording media with different microstructures and different layer stacks and in characterizing damping of high anisotropy energy magnetic media (very high frequency required due to high Hk), there is a lack of systematic study on the characterization of damping in recording media with different microstructures and layer stacks, which is critical for MAMR media design and optimization. System level simulation on the MAMR media with different damping and different Hk/K_u for the optimization of MAMR media (balancing of high writing efficiency and narrow transition jitter) is also needed.

In this talk, the requirements on STO and media for MAMR at 2 Tb/in² will be introduced. STO driving current reduction and STO stability will be discussed in detail, including STO design to simultaneously adjust STO frequency and write field to optimize MAMR performance. The talk also covers the development of high K_u CoPt media with small and well isolated magnetic grains and the measurements of microstructure-dependent damping constants in high K_u CoPt films.

II. MAMR at 2Tb/in²: Media and STO

Fig. 1 shows a rough layer stack design for MAMR media at about 2 Tb/in². The SUL, seed layers and interlayers are similar with the current PMR media. However the recording layers are different. Firstly, the bottom layer has high K_u of about (1.5-1.8)×10⁷ erg/cc to enable enough thermal stability at grain size of 5.5-6.5 nm. The damping constant of this layer is about 0.02-0.05. Secondly, the middle semi-hard layer has K_u of about (3-5)×10⁶ erg/cc but with very high damping constant of about 0.2, which is much higher than the current PMR media. A Pt content of about (40-45)% (Co₆₅₅₅Pr₄₅₄₀) may meet the requirements. A cap layer is needed to tune the inter-grain exchange coupling and to narrow down the switching field distribution. The second semi-hard is to bring down the media resonance frequency from 50-60 GHz to about 30-35 GHz. The high damping constant is to reduce the jitter noise to have sharp transition. The cap layer can further reduce the media resonance frequency to below 30 GHz. To switch such media, the in-plane AC magnetic field should be no less than 1k Oe in the media. Table 1 lists the basic requirements
for MAMR media and STO at about 2 Tb/in\(^2\).

**Table 1: Basic MAMR requirements on media and STO at 2 Tb/in\(^2\)**

<table>
<thead>
<tr>
<th>Media Materials</th>
<th>STO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ms (emu/cc)</td>
<td>K(_u) (10(^7)erg/cc)</td>
</tr>
<tr>
<td>800-1000</td>
<td>1.4-1.6</td>
</tr>
</tbody>
</table>

### III. STO Current Reduction and Stability

Fig. 2 shows the STO with reversible reference layer and negative K\(_u\) materials as the field generation layer (FGL). The design has very high symmetry that enables large-range stable precession of magnetization. With a perfect negative K\(_u\) material, the driving current can be greatly reduced as the magnetization can be at any place in the film plane and a very small torque can push the moment rotating in film plane due to the lack of energy barrier. Fig. 3 shows the FGL precession frequency as a function of media stray field, H\(_y\), for the reference layer of STO having variable anisotropy energy, K\(_u\)(ref), from 0 to 10\(^6\) erg/cc, under different head gap field, H\(_z\) of 3000 (a), 5000 (b) and 8000 Oe (c), respectively. From Fig. 3(a) to 3(c), one can clearly see both the gap field and the media stray field have big effects on the STO stability. Under smaller head gap field, the K\(_u\)(ref) has a big effect on the STO precession frequency, which gives us a knob to tailor the STO stability. However if the head gap field is too high, the effects from reference layer is negligible small. It is worth to point out that without the presence of media stray field, the K\(_u\)(ref) has little effect on the frequency as expected.

### IV. MAMR MEDIA DEVELOPMENT

Using industry-grade mass production sputter tool, we developed CoPt media with extremely high coercivity of 16.5 T and small and well isolated magnetic grains (Fig. 4a and 4b). Damping constants of samples with different microstructures and different composition (Co versus Pt) were measured using high frequency and high field FMR system. Some of the data are shown in Fig. 4c. The damping constant is weekly dependent on the media microstructures indicated by the sample IDs (S5 to S8 which were prepared under different sputtering pressure). Detailed results will be reported in the full manuscript.

**REFERENCES**


Advantages of MAMR Read-Write Performance

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I. INTRODUCTION

Microwave Assisted Magnetic Recording (MAMR) is one of the most promising candidate technologies for next-generation hard disk drives [1]. In MAMR, AC-field from Spin-Torque Oscillator (STO) in write gap in recording head is utilized to reduce switching field of media. Micromagnetic modeling have shown high signal-to-noise ratio (SNR) potential due to localized AC-field from the STO which effectively enhance write field intensity and gradient without significant widening of magnetic write width [2-4]. In terms of experimental results of MAMR using actual head and media, only a few evidences of media magnetization reversal and improvement on overwrite and SNR have been reported [5, 6]. In this paper we focus upon experimental results of MAMR gain on read-write performance, e.g. areal density capability (ADC), bit error rate (BER), magnetic core width (MCW), etc.

II. Experimental and Discussion

We fabricated the MAMR heads with the STO which was deposited between main pole and trailing shield. The STO consists of field generation layer (FGL) with higher magnetization, interlayer, and spin polarization layer (SPL) with high perpendicular anisotropy energy. Trailing gap length of fabricated head is around 30 nm, which is same as STO stack thickness. Main pole width for fabricated head is from 50 to 60 nm. STO width and stripe height are around 50 nm respectively. For read-write evaluation with fabricated MAMR head, we utilized conventional PMR media with magnetic coercivity (Hc) of around 5 kOe.

We evaluated RW performance in MAMR with fabricated samples under an enterprise HDD condition of high data rate of ~2 GHz. Media rotation speed and head position in media were 10000 rpm and 21 mm. Write current was ~40 mA. Read sensor bias was ~130 mV. Head and media surface-to-surface spacing was set to 0.6 nm for both write and read. Here, the bit error rate (BER) is defined as non-iteration BER with LSI Spyder LDPC channel.

Figure 1 shows a typical result on bit error rate (BER) of a function of linear density when we applied DC-voltage bias to STO (STO-On) and no bias (STO-Off). You can see clear BER improvement by around 15% with applying STO-bias in this particular case and also see that BER improvement does not degrade by increasing linear density.

Figure 2 shows BER of a function of magnetic core width (MCW) for many head samples with STO-On and Off. MCW is defined as sum of magnetic write width (MWW) and erase band width (EBW), and has good correlation to track pitch (TP). You can see significant improvement on BER by driving the STO even in the narrower MCW region. The average of BER improvement is about 0.5 order in the condition without LDPC iteration, which can increase the linear density by roughly 10–15%. You can also understand that the widening of MCW due to STO bias is much smaller than the trend of BER vs. MCW. The averaged change on the MCW with STO-On is only around 3 nm, which corresponds to 5% of averaged MCW of 60 nm. Such smaller MCW widening indicates applied AC-field on media is localized as expected with micromagnetic modeling [4]. At the conference, we will discuss more on experimental ADC gain and HDD unique features such as ATI/FTI and data rate dependency.
REFERENCES


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![Figure 1](image1.png)

Fig. 1 Measured bit error rate as a function of linear density with STO-On (Closed circle) and STO-Off (Open circle).

![Figure 2](image2.png)

Fig. 2 Measured bit error rate at 1600 kbpi as a function of Magnetic core width (MCW) with STO-On (Closed circle) and STO-Off (Open circle).
Optimizing Modeled ECC Media Structures for MAMR

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I. INTRODUCTION

Microwave Assisted Magnetic Recording (MAMR) has been suggested as a magnetic recording technology candidate [1, 2] for future progress in increasing areal density while maintaining write-ability, SNR, thermal stability, and reliability. A spin-torque oscillator (STO) between the write pole and trailing shield of the writer is the novel feature of this technology, and provides additional energy to assist in switching grains unable to switch by the writer field alone.

MAMR offers additional “degrees of freedom” to increasing areal density capability (ADC). The STO pumps energy into the media at a given frequency. This is a dynamic effect that may not be simply considered in terms of conventional perpendicular magnetic recording’s (cPMR) field and gradient paradigm. Now we must account for how quickly the media dissipates this energy (through damping and exchange), as well as considering the optimal configuration (frequency, position, etc.) of the STO.

In this talk we present modeling results that compare separately-optimized MAMR recording systems with different constraints. We discuss the changes in media parameters as ADC increases by reducing grain size over a range of values. The writer field is the same in all studies.

II. RESULTS

This study is focused on simultaneously optimized designs of sufficiently thermally stable 4-layer exchange-coupled composite (ECC) media, with the frequency, position, and precession angle of the STO being either the same for all considered grain sizes, or included in the optimization. For the set of studies in which the STO parameters are fixed, the crystalline anisotropy energy $K_u V$ is ~100 for all grain sizes; likewise, in the studies where the STO parameters are varied, the $K_u V$ is allowed to vary (with a lower bound of ~100). We acknowledge that there are some pre-existing MAMR performance studies in the literature [3, 4], but these tend to report regimes of $K_u V$ values that are too small for our purposes. We evaluate three grain areas (including boundaries) of 31, 43, and 52 nm$^2$; these correspond to circular grain pitches (average center-to-center distances) of 6.3, 7.4, and 8.1 nm, respectively. For the cases in which the STO parameters are fixed, the 7.4 nm grain pitch case includes the STO frequency, position, and precession angle as part of the optimization (with crystalline $K_u V$ of media ~100); these STO values are held constant for the 6.3nm and 8.1nm cases. The average packing fraction of the grains is 79% for all cases.

Excluding the three aforementioned STO parameters, there are twenty-three media dimensions to simultaneously optimize: $M_S$, $H_{K_u}$, thickness, lateral exchange constant, damping parameter of each of the media’s four layers (20 parameters), plus the vertical exchange constants between them (3 parameters). We employ a constrained variant of the Nelder-Mead Simplex algorithm [5] to find optimal designs for each grain pitch.

As grain size is reduced, both optimization schemes show 120 Gbpsi ADC growth per nm reduction of...
grain pitch. Expressed in terms of a currently shipping 700 Gbpsi reference, this is 17%/nm (Fig 1). The cases where $K_u V$ and STO parameters are bounded perform ~50 Gbps (~7% of 700 Gbps) better than the cases in which they are fixed. Linearly extrapolating the MAMR results to the cPMR reference grain size predicts a 150-200 Gbps gain (21%-28%) over the reference ADC.

These results, as well as examinations of performance metrics’ sensitivities to the various media and STO parameters, will be discussed. The authors wish to acknowledge Yimin Hsu, Ikuya Tagawa, and Adam Torabi for their helpful questions and comments.

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Figure 1. MAMR shows roughly 17% (or 120 Gbps) areal density growth per nm of grain pitch reduction. This rate is roughly independent of whether $K_u V$ and STO parameters are constant or bounded. The cases where $K_u V$ and STO parameters are bounded perform ~7% (~50 Gbps) better than the cases in which they are fixed. A currently shipping PMR reference is shown at 700 Gbps; linearly extrapolating the MAMR results to the larger grain size predicts a 21% to 28% gain (150-200 Gbps) with respect to this reference.

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ADVANCES IN FABRICATION AND RECORDING PERFORMANCE OF BIT PATTERNED MEDIA

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I. INTRODUCTION

Continued areal-density growth is critical for magnetic recording technology to meet the increasing demand for data storage. As extending perpendicular magnetic recording (PMR) is becoming challenging and considered to be reaching the limit, new technologies, such as heat-assisted magnetic recording (HAMR), are expected to be introduced. Bit-patterned media (BPM), which stores one bit of information on lithographically-defined single magnetic dot, is considered to extend the areal-density beyond the limit imposed by the granular media. Ultimately, heated-dot magnetic recording (HDMR), which combines the techniques used in HAMR with BPM, is expected to extend the areal density up to 10 tera-bits per square inch.

II. BPM/HDMR MEDIA FABRICATION

BPM/HDMR media fabrication starts with patterning of the dots in quartz wafers to form templates for nano-imprint lithography (NIL). Patterning of such templates by directed self-assembly (DSA) of block copolymers has been demonstrated as a viable lithography approach for areal density up to 5 tera-dots per square inch (Tdpi). A mix-and-match DSA and conventional lithography scheme has been successfully developed for fabricating imprint templates, each comprising regular arrays of dots in data sectors, and non-periodic dot patterns in servo sectors. Templates with fully integrated servo patterns and with areal density of up to 2 Tdpi have been fabricated. Subsequent media fabrication involves transferring the patterned features from a template into magnetic thin films by NIL and ion-beam etching. CoCrPt-based magnetic film was patterned for BPM, and FePt-based film was patterned for HDMR. Using this approach, BPM and HDMR media with fully functional integrated servo features has been successfully fabricated on 2.5” disks with areal density of up to 2 Tdpi for spinstand evaluation.

The extendibility of HDMR was also evaluated by patterning FePt-based film up to 5 Tdpi, and characterizing magnetic and thermal properties. Figure 1 shows magneto-optic Kerr effect (MOKE) measurement of continuous FePt film (before patterning), and patterned FePt film. Patterned film has high coercivity, \( H_c > 15 \) kOe, at 5 Tdpi with good thermal stability. Curie temperature distribution (\( \sigma T_c \)) of HDMR media was also measured to be less than 2%.

III. HDMR OPTICAL MODELING

Another advantage of HDMR over HAMR is that it requires less laser power, which is beneficial for product reliability. Figure 2 compares the optical-power-absorption efficiency in HDMR and HAMR media. We used the same HAMR near-field transducer (NFT) design and fixed the laser input-power, while moving the dot of interest in downtrack direction. For HAMR media, the absorption was calculated by integrating the optical absorption over the same volume at x-location as what we have in the HDMR media. We then normalized all the absorption value to the maximum in HDMR case. From Fig. 2, we find that for this NFT-media combination and in both HDMR and HAMR cases, the maximum absorption happens when the...
media is rotating away from the media center toward the trailing edge, which tends to be close to the location where the largest downtrack thermal-gradient is achieved. At this optimal writing location, the light-absorption efficiency is approximately 2.5x for HDMR compared with HAMR. Note that this enhancement will not fully translate into laser power requirement difference due to the thermal averaging effect, and it is possible to fully exploit this absorption efficiency ratio by optimizing the optical and thermal aspects of HDMR media.

IV. SPINSTAND RESULTS AND DRIVE INTEGRATION

Wherever possible, we have used the spinstand to validate designs and evaluate progress in the development of the BPM media up to 2.0 Tdpsi. First, at the lower densities (0.5, 1.0 and 1.5 Tdpsi) we have been able to do bit-error rate (BER) measurements focusing on the write error rate, which ultimately is expected to be the limiting factor in BPM products. We have used advanced software channels to get around limitations in the available readers and artifacts in the media patterning due to the fabrication equipment currently available. Second, we have done evaluations of the servo patterns that are produced in the media, both to investigate the quality and design of the servo features themselves and to use the patterns for position and timing control while conducting BER and other characterization tests on the spinstand. Third, we have done more fundamental characterization to better understand the behavior we see in BER testing and servo performance. One test has been used to evaluate how well we can erase one track without erasing the track next to it. Results from this test have shown us that, with the switching field distribution (SFD) of the media and the write field gradients of the available magnetic writers, little margin exists to support the track density required for 1.5 Tdpsi and higher in hexagonal-bit-layout media, where bit aspect ratio (BAR) is 0.87. Possible solutions are rectangular-bit-layout media with higher BAR and HDMR, where effective SFD and write field gradients are determined by both magnetic and thermal effects.

We have done initial spinstand testing to compare the efficacy of HAMR writers on conventional HAMR media and on similar HDMR media, and shown that HDMR requires roughly 40% lower laser power to write, close to the expectations we had from modelling.

A mule drive with 0.5 Tdpsi BPM media and a hardware channel incorporating BPM special features for write timing-synchronization has been developed. The drive has demonstrated servo tracking capability demodulating patterned-in servo for track-following and patterned-in timing features for write synchronization. The drive also demonstrated full track write validation for timing and pattern transfer integrity.

Fig. 1 MOKE results of continuous FePt (before patterning) and patterned FePt media (1 and 5 Tdpsi)

Fig. 2 Optical power absorption efficiency of HAMR and HDMR media as a function of downtrack position. Here Dcc denotes the center-to-center distance of two neighbored HDMR media dots, and the zero in x-axis denotes the location where the dot center aligned with the NFT center.
DIRECTED SELF-ASSEMBLY OF HIGH-CHI BLOCK COPOLYMER FOR NANO FABRICATION OF BIT PATTERNCED MEDIA VIA SOLVENT ANNEALING

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I. INTRODUCTION

Directed self-assembly (DSA) of block copolymers on chemical contrast patterns offers a potential solution to achieve feature dimensions substantially below the resolution limits of lithographic tools [1,2, 3, 4]. In the magnetic recording industry, DSA of block copolymers combined with rotary e-beam lithography, represents the only currently viable solution to fabricate the small features required for bit patterned media (BPM) technology. The current prevailing strategy originally developed by Ruiz et. al. [5] employs a double imprint process using line and space patterns in circumferential and radial directions to fabricate rectangular dot arrays. The line and space patterns are created by directing the assembly of lamellae-forming block copolymers on lithographically defined chemically patterned surfaces for which the resolution of the assembled features is typically three or four times higher than that of the chemical pre-pattern and the rotary e-beam tool. The bit aspect ratio (BAR) is controlled by the pitch sizes of the lamellar block copolymer for DSA, and a BAR>1 is favored.

Poly(styrene-block-methymethacrylate) (PS-b-PMMA), the most developed materials system for block copolymer lithography, is suitable for pattern transfer up to a limit of 22nm pitch structures. For bit pattern media (BPM) with densities above 1.6Tdot/in2 at bit aspect ratios higher than 1.2, sub-22 nm pitch dimensions are required for the circumferential lines [6]. To access pitch dimensions lower than 22nm, either a self-aligned double patterning technique or higher resolution block copolymer materials and processes must be developed.

Here we present the fundamental and technological basis for directing the assembly of poly(styrene-block-2-vinylpyridine) (PS-2VP) block polymers via solvent annealing [7] on chemical contrast patterns to enable fabrication of line and space patterns down to 16 nm pitch and below. Results will be presented detailing polymer properties, polymer assembly, pattern transfer to create nanoimprint masters, and analysis of pattern quality with respect to manufacturing constraints for BPM.

II. EXPERIMENTAL DETAILS

The DSA process is shown in schematic in Figure 1. An 8nm thick cross-linkable polystyrene mat (XPS) was deposited onto Si and further patterned by rotary electron beam lithography to write circumferential and radial lines, with periods commensurate to the integer multiple of the natural period of block polymers. Oxygen plasma was used to “break through” the opened area and “trim” the width of the “guide” stripes. Low molecular weight PS-OH brush was subsequently deposited in the interspatial regions as “background” to create a chemical pattern. The PS-2VP block polymer is deposited on top of the chemical pattern and annealed in acetone vapor to assembly into line and space patterns down to 16 nm pitch and below. Results will be presented detailing polymer properties, polymer assembly, pattern transfer to create nanoimprint masters, and analysis of pattern quality with respect to manufacturing constraints for BPM.

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**Figure 1.** Schematic of the directed self-assembly of block polymer on chemical patterns via solvent annealing.

**Figure 2.** Top: cross-sectional SEM image of 21.3nm pattern transferred into Si substrate. Bottom: Top-view SEM image of the imprint resist pattern (3nm Cr coated).
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ALL OPTICAL MAGNETIC SWITCHING: FROM FUNDAMENTALS TO NANOSCALE ALL-OPTICAL RECORDING


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Since the demonstration of magnetization reversal by a single 40 femtosecond laser pulse [1], the manipulation of spins by ultra short laser pulses has become a fundamentally challenging topic with a potentially high impact for future spintronics, data storage and manipulation and quantum computation[2]. The ability to control the macroscopic magnetic ordering by means of femtosecond laser pulses provides an alternative and energy efficient approach to magnetic recording. The realization that femtosecond laser induced all-optical switching (AOS) as observed in ferrimagnets exploits the exchange interaction between their sublattices[3,4], has opened the way to engineer new and rare-earth-free magnetic materials for AOS[5,6,7]. Expansion to hybrid magnetic materials, multilayers and FePt is an ongoing effort to expand AOS to future magnetic recording media technology. Recent developments using plasmonic antennas and optical waveshaping indicate the possibility to even scale the technique of AOS to the nanoscale. This, together with recent observations of AOS in FePt and other transition metal alloys makes AOS a potential candidate to replace HAMR in the near future. In this contribution, recent developments in this exciting field will be discussed.

AOS in multilayers.
The realization that the femtosecond laser induced all-optical switching (AOS) as observed in GdFeCo amorphous alloys [1,2] exploits the exchange interaction between their sublattices, has opened the way to engineer magnetic materials suitable for AOS [5,6,7]. On the other hand, time and spatially resolved experiments with the Stanford Free Electron laser [8] have indicated that the detailed structure of the materials, including nanoscale spin currents, could also play a role in the switching process, as was theoretically suggested recently[9]. Simulations[5] have demonstrated that AOS should be possible in synthetic ferrimagnetic materials, however, so far little is known about the reversal mechanism in these hybrid materials. Here we address the laser-induced magnetization dynamics in a Gd/FeCo multilayer system, where the RE and TM-elements are stacked in pure-element thin layers in contact with each other. We show that a single 60 fs laser pulse triggers a fast magnetization reversal process in this material. Using a single-shot pump-probe imaging technique, a strongly spatially inhomogeneous magnetization
reversal process is observed as a function of the local excitation. This observation, together with a high amplitude magnetization precession makes this magnetization dynamics very different from the one observed in RE-TM amorphous alloys. The study reveals changes of the effective magnetization precession damping within the laser-illuminated area, where the temperature gradient is suggested to be responsible for this dynamics.

FePt

Recently there have been reports on helicity dependent AOS in FePt [6,7] but so far only static data have been reported. On the other hand, femtosecond laser induced spin precession can be observed on virtually any magnetic thin film, also on granular HAMR media as was recently demonstrated [10]. This method allows for observation of spin resonance up to THz frequencies, only limited by the width of the laser pulse. Especially for new generation recording media such as HAMR, resonance frequencies and damping of spin oscillations are of great interest. Recent results on granular FePt have shown large inherent resonance frequencies in the THz regime and a damping parameter of 0.1. Ongoing research is focused on how far the intergranular spacing/exchange and grain geometry will affect those parameters, using laser induced spin resonance experiments in high magnetic fields up to 38 Tesla.

Nanoscale recording

Recent developments using plasmonic antennas and optical waveshaping indicate the possibility to bring the technique of AOS to the nanoscale. We have followed two approaches to investigate this possibility: structuring a continuous film of GdFeCo with lithography techniques down to the 100nm lengthscale and employing plasmonic antenness to focus a 800nm wavelength laser pulse down to 40nm. Nanostructuring was not only successful but also showed unexpected results: interference of the laser beam with the edges of the structures resulted in subwavelength structures[11]. These and other recent results using plasmonic antenness demonstrate the possibility of AOS on the nanoscale and thus its possibility for future storage applications.

All-optical control of magnetization in various metallic magnetic systems

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While historically magnetism was controlled by an external magnetic field there are many new and emerging ways to control magnetic order on the nano-scale. One of them that attracted the growing attention is manipulating magnetic systems, cleanly with ultra-short laser pulses as short as 40 fs is known as all-optical switching (AOS). This method takes the advantage of the interplay of light and magnetism and enables light to both read and write (magnetization reversal) at sub-picosecond timescales, characteristic to the rate of exchange interaction between the spins of the atomic sub-lattices present in the multi-magnetic system. AOS was first observed in rare-earth/transition-metal amorphous ferrimagnetic thin-film alloys. However, we have recently demonstrated AOS in multilayer structures, rare-earth free ferrimagnetic compounds [1], and in ferromagnetic thin-films, multi-layers and even granular films designed for next generation magnetic recording media [2]. These finding shows that optical control of magnetic materials is a much more general phenomenon than previously assumed and may have a major impact on data memory and storage industries through the integration of optical control of ferromagnetic bits. I will highlight recent experiments on all-optical magnetization reversal that probe the underlying mechanisms involved in optical control of ferromagnetic materials.


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CONSIDERATION ON VOLTAGE WRITING IN MAGNETIC RECORDING MEDIA WITH MAGNETOELECTRIC EFFECT

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I. INTRODUCTION

The recording areal density has continued increasing to nearly 1Tbpsi with Perpendicular Magnetic Recording (PMR). However, it seems that the growth rate of a recording areal density is fairly reduced for the trilemma problem due to particulate magnetic recording principle. Of course, such alternative technologies or methods as energy assisted recording (HAMR, MAMR etc.) have been worked on with energy towards realizing the next generation recording system where they are still based on a particulate magnetic recording principle. On the other hand, in a magnetic RAM research field, new spintronics physics such as Spin Transfer Torque (Current Induced Magnetization Switching), Spin Orbital Torque Induced Magnetization Switching (Spin Hall Effect or Rashba Effect) and Voltage Controlled Magnetization Switching are proposed and developed or studied. Considering a magnetic recording (i.e. head/media system), STT and SOT are not suitable for magnetic recording principle. So in this paper we propose a new magnetic recording principle with voltage effect on magnetization-switching, especially Magnetoelectric Effect of Cr_2O_3 sesquioxide, that is to say that magnetic bits are written on Cr_2O_3 antiferromagnetic media by E\(\times\)H product (Fig.1).

Magnetoelectric (ME) effect has so far been paid attention to be applied to a nonvolatile memory (NVM). Cr_2O_3 is a typical sesquioxide with ME effect and its antiferromagnetic Neel temperature is \(T_N = 307\) K, which is higher than RT. A robust isothermal electric control of exchange-bias at RT is actually reported for bulk Cr_2O_3 single crystal sample when both of electric field \(E = 0.02\) [MV/cm] and magnetic field \(H = -1.54\) [kOe] was applied [1]. But ME effect has not yet been clarified in Cr_2O_3 thin films because of its large leakage current and imperfect antiferromagnetic-ordering while ME effect like behavior up to 200K is reported to be observed in an ultrathin Cr_2O_3/Fe_2O_3 Nano-Oxide Layer (NOL) [2]. When considering the application of ME effect to magnetic recording technology with voltage-controlled magnetization switching, there are some problems except the above issue, which should be resolved. The first is to realize and design an effectually high exchange-bias filed between antiferromagnetic (AFM) Cr_2O_3 and ferromagnetic (FM) thin film multilayers in the higher temperature range than RT, which means higher Neel temperature (\(T_N\)) and higher blocking temperature (\(T_B\)), where the properly low coercive force of FM is also required. The second is to invest FM layer with a perpendicular anisotropy which is thought to be caused by both of the hybridization of FM 3d and O 2p orbitals and the magnetic coupling at the interface between FM and Cr_2O_3. The third is to confirm ME effect in the thin film Cr_2O_3 after getting Cr_2O_3 thin film which shows good electrical properties.

II. EXPERIMENTAL DETAILS

In this paper, electrical and magnetic performances of the thin film Cr_2O_3/Fe_2O_3 sesquioxide were investigated. We successfully fabricated the Cr_2O_3 and Fe_2O_3 thin films with small leakage current and good magnetic properties. Fig.2 shows our idea for \(T_N\) enhancement with spin correlation effect in sesquioxide multilayers where perpendicular-spin-alignment along c-axis should be realized in Fe_2O_3 too, which means \(T_M\) (Morin temperature) enhancement higher than 400K. The electrical properties were measured in the out of plane direction to the film plane. The leakage current density at \(E = 0.02\) [MV/cm] is as small as \(3 \times 10^{-6}\) [A/cm²]. From the impedance measurement, the parasitic resistance, the film resistance and the capacitance were 17 [\(\Omega\)], 80 [k\(\Omega\)] and 17 [nF], respectively. Dielectric constant \(\varepsilon_r\) calculated from these results was 14, which is almost same as that reported \((\varepsilon_r = 12)\). In addition, we also measured magnetic susceptibility of Cr_2O_3 thin film and weak ferromagnetic moment above \(T_M\) of Fe_2O_3 and Ir-doping Fe_2O_3 thin films by SQUID magnetometer. Mossbauer spectroscopy was also carried out for confirming perpendicular-spin-alignment of with and without Ir-doping Fe_2O_3 thin film samples.

III. RESULTS

We successfully confirmed ME effect of Cr_2O_3 thin films (100nm~500nm) and the switching of both exchange bias field and residual magnetization using Co/Cr_2O_3 exchange bias bilayer with low FM layer coercivity (~20 Oe) structure, shown in Fig.3 under both of ME filed cooling and isothermal process.
conditions for the first time in the world [3],[4]. In addition, we succeeded in enhancing $T_M$ of Fe$_2$O$_3$ higher than 400K by Ir-doping where perpendicular-spin-alignment of Fe$_2$O$_3$ was also confirmed in both of Mossbauer spectroscopy and weak ferromagnetic moment measurement with SQUID magnetometer. These results support our new magnetic recording principle concept with voltage controlled magnetization switching of AFM Cr$_2$O$_3$ thin film above room temperature at the first step.

ACKNOWLEDGEMENTS

This study was partially supported by ImPACT Program led by Council of Science, Technology and Innovation, Cabinet Office of Government of Japan, and JST-ALCA Program.

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Characterizing the advanced recording technology assets with hyper-scale applications

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I. INTRODUCTION

In recent drastic evolution of hyper-scale storage systems of data centers and cloud infrastructures, magnetic and solid state storage devices have been repositioned in the storage hierarchy for maximum efficiency over investment. Processing or analyzing data is the process to create valuable information out of given data and recently requires real-time class speediness for value propositions of Social Network System or Internet-of-Things. Furthermore, since number of access from edge devices and the data transactions across storage system are increasing, data access latency is becoming important as indication how many clients and edge devices it can support in critical time period per given storage resource.

In order to envision the clear pathway for magnetic storage technology research and development in coming future, it is essential to have an analytical approach of characterizing new storage technologies including magnetic recording and solid state storage devices.

II. LATENCY TIER OF COMPUTING DEVICES

In the geographic-scale distribution of data center and global expansion of cloud infrastructure, physical geographic distance in 100s-1000s km is considered as data transfer time delay or data access latency. The same context can be applied to architect computing structure from processor to lower tier of storage in terms of data transaction time design. Physical distance is equivalent to physical time delay as latency when host processor accesses the data that is required to store or to retrieve.

Fig.1 shows the latency tier structure of computing system from topping at processor down to HDD based cold storage tier. A processor running at 3 GHz has an instruction interval or latency at 0.3 nanoseconds (ns) which corresponds to about 9 cm of light travel distances. L1, L2 and L3 caches of SRAM have latencies of about 1.2 ns, 3.6 ns and 8.4 ns, respectively. In most typical cases, those caches are located within 30 CPU instructions in time, or 3 m of light travel distances. The latency of working memory DRAM is as far as 40 ns, about 130 CPU instructions or 12 m of light travel distances.

The fastest solid state drive (SSD) with PCIe interface has 10 microseconds (µs) latency which corresponds to as far as 3 km of light travel distances, still 5 to 10 times faster than typical SAS or SATA SSDs. There is a two-order magnitude latency gap between DRAM and PCIe SSD where new non-volatile random access memory such as Magneto-resistive RAM (MRAM) could fill at latency 10s-100s ns. Although magnetization in MRAM takes just single nanosecond or less to flip according to principle, magnetoresistive tunnel junction (MTJ) memory device takes longer time to respond due to spin injection circuitry, stray capacitance and resistance. MRAM will be an important component of storage class memory (SCM) which incorporates both non-volatility and short latency response.

In magnetic recording (writing) process in HDD, reluctance of write head yoke and magneto-motive force determine the write field gradient resulting in the magnetization reversal in nanoseconds or less. However,
access latency of hard disk drive is dominated by mechanical disk rotation and seek/positioning maneuver of actuator arm. Even at highest 15,000 rpm disk rotational speed, the total latency is 4-5 milliseconds (ms) as a summation of half revolution latency 2 ms and average track seek latency of a couple of ms which is about six-order of magnitude longer than magnetization reversal time at nanoseconds. The distance in time between processor and cold storage tier of HDD is as far as 1,350-3,800 km of light travel distances which is comparable to geographic distances between remote data centers as shown in Fig. 2.

### III. RECONSTRUCTION OF STORAGE ARCHITECTURE

The SMR technology enables to enhance track density by overlaying recording tracks in part within specified band capacity volume. In knowing the limiting mechanical condition of longer latency for HDDs compared to other solid state storage devices, it will be essential for HDDs to concentrate to capacity optimization such as SMR even it takes additional latency time to read-modify-write. The latency issue needs to be overcome by structural architecture of computing systems. One good example is an adoption of Key Value Store (KVS) [1]. Different from traditional block file approach, KVS splits a data file into a set of key (identifier) and value (data content). It is also possible for KVS to store key and value at optimal allocation such a way that a key is stored in SSD or faster SCM and a value is stored in high capacity HDD. KVS stores the data set vertically through storage tiers rather than horizontally in a storage tier like conventional block file system. That structure makes the access latency shorter and especially makes key search speedy.

In this paper an analysis of principle-based characterization for advanced magnetic recording technologies and solid state storage technologies will be discussed. The analysis embodies the application driven measures and is applied to the current HDD and the enhanced version such as singled magnetic recording (SMR) HDD as well as spintronics memories.

### REFERENCES

Areal-Density gains and Technology Roadmap for Two-Dimensional Magnetic Recording

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I. INTRODUCTION

Two-dimensional magnetic recording (TDMR) focuses on multi-reader technology, signal-processing, and a systems-driven approach to increase areal-density [1]. Such an approach is especially valuable since the gains are generally additive to those from other proposed new technologies such as heat-assisted magnetic recording (HAMR) [2], microwave assisted magnetic recording (MAMR) [3], and bit-patterned media (BPM) [4]. Ultimate implementations of TDMR are expected to include multi-track detection and coding using a multi-sensor array and may require adjacent tracks to be written synchronously. Initial implementations, however, are proposed with just two stacked readers and a 1-D detector recovering a single track [5].

In this digest, we will focus first on a system using two readers and a two-input/one-output equalizer feeding into a 1D detector and also describe a method to estimate the areal density gain obtained using this system. This estimation method uses waveforms from a spin-stand and a drive in conjunction with a software-based and an FPGA-based read channel to estimate the areal density (AD) gain provided by the proposed multi-sensor-array based read channel. This methodology was used to evaluate the AD gains on a shingled magnetic recording (SMR) system. The gain estimation procedure was also performed on a non-shingled perpendicular magnetic recording (PMR) system, where adjacent-track interference (ATI) imposes constraints on areal density improvements.

II. CRITERIA USED FOR QUANTIFYING AREAL DENSITY CAPABILITY (ADC)

In this digest, we use two different tests to quantify Areal-Density as described below:

1. Off-Track-Capability (OTC) based AD: This corresponds to the highest areal-density that can be obtained while ensuring a prescribed margin against failure due to read-position error. Failure here is defined as the Bit Error Rate (BER) or Sector Failure Rate (SFR) exceeding a given threshold with the reader in the worst position within the prescribed OTC margin. (the margins for both these tests are quoted in either % of track pitch or in nm)

2. Squeeze-to-Death (SQ2D) based AD: This corresponds to the highest AD that can be obtained while ensuring a prescribed margin against failure due to write-position error (squeeze failure). Failure here is defined as the BER or SFR exceeding a given threshold with the reader in the best possible position.

The OTC criterion is more appropriate during On-The-Fly (OTF) operations and is set to ensure that not too many sectors have to be re-read to better position the reader. The SQ2D criterion is, on the other hand, more relevant to the Error Recovery (ER) mode where the written data has been partially destroyed and many steps (revs.) may be required to correctly recover the data. In either case (reader off-center or data-tracks squeezed), the drive throughput drops because of the additional revs. The setting of the OTC and SQ2D margins and the balance between them depends on a given market segment and the performance expectations. Here, we evaluate the areal-density gains separately for both criteria instead of choosing a specific one for a given market segment.

III. NUMERICAL RESULTS

In this work, we used three different platforms, (modeling, spinstand, and drive) in three different drive companies (Seagate Technology, Western Digital, and HGST) to quantify the ADC advantages of the first version of TDMR architecture. This first version of the TDMR technology is chosen such that it can be implemented with reasonable cost. From modeling to spinstand and drive environments (where the drive environment also includes full-build heads with dual-readers and a writer capable for full stroke testing), the
ADC gains of this first dual-reader version of TDMR are consistent, and range from 6% (SQ2D) to 12% (OTC) based on the criterion used. More details will be presented during the conference.

A technology roadmap, as shown in Table 1, is also defined under IDEMA ASTC (Advanced Storage Technology Consortium) by the three drive companies. The roadmap starts with this first version of TDMR and progresses towards more complex TDMR architectures that make better use of the 2D environment. The final column indicates a doubling of areal-density. This is due to the application of TDMR techniques that include cross-track coding, synchronous writing, a multi-element reader, a 2D-equalizer, and a 2D-detector that jointly estimates the data and media granular structure on which the data is written. A further underlying assumption is the continued improvement in the regularity of the grain structure in the recording medium. Further details of this roadmap will also be given during the presentation.

REFERENCES


<table>
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<td>13 to 25%</td>
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<td>random with greatly improved distributions</td>
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<td>2D Grain-per-bit Detection &amp; 2D Code, etc.</td>
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Table 1: TDMR Technology Roadmap defined by Seagate Technology, Western Digital, and HGST under the IDEMA Advanced Storage Technology Consortium (ASTC). TDMR capacity gains are quantified over the capacity for single reader. The capacity gains would also apply to HAMR & MAMR and to reduced grain-sizes. TDMR benefits from and assumes continued improvement in writing & reading quality and resolution.
COMPARISON OF TWO-READER AND THREE-READER TDMR SYSTEMS

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I. INTRODUCTION

Two-dimensional magnetic recording (TDMR) system with two readers has been the focus of hard-disk drive (HDD) industry in recent years. Several studies have shown how to derive maximum benefit from the second reader, including studies on system parameters such as optimal reader placement, track-pitch and bit-aspect ratio as well as studies on various signal processing techniques [1][2]. Depending on the reader position, it is now well-known that signal-to-noise ratio (SNR) improvement from the second reader is obtained due to a combination of electronics noise averaging and inter-track interference cancelation (ITIC). Areal density (AD) gains of up to 10% over conventional perpendicular magnetic recording (PMR) system can be obtained with the second reader. For further AD gains, we study behavior and optimization of the three-reader TDMR system with a particular focus on the reader placement and cross-track error-correction coding (ECC) gains [2]. As an alternative to employing three readers, we also consider a lower cost two-reader solution with streaming ITIC.

II. SYSTEM MODEL AND EXPERIMENTAL RESULTS

A. Channel Model

Our software simulator of HDD system assumes a shingled writing of 6 tracks on a Voronoi based grain media model with a log-normal grain size distribution and an average grain diameter of 9.0nm. The read process is modeled as a 2D convolution of the head response with media magnetization, where the head response assumes a 2D Gaussian profile. We set pulse width at half the peak amplitude (PW50) of the reader response to be 20.65nm in the down-track and 33.0nm in the cross-track direction.

In order to gain more intuition about the system characteristics, in some experiments, we utilize a much simplified version of the grain media channel model: In such model, the waveforms for each read-head are generated separately and then combined according to the amount of signal they are expected to pick up from each of the 6 tracks involved in the model.

B. Equalization and Detection

We consider an M-reader system architecture, where M is 2 or 3. In this architecture, an M-input two-output equalizer [2] is employed in order to jointly equalize two tracks of interest: these tracks are denoted as track N and track N+1. The equalizer is followed by a 2D Viterbi detector that jointly detects data in these two tracks.

C. Three-Reader TDMR System without Track Mis-Registration

In the first set of experiments, we consider an idealistic system with no write track mis-registration (TMR). In such system, Fig. 1 and Fig. 2 respectively illustrate the optimal reader placement strategy for small values of track pitch (TP) (e.g. TP<28nm) and intermediate TP values (e.g. 28nm<TP<38nm). With the reader placements as shown in Fig. 1 and 2, the AD gains are found to be maximized: Approximately, an additional 6.5% AD gain over the two-reader system studied in [2] is attained. One important observation is that at very low values of track pitch, it is most beneficial to place readers allowing to pick up a significant amount of signal from three different tracks (track N-1, N and N+1) as shown in Fig. 1. As the track pitch increases, it becomes most beneficial to mainly pick up signal from the two tracks modeled in the detector (track N and N+1) as shown in Fig. 2. Another important observation from the experiments is that the optimal reader placements are very similar regardless whether we focus our attention on decoding a single track (track N) or decoding both track N and track N+1 simultaneously. We note, however, that unlike the system with two readers, the optimal placements of three readers is always asymmetric with respect to the two tracks modeled in the detector. As a consequence, there is a significant difference in the detector bit-error-rate (BER) on the track N and the detector BER on the track N+1. Given this, focusing on decoding one track at a time would result in a better overall system performance under the ideal conditions in which TMR does not exist. For additional gains with cross-track ECC.

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D. Three-Reader TDMR System with Track Mis-Registration

We introduce write-TMR by generating variation in the position of the write head (and consequently the tracks edges) via an i.i.d. random process with a Normal distribution $N(0,\sigma^2)$. Fig. 3 shows the codeword-failure-rate (CWFR) performance comparison of cross-track ECC and along-track ECC [2] under the write-TMR model with the standard deviation $\sigma = 2.4\text{nm}$. Noting that the cross-track ECC scheme requires decoding tracks N and N+1 simultaneously, while the along-track ECC scheme does not, the loss with the cross-track ECC is expected at high CWFRs given that the SNR on track N is nominally better than the SNR on track N+1. However, as the CWFR decreases, the failures are observed only in the instances of very significant track squeeze, which is present when one of the tracks covered in the cross-track ECC is much wider than the other. As the cross-track ECC effectively “averages” SNR across two tracks this results in gains relative to the along-track ECC: The linear-density gain estimate is ~ 3.3% and 4.2% at CWFR ~ 1e-2 and 2e-3, respectively.

E. Two-Reader TDMR System with Streaming ITIC

In addition to better write-TMR tolerance, three-reader TDMR system also benefits from wider offtrack bathtub. We can derive this benefit even from a two-reader system if we perform ITIC with the knowledge of data in an adjacent track. As shown in Fig. 4, at optimal two-reader placement, bathtub width can be improved by ~10% of TP. This is a potential low-cost alternative to three-reader system for certain sequential read applications.

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CROSS-TRACK DISTRIBUTION OF LDPC CODEWORDS FOR AREAL-DENSITY GAIN

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I. INTRODUCTION

The signal-to-noise-ratio (SNR) of each data sector on a hard-disk drive varies in the cross-track and down-track directions due to a number of factors, including variations in the media, fly height, and track misregistration (TMR). The areal-density (AD) of the drive is hence often determined by certain critical error events, or the worst-case SNR. Breaking up and distributing (interleaving) the Low Density Parity Check (LDPC) codeword that encodes a sector, in the down-track or cross-track direction, allows this variation in SNR to be “averaged out” over the physical span of the sector codeword [1]. As a result, the AD capability depends less on the worst-case SNR, and more on the average SNR, which results in a net AD gain.

The goal of such a distributed scheme would be to make it less likely that more than one segment of the sector codeword has poor SNR at the same time. With respect to TMR during writes, consecutive sectors tend to have similar levels of squeeze (positive down-track correlation of squeeze), so it is necessary to distribute codewords over a large area in the down-track direction for maximum advantage. This incurs increased latency during readback. In contrast, distributing sectors in the cross-track direction requires smaller physical area to gain the same (or better) advantage, since sectors on adjacent tracks tend to have opposite levels of squeeze (negative cross-track correlation of squeeze).

For example, consider track 2 in Fig. 1(a). The dashed lines refer to the two write “edges” of tracks 2 and 3, which define the width of the sector in track 2. Track 2 is squeezed in Fig. 1(b) due to writing track 2 “lower” than normal and/or writing track 3 “higher” than normal, as indicated by the solid arrows. Hence, the squeezed sector in track 2 has poor SNR, and with no distribution in Fig. 1(b), it may fail to decode.

However, there is an above-average chance that the sectors in the adjacent tracks (tracks 1 & 3) are “anti-squeezed”, or have better-than-average SNR. With 2 track distribution in Fig. 1(c), the sector in track 2 is broken into two equal segments: 2A and 2B, and distributed over both tracks 1 & 2 as shown (track 3 is irrelevant to this case). When track 2 is squeezed, 2A has poor SNR, but 2B has good SNR. Since the bits in 2A and 2B participate in common parity equations during iterative LDPC decoding, the reliable bits from 2B can fix errors in 2A, and effectively compensate for the SNR loss in 2A. Hence, the AD capability is defined by the average SNR over 2A and 2B in Fig 1(c), rather than the worst-case SNR of 2 alone as in Fig. 1(b). This is exploited further in Fig. 1(d), where the sector in track 2 is split into 2A, 2B and 2C, and distributed over three tracks. Hence 2B and 2C both have good SNR, while 2A alone has poor SNR. This is a simple example, but gains due to this effect can be achieved in a number of other squeeze scenarios as well.

In this work, to avoid increased latency during readback, we focus on decoding a cross-track distributed sector using Two-Dimensional Magnetic Recording (TDMR) based on simultaneous input from 2 or 3 readers. Note that there are buffering requirements while writing tracks to distribute the codewords, and hence we focus on Shingled Magnetic Recording (SMR), where similar buffering requirements already exist. AD gain using TDMR with SMR has been extensively studied [2] [3]. In this work, we focus particularly on gains from cross-track distribution.

II. CRITERIA USED FOR QUANTIFYING AREAL DENSITY CAPABILITY

We focus on two different criteria to quantify AD capability:

1. Off-Track-Capability (OTC) based AD: This corresponds to the highest areal-density that can be obtained while ensuring a prescribed margin against failure due to read-position error. Failure here is defined as the Bit Error Rate (BER) or Sector Failure Rate (SFR) exceeding a given threshold with the reader in the worst position within the prescribed OTC margin. The margins for both these tests are quoted in either % of track pitch or in nm.

2. Squeeze-to-Death (SQ2D) based AD: This corresponds to the highest AD that can be obtained while ensuring a prescribed margin against failure due to write-position error (squeeze failure). Failure here is defined as the BER or SFR exceeding a given threshold with the reader in the best possible position.

For cross-track distribution, we consider the dominant squeeze failure modes for simplicity. The OTC criterion is more relevant to On-The-Fly (OTF) operations, while the SQ2D criterion is more relevant to the Error Recovery (ER) mode. The setting of margins for each case, and the balance between them,
depends on a given market segment and performance expectations. Here, we focus on evaluating AD gains separately for each criterion, rather than specialize the gain to a particular market segment.

III. RESULTS

The results presented in Table 1 are based on spin-stand captures with a single reader (of width about 60% of the track pitch), where multiple reads from the same reader are used to emulate 2 and 3 reader TDMR configurations. The gains include TDMR 2D-equalization gains (i.e., using multiple reader inputs to improve equalization) as well as cross-track distribution gains. Standard 1D detectors are used to decode the sectors.

The gain based on the SQ2D criterion is impressive, but when using 2 stacked readers over 2 tracks or 3 readers over 3 tracks [4], the gain in practice would seem to be limited by the low OTC capability. However, using 3 readers over 2 tracks provides very interesting and encouraging results. We discuss further details, challenges (including skew) and extensions for future work in our presentation.

ACKNOWLEDGEMENT

We are indebted to the contributions of Dr. Jonathan Coker toward cross-track distribution and TDMR at HGST, without which the results of this work would not have been possible.

REFERENCES


Figure 1: 3 sectors in 3 tracks with (a) no distribution/squeeze, (b) no distribution & track 2 squeezed (dominant squeeze failure mode), (c) 2 track distribution & track 2 squeezed, and (d) 3 track distribution & track 2 squeezed.

<table>
<thead>
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<th>3 Track Distribution</th>
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<td><img src="image_d" alt="Track 2 Squeezed" /></td>
<td><img src="image_e" alt="Track 2 Squeezed" /></td>
<td><img src="image_f" alt="Track 2 Squeezed" /></td>
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Table 1: AD gain estimates for different distribution/reader configurations based on OTC and SQ2D criteria

<table>
<thead>
<tr>
<th>2 Reader TDMR 2 Track Distribution</th>
<th>3 Reader TDMR 2 Track Distribution</th>
<th>3 Reader TDMR 3 Track Distribution</th>
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<td>AD Gain at 0 Skew (SQ2D)</td>
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<td>14%</td>
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TMR Sensitive Equalization for Electronic Servoing in Array Reader based Hard Disk Drives

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I. INTRODUCTION

To achieve enhanced recording density, hard disk drive (HDD) industry is transitioning into array-reader based magnetic recording (ARMR) technology which provides enhanced signal-to-noise ratio for data detection by making use of the diversity in signal, interference and noise provided by the multiple read-elements. A 2D equalizer, which is the heart of ARMR signal processing, acts to electronically steer the array-reader to provide optimum signal pick-up from the track, thereby resulting in wider & deeper cross-track profile in error-rate performance. To realize this enhanced performance, the 2D equalizer should be matched to the reader-location on the track, which cannot be guaranteed in practice due to track mis-registration (TMR) arising from practical limitations of the servo control system. In this paper, to mitigate this, we present an electronic servoing scheme that estimates the location of the dual-reader on a per-fragment basis and uses this to transform the reference equalizer to a new equalizer that is matched to the estimated location, hence the name "TMR sensitive equalization". Performance evaluation done around 1Tb/sq.in shows that the proposed approach significantly improves read performance in the presence of large read/write TMR even without additional adaptation cycles for the 2D equalizer.

II. TMR SENSITIVE EQUALIZATION AND PERFORMANCE EVALUATION

The TMR sensitive equalization approach involves two key steps: firstly, estimation of the reader-location and secondly, transformation of reference equalizer to a new equalizer that is near-optimum for the estimated location. We use the orthogonal preamble scheme present in ARMR drives for estimating reader-location. HDDs with aggressive track-density require orthogonal preamble patterns on adjacent tracks to ensure satisfactory operation of control loops during read. As supported by Avago read channels, we assume that 2T pattern (0011) and 3T pattern (000111) are used as preamble patterns on consecutive tracks N-1, N, N+1 etc, as shown in Fig.1(a). Also shown in Fig.1(a) are read-TMR and write-TMR, where read-TMR causes an undesired shift of reader in cross-track direction, while write-TMR causes an undesired shift of writer resulting in track-squeeze. Fig.1(b) shows the ratio of powers of 2T and 3T patterns (i.e. \( P_{2T/3T} = 10\log_{10}(P_{2T} / P_{3T}) \)) from the output of one reader in the dual-reader at various cross-track locations of target track N. The red trace in Fig.1(b) corresponds to \( P_{2T/3T} \) for zero write-TMR, averaged over multiple sectors. The specific behavior of \( P_{2T/3T} \) with reader-location seen in Fig.1(b) forms the basis for the approach to estimate reader-location from measured power-ratio. The concave nature of the power-ratio curve indicates that there are two possible reader-locations for any given \( P_{2T/3T} \). Further, write-TMR causes the power-ratio curve to be reduced in amplitude and shifted in location, as illustrated by the green trace in Fig.1(b) which is for 30% squeeze of Track N by Track N+1. The reader-location estimation algorithm is able to resolve the ambiguity in location as well as to take care of the deformation in power-ratio curve due to occurrence of write-TMR. Once the reader-location is estimated, a linear transformation (LT) is used to map the reference equalizer to an equalizer that is near-optimum for the estimated location. To do this with minimum overhead, the zone-table stores the averaged power-ratio and four LT coefficients per location for a sparse grid of cross-track locations (e.g. -40%:10%:40%) for zero write-TMR, in addition to the reference equalizer corresponding to track-center.

When the dual-reader enters a new sector or fragment, the TMR sensitive equalization algorithm first estimates the reader-location by comparing the measured power-ratio against the reference power-ratio curve, applies the...
ambiguity elimination approach along with a write-TMR detection based calibration approach for refining the estimated location, estimates new LT coefficients using the reference set of LT coefficients and estimated reader-location, and obtains a new equalizer using the estimated LT coefficients and reference equalizer.

Performance evaluation of the proposed approach is done using a 2D model of high-density magnetic recording (perpendicular, non-shingled) at the areal density of 1.034 Tbits/sq.in with 2200 KBPI and 470 KTPI. This corresponds to a track-pitch of 54.04 nm and bit length of 11.55 nm, with 54.04 nm magnetic write width for writer and 30 nm magnetic read width for readers. For a dual-reader with reader-to-reader cross-track separation (CTS) of 20%, Fig. 2 shows the bit error-rate (BER) performance of Viterbi-detector when the 2D equalizer is set according to different choices. While the red and blue traces show the performance with optimum equalizer and fixed reference equalizer, respectively, for all reader-locations, the green trace shows the performance of the proposed TMR sensitive equalization (without any adaptation). The cyan and magenta traces show the performance obtained after one 4K sector of adaptive equalization starting from the fixed reference equalizer and TMR sensitive equalizer, respectively. Comparing blue with green or cyan with magenta, we see that the proposed approach gives significant improvement in performance, and the resulting performance is close to optimum (red trace) within one sector of adaptation or even without adaptation. In other words, the proposed approach helps to circumvent the need to adapt the equalizer over a long number of sectors to compensate for the change in reader-location, thereby enabling the read channel to respond quickly to changes in reader-location that may happen from sector-to-sector in ARMR HDDs. Also to be noted from Fig.2(b) is that the proposed algorithm is able to detect and calibrate out the error caused by write-TMR during estimation of reader-location and setting the 2D equalizer.

REFERENCES


Fig. 1 Illustration of (a) orthogonal preamble and read/write TMR, (b) cross-track profile of 2T/3T power-ratio.

Fig. 2 BER performance for dual-reader ARMR with 20% CTS under (a) no squeeze, (b) 30% squeeze.
OPTIMIZATION OF BIT GEOMETRY AND MULTI-READER GEOMETRY FOR TDMR

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I. OVERVIEW

The move from traditional single-track magnetic recording to TDMR [1][2] with squeezed tracks and multiple readers opens up new design degrees of freedom beyond the track pitch and bit aspect ratio, including the widths, spacing, and crosstrack positions of the readers. In this paper we present a systematic method for determining the combination of multiple-reader geometry, track pitch, and bit-aspect ratio that maximizes the areal density of a TDMR system. The method combines realistic modeling of the medium and write/read processes, advanced signal detection, and information-theoretic tools. The optimal reader geometry was found to use two comparably sized readers (widths of 14.6 nm and 17.7 nm) with significant overlap in the crosstrack direction (centers spaced by 2 nm). The optimal track pitch was 16.1 nm and the optimal bit length was 8.3 nm. At the optimal operating point, the information rate per coded bit is 0.8.

II. QUASI-MICROMAGNETIC CHANNEL MODEL AND MULTI-READER DETECTION

Waveforms are derived from a simulation that uses realistic head fields and a Voronoi medium with Stoner-Wohlfarth switching [2]-[5]. The mean grain-pitch is 6 nm and there are distributions in the anisotropy magnitude and angle. Magnetostatic and exchange interactions are included. The read sensitivity function is obtained by 3D-finite element modeling of a double-shielded magnetoresistive (MR) reader at several widths.

We limit consideration to single-track detectors which separately equalize the readback waveforms before adding; the equalizers and one-dimensional target are jointly optimized using standard techniques, so that subsequent processing can use conventional one-dimensional Viterbi and BCJR detectors. Mutual information rate (MIR) is an information-theoretic bound and useful benchmark for achievable storage densities. In [5], using the BCJR forward recursion, MIR is computed for a one-dimensional white Gaussian noise channel with memory, and is accurately estimated by Monte Carlo methods. To account for the correlation and data-dependent noise in a TDMR system, we use pattern-dependent noise predictive filters in the BCJR algorithm to whiten the noise, and we estimate MIR by assuming the residual noise is Gaussian.

III. RESULTS

We consider a set of five consecutive tracks written in a shingled fashion with independent PRBS sequences of length 40950, with the center track being the track of interest. A total of 900 readback waveforms were generated, as described in Sect. II, with a bit length of 7.3 nm, one for each of six track pitches (from 16.1 nm to 26.1 nm in 2 nm increments), six reader widths (from 70% to 145% of a nominal reader width of 20.8 nm), and 25 reader positions (spanning the center three tracks at one-eighth of a track increments). An additional 100 readback waveforms were generated at a track pitch of 16.1 nm and 70% reader width, one for each of four additional bit lengths (5.3, 6.3, 8.3, and 9.3 nm) and the same 25 reader positions. All readback waveforms were oversampled (perfect synchronization) at two samples per bit. The same amount of electronic ratio thus loses 6 dB per halving of read-width. The power of the added noise was chosen to be 24.6 dB below

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the peak (constant response) signal level for a centered 100% reader at 22.1 nm track pitch.

We first assume a bit length of 7.3 nm and optimize all other parameters. We then fix these remaining parameters and optimize bit length. In particular, for 7.3 nm bit length and every pitch and reader geometry, the corresponding pair of readback waveforms was processed according to Sect. II, and both the MIR and BER computed. An exhaustive search over all possible candidate geometries was then performed. A similar exhaustive search was also performed for a single-reader system. Results are shown in Fig. 1, where we plot BER after Viterbi detection versus track pitch. Every parameter of the system (bit geometry, reader geometry, equalizer, and target) is optimized separately for each point in the curves so as to minimize the resulting BER. The two-reader system is seen to offer an 11% increase in areal density over the single-reader system.

In Fig. 2 we plot versus track pitch the optimized areal density as predicted by \( (1 - h_2(BER))/G \), where \( h_2(p) = (p)\log_2(p) + (1 - p)\log_2(1 - p) \) and \( G \) is the number of grains per written bit. A maximum areal density of 3.6 Tb/in\(^2\) (or 0.165 bits/grain) is achieved at a track pitch of 16.1 nm, with reader widths 14.6 nm and 17.7 nm and center spacing 2 nm. The corresponding code rate is 0.67. Compared to an optimized single-reader system, the second reader provides a 10% increase in areal density. Optimizing bit length while keeping the reader geometry and track pitch (16.1 nm) fixed yields a further increase in areal density of 5%, achieved by increasing the bit length from 7.3 nm to 8.3 nm, with a corresponding increase in code rate from 0.67 to 0.8.

REFERENCES

This talk describes probabilistic message-passing TDMR turbo-detection algorithms that jointly estimate magnetic grain configurations together with the coded data bits, and thus iteratively assist channel decoding. Such dynamic grain state estimation (DGSE) techniques are effective at densities ranging from about 3 magnetic grains per coded bit down to about 1 grain/bit, where occasionally a bit will not be written on any grain, and hence will effectively be “overwritten” (or erased) by bits on the surrounding grains. DGSE enables detection of these overwritten bits so that their log-likelihood ratios (LLRs) are assigned small magnitudes, effectively making them erasures. As it is easier for a channel decoder to fill in erasures than correct errors, DGSE-based detectors can potentially achieve acceptable bit error rate (BER) performance at higher channel coding rates, resulting in higher user information areal densities.

An earlier DGSE paper [1] employed a BCJR-based detector for the four-rectangular grain model (FRGM) of [2]; [1] showed that FRGM information densities greater than 0.5 bits/grain could be achieved, and that, surprisingly, the FRGM-based detector could achieve densities of 0.25 bits/grain even on data generated by the random Voronoi grain model of [3]. Motivated by these results, we present a novel DGSE detector based on the generalized belief propagation (GBP) algorithm [4]. The new detector employs a random discretized-nuclei Voronoi grain model (DNVGM). Simulation results show that the GBP-based detector can accurately detect overwritten bits, and that the overwritten bits can be effectively filled in by a soft-in/soft-out (SISO) channel decoder.

II. DISCRETIZED-NUCLEI VORONOI GRAIN MODEL

In order to track local grain states with manageable computational complexity, we approximate a true random Voronoi grain model by discretizing the possible grain nuclei locations, as shown in Fig. 1. This model divides each channel coded bit into $2 \times 2$ mini-cells, and restricts the Voronoi grain nuclei to lie at mini-cell centers. The model avoids spatial correlation of grains with bits by randomly distributing $N_g$ grain nuclei over an area of $3 \times 3$ bits; $N_g$ is chosen randomly according to a PMF $P(N_g)$ computed from the random Voronoi model in [3]. A grain nucleus is not placed in a given mini-cell if another nucleus is already present at one of the four closest adjacent mini-cell centers. The ratio $\sigma_A/\mu_A$ of grain area standard deviation to mean is about 0.25 with this model, consistent with [3]. This model gives an increasingly close approximation to a true random Voronoi model as the number of mini-cells per bit increases. We assume the centroid write model, where a given Voronoi grain cell is magnetized (to a value of $\pm 1$) by the channel bit containing that grain cell’s centroid. We assume a soft-bit read model that computes the value $y_i$ read at the center of the $i$th bit cell as the area integral of magnetizations of all grains contained within the bit cell.

III. GENERALIZED BELIEF PROPAGATION BASED TDMR DETECTOR

The $a$-posteriori probabilities (APPs) of the $3 \times 3$ coded bits $u$, given nine soft-bits $y$ output from the read model, are estimated as $P(u \mid y) = \sum G P(G \mid y)P(G \mid y)$, where the grain state $G$ is a 36-bit binary vector specifying the grain-nuclei locations in the mini-cells. The factor $P(u \mid G, y)$ is tabulated by computing which $u$ vectors are consistent with a given $G$ and $y$. The probability $P(G \mid y)$ is estimated by the GBP algorithm. As there can be many grain configurations $G$ consistent with a given $y$, and use that set to estimate the APPs.
In the turbo-GBP detector, channel bits $u$ are written/read from the DNVGM, giving sample vector $y$, which flows into the GBP detector. The GBP detector computes $P(G|y)$, which flows into a block that computes APP LLRs as described above. The LLRs flow into a SISO decoder, which returns output LLRs back to the GBP to iteratively aid the GBP’s estimation and thereby improve the quality of the APPs.

In order to limit the GBP algorithm’s computational complexity, Monte Carlo simulations are done on $2 \times 2$ bit areas to randomly generate a fixed number of $(y,G)$ pairs, and from these $P(G|y)$ tables are computed and stored for each of the four $2 \times 2$ bit areas A-D in Fig. 1. These tables form the top level functions for the GBP region graph shown in Fig. 2; the letters and numbers in Fig. 2 denote the regions labeled in Fig. 1. Message passing on the region graph ensures that the conditional PDFs on a given level are consistent with the conditional PDFs of their parents and their descendants; message passing continues until the $P(G|y)$ probabilities converge sufficiently.

IV. SIMULATION RESULTS

Fig. 3 shows histograms of the binary LLRs computed from the turbo-GBP detector’s $P(u|y)$ for fifty $3 \times 3$ bit blocks at a density of one coded bit per grain; LLR magnitudes saturate at 10. Overwritten bits occur in bit cells that contain no grain centroids. The overwritten bits have about 90% of their LLRs concentrated around zero, indicating that the detector has correctly classified most of them as erasures; this helps the SISO decoder estimate the correct channel bits. By contrast, non-overwritten bits have only 36% of their LLRs concentrated around zero, as the GBP is able to estimate their APPs with more certainty.

Fig. 4 shows the cumulative decoded BER vs. number of overwritten bits per $3 \times 3$ block when a toy example SISO (9,4) shortened Hamming decoder with $d_{\text{min}} = 4$ operates on two hundred $3 \times 3$ blocks of GBP output LLRs. This code can correct $t$ errors and $\lambda$ erasures, subject to $4 \geq 2t + \lambda + 1$. Errors can occur even with non-overwritten bits if a majority area of a bit cell is dominated by grains with centroids outside the cell. Fig. 4 shows low BERs with less than 3 overwrites; also, as expected, the BERs decrease as the grains/bit increase and less overwrites occur. Future work will generalize to longer $3 \times N$ blocks and employ more powerful LDPC codes, which should give improved results.

REFERENCES

Relaxing media requirements by using multi-island two-dimensional magnetic recording (TDMR) on bit patterned media (BPMR) 
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I. INTRODUCTION

Bit patterned media recording (BPMR) is considered to be a promising candidate to achieve above 1 Tb/in\(^2\) areal density magnetic recording [1]. However, media fabrication imperfections can manifest as island position jitter and island size fluctuation in both down-track (DT) and cross-track (CT) directions, degrading both the write and the read performance of BPMR. We introduce and investigate the use multiple islands to record one bit and show that such a multi-island approach can provide more tolerance to reader noise and media noise compared to standard BPMR with one bit per island and to granular media at the same channel bit density.

II. MODELING

We investigated four media structures (shown in Fig. 1) all corresponding to 1 Tb/in\(^2\) areal density: granular BPMR with one bit per island and to granular media at the same channel bit density.

The readback signal (MMSE) equalizer and detected with pattern-dependent noise predictive (PDNP) BCJR detector to obtain the bit decisions from which the bit error rates (BER) are estimated.

\[
H(z + \Delta z, x + \Delta x, \Lambda z, \Lambda x) = g \cdot \exp \left( -a \left( \frac{\Delta x + \Delta z}{T50_x} \right)^2 \right) \cdot \left( c(\Lambda x)^2 + e \cdot \Lambda x + 1 \right) \cdot \exp \left( -b \left( \frac{\Delta x + \Delta z}{T50_z} \right)^2 \right) \cdot (d(\Lambda z)^2 + f \cdot \Lambda z + 1)
\]

where \(T50_x, T50_z\) are the intervals for the transition response to rise from -50% to +50% amplitude in the DT and CT directions, respectively. Here \(g\) is the normalized amplitude of pulse response, while \(a, b\) denote the widths of pulse response and \(\Delta x, \Lambda x, \Delta z\) and \(\Lambda z\) denote island position jitter and island size fluctuation in the DT and CT directions. The readback signal \(r_{j,k}\) can be obtained as in Eq. (2) by convolving the \(H(.)\) with the 2-D input data, where the 2-D interference, the media noise and AWGN \(n_{j,k}\) are included.

\[
r_{j,k} = \sum_{m=-M}^{M} \sum_{n=-N}^{N} \bar{a}_{j-m,k-n} H(mT_x + \Delta z_{j-m,k-n}T_z, nT_z + \Delta x_{j-m,k-n}T_x, \Lambda x_{j-m,k-n}L_x, \Lambda z_{j-m,k-n}L_z) + n_{j,k}
\]

(2)

Here \(\bar{a}_{j,k} \in \{-1, +1\}\) is the \(k\)th written bit of the \(j\)th track, which might be different (due to the miswriting) from the bit \(a_{j,k}\) intended to be written and \(T_x, T_z, L_x\) and \(L_z\) are the island period and island size in the DT and CT directions. The readback signal \(r_{j,k}\) from the optimized reader (free layer dimension 3nm x 18nm x 18nm, shield to head spacing 13nm and magnetic fly height 4 nm) are processed with 1-D or 2-D minimum mean squared error (MMSE) equalizer and detected with pattern-dependent noise predictive (PDNP) BCJR detector to obtain the bit decisions from which the bit error rates (BER) are estimated.

III. NUMERICAL RESULTS

When we investigate the BER vs reader noise for 1Tb/in\(^2\) density, the media noise (comprising of island position jitter, size fluctuation) is kept at 5% (1.27nm, 0.9nm) and the AWGN level is kept such that the AWGN-only SNR is 20 dB. As shown in Fig. 3, for the target BER of 10\(^{-2}\) and readdback with a single reader, BPMR schemes using 1 bit per dot and 1 Tdot/in\(^2\), 1 bit per 2 dots and 2 Tdots/in\(^2\) and 1 bit per 4 dots and 4 Tdots/in\(^2\) can tolerate 0.8 dB, 2.0 dB and 2.3 dB more reader noise than the granular media, even though all 4 media structures are used at 1 Tb/in\(^2\) bit density. If a head array with two read elements is assumed, readback at BPMR based on 1 Tdot/in\(^2\), 2 Tdots/in\(^2\) (2 dots/bit) and 4 Tdots/in\(^2\) (4 dots/bit) island density can tolerate 1.0 dB, 3.1 dB and 3.3 dB more reader noise than the granular media, even though all 4 media structures are used at 1 Tb/in\(^2\) bit density.
scheme appears to be due to two factors: 1) the multiple islands/bit reduces the impact of the write in errors compared to the single island/bit and 2) the media noise is decreased by averaging multiple islands’ effects during the readback process. We also investigated the noise tolerance advantages of the multi-island BPMR schemes at the higher recording density of 1.5 Tbits/in². Through simulations, it is seen that for the target BER of 10⁻², readback at BPMR based on 1.5 Tdots/in² (1dot/bit), 3 Tdots/in² (2 dots/bit) and 6 Tdots/in² (4 dots/bit) island density can tolerate 4.4 dB, 5.5 dB and 6.4 dB more reader noise than granular media with 1.5 Tbit/in² density. Also, for 10⁻² target BER, writing BPMR based on 3 Tdots/in² (2 dots/bit) and 6 Tdots/in² (4 dots/bit) island density can tolerate media noise levels (island position jitter, size fluctuation) of 9.5% (1.97 nm, 1.39 nm), 8% (1.66 nm, 1.17 nm) compared to the 1.5 Tdots/in² islands with media noise levels of 5% (1.04 nm, 0.73 nm). Because of space limitations, we have not included the corresponding plots.

In conclusion, we compared the BER performance of multi-island BPMR to the standard BPMR and granular media. Simulations suggest that the multi-island BPMR scheme can tolerate more reader noise and more media noise compared to standard BPMR and granular media and thus relax the media requirements.

REFERENCES

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NON-CONTACT BASED METHOD FOR DETERMINING BY HEAD LASER PROTRUSIONS USING LASER GAMMA

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I. INTRODUCTION

With the introduction of lasers into the magnetic recording system with HAMR [1], the laser introduces new heat sources and protrusions in the head surface at the air bearing surface (Figure 1) that need characterizing in order to accurately set clearance to improve performance and reliability. Currently for HAMR heads, laser on protrusion measurements involve head contact with the HAMR media that reduces performance and reliability. In order to meet the performance and reliability requirements for a HAMR drive, a non-contact based by head measurement capability is desired to more accurately set clearance without sacrificing performance or reliability.

II. EXPERIMENTAL DETAILS

We investigated the dependence of Laser Induced Reader Protrusion (LIRP) on Broad Laser Induced Writer Protrusion (BLIWP) by measuring LIRP and BLIWP on the spinstand to calculate the population laser gamma for a given head type. For a small sample of HAMR heads, LIRP was measured on the spinstand with the reader using the Wallace Equation [2-3] near passive fly height and BLIWP was measured with an Acoustic Emission (AE) sensor in contact with the media as seen in Figure 2. A laser gamma was calculated from the LIRP and BLIWP data and then applied to the volume data. To apply the laser gamma, LIRP was measured first in volume and BLIWP was then calculated from the laser gamma (BLIWP = LIRP \* \( \gamma \)) in order to obtain by head determined laser protrusion near the writer without bringing the HAMR head into contact with the media as seen in Figure 3.

III. RESULTS

We applied this non-contact laser gamma method to two different head types (Head Type 1 and Type 2) and observed a laser gamma of 1.58 for Head Type 1 and 1.47 for Head Type 2. These laser gammas were then applied to the volume data for these two different head types as seen in Figure 3. The difference between Head Type 1 and Type 2 were minor changes in the laser light delivery system. The BLIWP dependence on operating laser current changed between these two designs. The laser protrusion near the writer was slightly reduced for Head Type 2 compared with Head Type 1. Obtaining this feedback from the volume data enables better informed design decisions as well as more accurately set clearance in volume testing and in drive.

IV. CONCLUSION

This non-contact laser gamma laser protrusion measurement method enables volume BLIWP collection without sacrificing performance or reliability of the screened heads by measuring the laser gamma through LIRP and BLIWP on a small sample of the population of HAMR heads. By using the laser gammas from this small sample, clearance can more accurately be set during volume screening and in drive as well as help make better design decisions to reduce laser protrusions for future designs. This non-contact laser protrusion method improves reliability of the HAMR heads by enabling more accurate clearance setting capability.

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![HAMR Head Protrusion Diagram](image1)

**Figure 1: HAMR Head Protrusion Diagram**

![Laser Gamma Calculation from Experimental Data for Head Type 1 and 2](image2)

**Figure 2: Laser Gamma Calculation from Experimental Data for Head Type 1 and 2**

![Volume Data of LIRP and Calculated BLIWP from Laser Gammas](image3)

**Figure 3: Volume Data of LIRP and Calculated BLIWP from Laser Gammas**
BENDING LOSS ANALYSIS OF GaAs/AlGaAs QUANTUM DOT RIDGE-GUIDED RING LASERS FOR COUPLING TO HAMR NFT

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I. MOTIVATION

The energy delivery system for heat assisted magnetic recording (HAMR) may employ a laser to temporarily heat the magnetic recording media during the data writing process. A significant challenge is the delivery of sufficient incident optical power from the semiconductor laser to a nanometer scale area on the recording medium. We designed a ring geometry for the laser since this can be more compact than a straight bar laser for the same operating parameters (e.g. threshold current density, optical power output) and thus more favorable for a HAMR light delivery system. Light guided within a ring laser will experience additional loss due to bending compared to bar lasers, but this loss only becomes significant below a minimum ring radius. Generally for the same threshold current densities, ring lasers require a smaller footprint than bars which helpful since there is a space constraint associated with HAMR laser integration. In this work, the optical losses in GaAs/AlGaAs quantum dot (QD) ridge-guided ring lasers due to waveguide bending are analyzed after fabrication. A model for bending loss is developed by fitting and extracting parameters from experimental data. Threshold current density \( J_{th} \) as a function of radius is plotted for radii 50-380 \( \mu \)m, and we fit a calculated \( J_{th} \) to this data to verify the accuracy of our model. Our results show that ring lasers start to incur significant bending loss when radius decreases below 150 \( \mu \)m, causing \( J_{th} \) to increase exponentially. However, above this value the threshold current density is the same as bar lasers and offer the advantage of a smaller footprint.

II. RING LASER FABRICATION

Ring lasers were fabricated in wafers consisting of 12 layers of 5 nm InAs quantum dots active region in a 200 nm thick intrinsic GaAs active region sandwiched between 1500 nm layers of p- and n-type AlGaAs. A 200 nm layer of p-GaAs covers the top p-AlGaAs layer and the entire structure was grown on n-GaAs substrate. To be able to measure the electroluminescence at each major step of the fabrication process, we sputtered top and bottom Ti/Pt/Au electrode contacts before any other processing of the wafers. A layer of AZ4110 photoresist was patterned onto the ridge so that during the etch in a Plasma-Therm Versaline ICP system it will serve as an etch mask. For testing purposes, the ridge height was etched to 2.3 \( \mu \)m deep to ensure that the active region was exposed so as to increase light output. A layer of insulating SiO₂ was deposited onto the ridge using PECVD, and a via was etched using RIE to allow for creation of metal contact pads to the ridge which stopped on the pre-deposited metal contacts. Lastly, an additional layer of Ti/Pt/Au was deposited for contact pads to assist in device probing. The final cross section of the device and the top view of a completed 680 \( \mu \)m diameter ring laser can be seen in Fig. 1.

III. RING LASER BENDING LOSS ANALYSIS

Below we note the relationship between threshold current density \( J_{th} \) and bar length \( L \) for straight cavity lasers [1]:

\[
J_{th} = J_0 + \frac{1}{A} \left[ \alpha_t + \frac{1}{2L} \ln \left( \frac{1}{R_F R_R} \right) \right]
\]

where \( J_0 \) is the transparency current density, \( A \) is a constant with units of cm/A, \( \alpha_t \) is the internal loss in cm\(^{-1} \), and \( R_F \) and \( R_R \) are respectively the front and rear mirror reflectivity. We note that the second term in the brackets is the mirror loss, and for ring lasers this will be replaced by the bending loss since the sidewalls can be thought of as mirrors. In literature, \( \alpha_B \) has been derived to increase exponentially with decreasing radius [2]:

\[
\alpha_B = C_t e^{-C_2 R}
\]
where \( C_1 \) (Nepers/m) and \( C_2 \) (m\(^{-1}\)) are constants and \( R \) is the ring radius. The final model for a ring laser is the combination of (1) and (2):

\[
J_{th} = J_0 + \frac{1}{A} \left[ \alpha I + \frac{1}{2} \ln \left( \frac{1}{R^2 R_0} \right) + C_1 e^{-C_2 R} \right]
\]

(3)

Using our experimental data for \( J_{th} \), we fit the parameters \( C_1, C_2, \) and \( A \) with the latter constrained to be the same for both bar and ring lasers. We do not obtain separate values for \( J_0 \) and \( \alpha I \). The results for the fitted parameters are respectively \( 3.84 \times 10^4 \) Nepers/m, \( 2.13 \times 10^4 \) m\(^{-1}\), and 0.015 cm/A. The final fits for bar and ring lasers are shown in Fig. 2 versus their respective maximum device dimensions, in this case bar length and ring diameter.

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ILLUSTRATIONS

FIG. 1. (a) Cross section of finished ring laser device. A layer of SiO\(_2\) provides electrical insulation as well as index contrast for waves traveling in the ridge. (b) Completed ring device 680 \( \mu \)m in diameter and 10 \( \mu \)m wide with square contact pads.

FIG. 2. Scatter plot shows experimental data of \( J_{th} \) vs. length for bar lasers (a) and diameter for ring lasers (b). The length and diameter are treated as the maximum length of the footprint for their respective devices. Solid line shows the fitted result using (2) and (4).
IMPEDANCE MATCHING HAMR NEAR FIELD TRANSDUCERS TO THE MEDIUM THROUGH TAPERING AND DISCONTINUITIES

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I. INTRODUCTION

Heat assisted magnetic recording (HAMR) is considered the leading candidate for increasing areal density of magnetic recording medium to greater than 10 Tb/in². HAMR requires heating high coercivity magnetic recording media with a localized subwavelength optical spot to above the media’s Curie temperature. A near field transducer consisting of a good plasmonic material such as gold clad in a dielectric takes advantage of the high field confinement near the surface of the transducer to produce a highly localized optical spot. This coupling process to the medium is inefficient, resulting in power dissipation in the near field transducers that causes several hundred degrees temperature rise inside the NFT [1]. This is a primary failure mode for HAMR NFTs. This work studies the transmission efficiency between the optical source, the near field transducer and magnetic recording media by using wave impedance to analyze power coupling and design improvements based on mode conversion and impedance matching.

II. MODELLING APPROACH

We have used COMSOL to study the propagation of the circumferential modes of a gold wire NFT, as a function of wire diameter (for uniform cross sections) and taper angle (for tapered sections). Specifically, we were able to quantify mode impedance, and complex propagation constant. Additionally, we examined the excitation of these NFT modes using the evanescent wave from a dielectric waveguide oriented at 90 degrees to the NFT. Finally, we examined the interaction of these propagating modes with an air gap and a medium surface. We used these derived insights to design impedance matched structures for improved coupling efficiency.

III. RESULTS AND CONCLUSIONS

A sharp increase in characteristic impedance of the gold wire and the reflection coefficient at the air bearing surface is observed for decreasing radii. An analytical model was developed that suggested the load impedance actually increases more quickly than the source impedance by a factor of the radius, resulting in a reflection coefficient of -1. For radii less than 10 nm, transmission to media is less than 10%. Achieving good excitation of the NFT by the source presents a second challenge, and requires cross-sectional area larger than the final output area, resulting in a large mode mismatch between the input and output ends of the NFT.

The dependence on the radius of the NFT’s characteristic impedance suggests matching to the load impedance of the air gap and media is possible using NFT sections different radii and lengths to reduce the reflection of the NFT to zero. An example of such a design is shown in Figure 1. Characteristic impedances of the NFT sections are extracted from the simulations. This design results in a zero reflection coefficient at the interface between the first and second NFT sections. In addition to the quarter wave matching sections in Figure 1, tapers were also examined as a way to connect the large NFT driven end with the narrow media end. The fraction of power reflected vs. transmitted, delivered to media, or dissipated by the NFT is extracted. Figure 2 shows a plot of the fractional portions of power in the system. A summary of the different designs and their transmission efficiencies will be provided.

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Fig. 1. NFT design with impedance matching sections, resulting in zero reflection coefficient at output of 100 nm transducer section.

Fig. 2. Power modes as fraction of incident power on tapered section.
INCREASE OF THERMAL INTERFACE CONDUCTANCE IN Au/Al2O3 INTERFACE WITH Cu AND Cr ADHESION LAYERS

Minyoung JEONG¹, Joe LIANG¹, Justin FREEDMAN¹, Vicent M. Sokalski¹, James A. BAIN¹, and Jonathan A. MALEN¹

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In Heat Assisted Magnetic Recording (HAMR) the peak temperatures of the near-field transducer (NFT) can be heated to hundreds of degrees above room temperature due to parasitic heat that is generated in the gold (Au) [1] and dissipated to a surrounding dielectric. To mitigate this overheating issue which degrades performance, high-thermal conductivity dielectrics such as aluminum nitride (AlN) or sapphire (Al2O3) are being considered as cladding materials that will enhance heat dissipation. Thermal resistance at the Au/dielectric interface itself then becomes the bottleneck for heat dissipation from the NFT. Therefore, increasing thermal interface conductance (G) at this interface is desirable. The reported values of G in the Au/Al2O3 interface range from 22 MW/m²K to 66 MW/m²K [2,3].

We attempted to enhance G by inserting thermally-conducting adhesion layers between the two materials that enhance interface thermal conductance. Adhesion layers need to improve G without degrading optical performance across plasmonic interface. Considering these conditions, our candidate materials were chosen to be copper (Cu), a relatively low loss metal the wavelengths of interest. (free space wavelength, λ₀= 800 nm) and chromium (Cr), a relatively lossy metal but with excellent adhesion promoting properties. Phonons in a metal side obtain their energy from metal-electrons, and then transfer through the interface to interact with phonons on the non-metal side. [4] Thus, understanding a phonon transport at the interface is critical. In our study, tapered adhesion layers of Cu and Cr were sputtered in a wedge geometry with thicknesses ranging from 0 to 7.5 nm between a Au-layer (~70nm) and single crystal Al2O3-wafer. The thicknesses of each material were measured with X-ray reflectivity (XRR). A wedge-like shape was desired for adhesion layers because it enables a continuous measurement of G as a function of layer thickness in one sample.

A non-contact optical technique, known as frequency-domain thermoreflectance, was used to measure G in Au/Cu/Al2O3 and Au/Cr/Al2O3. In this technique, a 488nm continuous wave (CW) pump laser is intensity-modulated from 200kHz to 10MHz by an electro-optic modulator, and absorbed by the sample surface. The sample surface will be heated periodically at a certain frequency due to the modulated pump beam and thus will exhibit a corresponding periodic temperature change. Then, a 532nm CW probe laser beam that is co-linear with the pump at the sample surface will be reflected at the same frequency with the pump beam and detected by a photo diode. Due to a thermal resistance inherent in the sample, a phase lag between the modulated pump and reflected probe beam occurs. This phase-lag data in a range of frequencies at different positions on the substrate was obtained using a lock-in amplifier and fit to an analytical solution of the heat diffusion equation to extract out G [5].

As seen in Fig.1, the experimentally observed G values showed significant enhancement even with a 1nm-thick adhesion layer. Both Cu and Cr specimens saturated at maximum G to 183±31MW/m²K and 400±116 MW/m²K, respectively, once the layer became as thick as approximately 5nm. More importantly, with just a 1 nm thickness the Cu and Cr adhesion layers offer a two and four fold enhancement relative to the Au-Al2O3 interface. These values were then compared with the values calculated from an accumulation function of thermal interface conductance based on the Diffuse Mismatch Model (DMM). While the DMM prediction plateau at large thicknesses is comparable to the experimental measurements, it’s predicted enhancement of G does not grow as rapidly with

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thickness. This comparison suggests that both adhesion at the interface and alignment of the phonon spectra on either side of the interface, are important considerations in enhancing $G$ with thin intermediate layers.

Fig.1: Experimentally obtained $G$ values in Cu and Cr adhesion layer specimens as a function of position on Al$_2$O$_3$ wafer, and calculated $G$ values from the thermal interface conductance accumulation function as a function of wavelength.

REFERENCES

WRITE CONDITION OPTIMIZATION IN HAMR HEADS: THE EFFECT OF RISE TIME ON PERFORMANCE

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I. INTRODUCTION

Over the last few years, heat assisted magnetic recording (HAMR) technology has become a viable solution to the problem of the current explosion in requirements for growth in areal density[1,2]. The implementation of such a radical new technology is accompanied by further overcoming several challenges [3], one of which is the optimization of the writing procedure. While laser current and write current are the knobs to tune the thermal and the magnetic components of writing, write current alone does not optimize the magnetic system completely.

II. EXPERIMENTAL RESULTS

A spin stand study of several HAMR heads was conducted. The write current was fixed at 65mA and the overshoot pulse accompanied the DC write current was varied for different duration. The fly height was adjusted to 2 nm taking into account the protrusion for the different write field conditions. The laser current was then optimized to yield the lowest bits in error (log(BER)) for the center track, when adjacent tracks were written at a separation of 68nm in either cross track direction. This optimization was performed at each of the triplet values of write current, overshoot amplitude (OSA) and overshoot duration (OSD). The laser current requirement was seen to decrease with the increase in the write field. The effect on performance was gauged by the change in the log(BER). Figure 1 shows the experimental results viz. the log(BER) as a function of overshoot duration for different overshoot amplitude. The solid green circle denotes the datum for the zero OSA, OSD condition. The solid red squares and solid blue diamonds show the data for an OSA of 3 and 12 DAC units respectively. Results show conclusively that the application of overshoot improved the log(BER) by almost 0.2 decades. Figure 2 shows a contour plot of log(BER) as a function of overshoot amplitude and duration over all measured values for ten heads with the same design. It can be seen that an optimal point is obtained for the write triplet at an OSA of 10 DAC units and an OSD value of 12 DAC units.

III. MODELING RESULTS

Micromagnetic modeling was used to understand the impact of write current triplet on recording performance, more specifically bit error rate (BER). The modeling consisted on two major steps. First we performed modeling of write field roll-off versus high frequency on write current triplet, using a publicly available tool: magpar. The analysis showed that roll-off improves with increasing steady state current and overshoot amplitude. This result is in agreement with previous modeling and experimental observation on perpendicular magnetic recording (PMR) write heads. Second we performed modeling of the HAMR recording process, to extract the impact of field roll-off on BER. This modeling showed HAMR was less affected by the loss of field at high data rate compared PMR. We also found that the presence of overshoot amplitude and duration lead to improvement to recording quality (BER). But high values of OSA and OSD can also lead to down-track and cross-track erasure due to the slow saturation of the write field vs. write current for some writer designs.

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Figure 1: Experimental log(BER) as a function of overshoot duration for different overshoot amplitude values

Figure 2: Contour plot of experimental log(BER) as a function of overshoot amplitude and duration for a given write current
AMBIENT TEMPERATURE AND HEAT SINK EFFECTS IN HAMR

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I. INTRODUCTION

In a Heat Assisted Magnetic Recording (HAMR)¹ system, it is observed that ambient temperature changes affect both the on track performance and adjacent track interference (ATI). This effect could be due to the thermal gradient changes in the media which occur for different ambient temperatures. In HAMR, thermal gradient¹,² changes can be achieved by modifying the thickness of the media’s heat sink layers which control the heat flow from the storage layer.

II. EXPERIMENTAL DETAILS

To explore the HAMR ambient temperature effects, HAMR drives were built and tested by varying the ambient temperature for each drive using an oven. On the spinstand, experimental tests were conducted with a heat sink (HS) ladder of HAMR media at fixed temperature. For the spinstand experiments, the same heads were used for all media types. The experiments evaluated the effects of ambient temperature and media heat sink thickness using three metrics, i.e., the slope of the write width (WW) vs laser power, the on track BER (Bit Error Rate) and the ATI.

III. RESULTS

The HAMR drive results where the ambient temperature was changed are shown in Figs. 1(a), 2(a) and 3(a). The spinstand results of the HS thickness ladder on WW, BER and ATI are shown in Figs. 1(b), 2(b) and 3(b).

Figs. 1(a) and 1(b) show the WW vs laser current at different ambient temperatures and HS thicknesses, respectively. As shown in Fig. 1(a), when the ambient temperature increases, the laser current required for the same WW is lower. This is because when ambient temperature increases, the initial media temperature is elevated, thus less thermal energy from the NFT (near field transducer) is required to reach the recording temperature and therefore less laser current is required. Moreover, as shown by Fig. 1(a), the slope of WW vs laser current increases when ambient temperature increases. A similar laser current reduction and slope change of WW vs laser current is observed when the HS thickness decreases. This is shown in Fig. 1(b).

Based on the above, when the ambient temperature changes, the effective thermal gradient of the recording system changes, impacting both the required laser current and the slope of WW vs laser current. Figs. 2(a) and 2(b) show the T_T_BER (triple track BER). The BER is worse when the ambient temperature increases or when the HS thickness decreases. This is consistent with a reduction in thermal gradient.

Figs. 3(a) and 3(b) show the adjacent track BER degradation (ATI effect). ATI gets better when the ambient temperature decreases or HS thickness increases, illustrating how the thermal gradient affects ATI.

IV. CONCLUSION

Based on the results obtained, it is found that in terms of all the three metrics (write width, T_T_BER and ATI), the effects from ambient temperature increases show similarities to the effects from HS thickness reductions.

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Figure 1 (a)/(b): Write width (WW) vs laser current, with varied temperature / HS thickness.

Figure 2 (a)/(b): Triple track BER (T_T_BER) vs temperature/HS thickness.

Figure 3 (a)/(b): BER degradation vs number of writes, with varied temperature/HS thickness.
RADIATION AND CONDUCTION HEAT FLUX IN THE HEAD-DISK INTERFACE OF HAMR SYSTEMS WITH LARGE TEMPERATURE DIFFERENTIALS

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In recent papers [1,2] we derived the heat transfer coefficient as a function of the head-disk separation (gap) in a HAMR type layered structure. The definition of this coefficient allowed us to make extensive use of Taylor series expansions in the limit of small heat flux and small temperature differences in the main equation that relates the heat flux Q to the base temperatures TA and TB.

which is equally applicable for the analysis of heat transport by electromagnetic radiation and by phonon tunneling. The work [1] was focused on the analysis of heat radiations, and [2] highlighted the heat transfer contribution of phonon tunneling across the small gap due to the van der Waals forces that connect the two sides. The restriction to small temperature differences permitted us to compute the heat transfer coefficient analytically, but with this restriction we were not be able to calculate the heat flux for the case of large base temperature differences.

In the present paper we relax the restriction to small quantities and solve the above equation for the heat flux associated with large temperature differences, up to 500 degrees, similar to those found in HAMR systems. In this case the equation for heat flux is highly non linear, and it requires a numerical solution.

Here we calculate the heat flux radiation in a benchmark structure, which was studied experimentally in [3] and theoretically in [2]. This structure consists of two bulk plates, modeled by half-spaces, which are separated by a vacuum gap, whose width decreases to a few nanometers. First we considered the case with two plates made from identical materials (Silica), and computed the heat flux caused by the temperature difference up to 500 K. Computations shown in Fig.1 agree with the measurements reported in [3] and confirm the 1/H² divergence of the heat flux as the width of the gap H decreases. Fig.2 shows the calculation of the heat transport coefficient of a vacuum gap between not necessarily identical materials. Two lower graphs clearly show that even a small difference between speeds of light in the plates sharply changes the dependence of heat transport on the gap’s width. Thus, if the materials are identical, then at the limit H>0 the heat transport coefficient does not diverge but approaches a finite limit.

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Fig. 1. The heat flux $Q$ and the ratio $Q/dT$ for a vacuum gap between identical materials.

Fig. 1. The heat transport coefficient $K=Q/dT$ for a vacuum gap between different and identical materials.
MICROSTRUCTURE AND MAGNETIC PROPERTIES OF Co-SPUTTERED FePt-C GRANULAR FILMS

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I. INTRODUCTION

The ordered L10 FePt granular films are well-considered to be the future heat assisted magnetic recording media with area density above 2Tb/in² due to high magnetocrystalline anisotropy (K_u). The FePt films can be prepared to have high [001] texture which shows high perpendicular magnetic anisotropy. Epitaxial growth of FePt films on MoC/CrRu/glass have been proved to promote chemical ordering and texturing. The chemical composition of Mo50C50, and Mo40C60 intermediate layers have been studied previously and the excess C was used as segregant to diffuse up to separate FePt grains from intermediate layer [1, 2]. To change the morphology of FePt grains further, the co-sputtered FePt-C films were prepared on Mo50C50 intermediate layer in the study. Compared with FePt single layer, the co-sputtered FePt-C films illustrate higher coercivity and better granular structure. When the atomic concentration of C is 29%, the FePt grains illustrate higher contact angle (69°) and higher out-of-plane coercivity (~12 kOe).

II. EXPERIMENTAL

The FePt thin films with a layer structure of (FePt-C(x))/MoC(25nm)/CrRu/glass (x=0, 9, 17, 23, 29 at%) were all prepared using direct current (dc) magnetron sputtering and the background pressure of sputtering system was below 5x10⁻⁷ Torr. The CrRu seed layer with a thickness of 80nm was sputtered on bare glass at 200°C by using alloy targets. The film chemical composition is Cr78Ru22 measured by energy dispersive spectrometers. After CrRu seed layer deposition, the substrate temperature was raised to 425°C. The MoC intermediate layer with thickness of 25 nm was prepared at 425°C by using Mo40C60 alloy target. Finally, the FePt with thickness of 10 nm was co-sputtered with Carbon at 425°C. The crystal structure of the samples was identified using a standard X-ray diffraction (XRD) technique (BRUKER, D8 Discover). Magnetic hysteresis loops were measured at room temperature by using superconducting quantum interference device (SQUID) magnetometer. The film microstructure was observed using transmission electron microscopy (TEM, JEOL JEM-2010). The surface roughness was measured using atomic force microscopy (AFM).

III. RESULTS AND DISCUSSIONS

The XRD patterns of the FePt-C(x)/MoC(25 nm)/CrRu(60 nm) films (x=0, 9, 17, 23, 29 at.%) were investigated. The MoC intermediate layer was epitaxially grown on CrRu (200) seed layer and shown (200) texture. The (001) superlattice diffraction peak and the (002) fundamental reflection of the L10 FePt are clearly observed and suggesting that the L10 FePt crystal has a (001) preferred orientation. The FePt thickness was fixed at 10 nm and the relative integrated intensity of L10 FePt (001) and (002) peaks was almost not changed in FePt and FePt-C films. The ordering degree was changed from 0.76 for FePt to 0.71 for FePt-C(29%) film.

The out-of-plane and in-plane magnetic hysteresis loops of FePt-C(x)/MoC/CrRu (x=0, 9, 17, 23, 29 at.%) films measured by SQUID. The FePt and FePt-C films illustrate square like out-of-plane loops with high perpendicular magnetization and linear-like in plane loops. When the content of C increased to 29%, the out-of-plane coercivity was increased to around 12kOe.

Fig. 1 shows cross-sectional and plane-view TEM images and the selected area diffraction (SAD) patterns of the FePt-C(29at.%)/MoC/CrRu films. In Fig. 1(a), the FePt grains were well isolated by C segregant and shown granular structure. The FePt grains are smaller in FePt-C(29at.%) film. From cross-sectional TEM images shown in Fig 1(b), the FePt islands were still not separated and each island contains many grains. The carbon grains were appeared in island side and top areas. However, the contact angle of FePt grain was increased up to 67°C in FePt-C(29at. %) film as compared with FePt film.

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Fig. 1TEM images of FePt-C(29at.%)/MoC/CrRu films (a) plane-view image, (b) cross-sectional image
APPLICATION OF AC MAGNETO-OPTICAL KERR EFFECT AND MULTISCALE MODELLING FOR Tc AND \(\sigma T_c\) ANALYSIS OF FePt-X HAMR MEDIA

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Heat Assisted Magnetic Recording (HAMR) is commonly recognized as a leading contender for the next generation of magnetic storage technology, offering potential for a significant increase in areal density and hard disk drive (HDD) capacity. The HAMR system’s performance (SNR, bit-to-bit transition jitter) and reliability are strongly affected by the design of the recording media. Among the key parameters of HAMR media are the Curie temperature (Tc) of the FePt-X grains and the distribution of Tc (\(\sigma T_c\)). The Curie point sets the characteristic write temperature of the recording process and the light power needed to be delivered by the near field transducer (NFT) to the media, and thus critically affects the lifetimes of both the media and the head. In addition, Tc distribution is thought to be a major factor contributing to media SNR and thus achievable areal density.

Recently [1] we proposed to apply the technique known as Alternating Current Magneto-Optical Kerr Effect (AC MOKE) to characterize the Tc and \(\sigma T_c\) of the FePt-X granular films in the context of HAMR media applications. This approach is based on the use of magneto-optical measurements to probe the longitudinal AC magnetic susceptibility (d\(M/dH\)) of a thin granular magnetic film in the presence of a small oscillating magnetic field at the broad range of temperatures. It was demonstrated with a number of FePt-X granular films that near Curie temperature a peak position and width of the magneto-optical response (Figure 1) is a sensitive function of ferro- to paramagnetic phase transition (Tc) and its grain-to-grain distribution (\(\sigma T_c\)). This technique provides sensitivity sufficient to measure magnetic films of just a few monolayers thick in terms of probing magnetic properties as a function of doping, film thickness, grains size, impurities, crystal lattice quality, stress, etc.

Another important ingredient of this approach is simulations-based analysis of experimental results. Here we present a multiscale modeling approach based on a combination of relaxation rate theory and atomistic simulations using the earlier proposed model of atomic scale magnetic interactions [2]. This approach was used to simulate magnetization dynamics in FePt grains at elevated temperature around the Curie point in the presence of a small oscillating magnetic field. Atomistic modeling was also used to evaluate relative contributions of finite size fluctuations, surface effects and chemical ordering effects to \(\sigma T_c\).

Figure 1. Temperature dependence of longitudinal AC magnetic susceptibility (both real-red symbols and imaginary-blue symbols parts) measured for granular magnetic FePt-X layer of HAMR media. Dashes and solid black lines show the best fit used to determine the value of Tc and its distribution.
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LARGE-AREA PATTERNED SUB-100 NM DOTS ARRAY OF L10 FePt VIA NANOIMPRINT LITHOGRAPHY

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ABSTRACT

Bit-patterned media (BPM), a promising candidate for next generation high density magnetic recording, requires sub-100 nm dots array on a wafer scale¹, a high degree of patterning control of the size distribution², and a material with high perpendicular anisotropy³.

In this work, large area (0.75 cm×0.75 cm) dots array was achieved by nanoimprint lithography (NIL) and ion milling from FePt thin films. First, we demonstrated the fabrication of L10 ordered FePt films at a lower growth temperature (450 °C) using ultra-high-vacuum ion beam sputtering system (UHV-IBS)⁴,⁵, with high crystalline quality, and perpendicular magnetic anisotropy. Then, large-area (0.5 cm×0.5 cm) dot arrays are fabricated using post-patterning of NIL combined with Mo mask-transfer technique and ion milling. The sub-100nm dots array shows high coercivity of 11 kOe and is characterized by MFM and VSM. The magnetization reversal mechanism is also studied by d.c. demagnetizing curves, providing a promising candidate for BPM.

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Figure 1. (a)-(g) Schematic of the nanofabrication process by NIL and ion milling: after (a) thermal imprinting, (b) RIE-dry etching, (c) TMAH wet etching, (d) Mo deposition, (e) lift-off, (f) ion milling, and (g) Mo-residual removal by H₂O₂. (h) Cross-sectional SEM image of the bilayer resist undercut profile. (i) Top-down SEM of the Mo dots after (e). (j) AFM image of FePt dots array morphology.
Heat assisted magnetic recording (HAMR) is a promising approach to increase the magnetic recording areal density beyond the conventional perpendicular magnetic recording limit. In a HAMR system, an optical near-field transducer (NFT) is used to locally increase the media temperature and reduce the coercivity so that the writing head can write information on the recording media. Various types of NFT designs have been investigated to improve the optical efficiency and the shape of the optical beam on the recording media [1]-[3]. However, the effects of the recording media structure on the performance of the NFT are not well understood yet.

Due to the small thickness of the recording layer compared to the wavelength, and the multilayer geometry that is used for recording media, one promising approach for designing recording media is using circuit theory to approximate the Maxwell equations. The concept of circuit nanoelements in the optical domain was first introduced in [4] by extending the conventional circuit model at microwave frequency to the optical frequency, and defining the equivalent impedance of nanostructures as a ratio between the average potential difference between two parts of the nanostructure and the effective displacement currents that go through it. In this work, although we use circuit analysis to design recording media, we develop a more physical model that describes the impedance of a nanostructure in terms of kinetic motion of the electrons and the vacuum impedance. We apply this circuit model to investigate the efficiency of different recording media design for a Lollipop NFT, which has the dominant electric field component along the surface perpendicular [5]. We show that a significant change in the power delivered to a recording bit can be obtained by modifying the impedance of continuous media along the cross track direction by converting it into discrete track media, and along both down track and cross track direction by converting it into bit patterned media. The field intensity profile within the recording layer of different recording media structures (Figure 1 and 2) shows that this impedance modification can increase the efficiency of the HAMR system if we assume some materials with high capacitance, such as air, between the recording tracks and bits.

Fig. 1. Normalized profile of the field intensity within the middle of (a) the continuous recording layer (b) the bit patterned media.

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Fig. 2. (a) Schematic of DTM (b) Normalized profile of the field intensity within the middle of the discrete track media

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PROBING THE EFFECT OF TWO-STEP TEMPERATURE DEPOSITION ON TOPOGRAPHICAL PROPERTIES OF FePt MEDIA

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L10 FePt displays a large magneto-crystalline anisotropy ($K_u \sim 7 \times 10^7$ ergs/cc), thereby making it a potential candidate for advanced magnetic recording technologies [1, 2]. FePt requires a very high in-situ deposition temperature of ~600 °C for transformation to L10 ordered phase. Although the high temperature induces ordering in FePt but this leads to undesirable topographical properties such as high surface roughness [3-5]. Increase in surface roughness adversely impacts head-media spacing in heat assisted magnetic recording (HAMR) [6]. Moreover, surface patterning for bit pattern media (BPM) fabrication is also hindered by higher surface roughness [7].

In this report, we have studied a two-step temperature-deposited FePt bilayer wherein, the first layer of FePt is deposited atop the underlayers MgO/CrRu at 600 °C followed by a second FePt layer deposited at lower temperatures ($T_{dep}=25, 75, 150, 250, 350$ °C). The first FePt layer, deposited at 600 °C resulted in ordered FePt with superior magnetic properties but higher surface roughness. On the other hand, the second FePt layer compensated to reduce the surface roughness (Fig. 1). However, this improvement came at the cost of slightly degraded magnetic properties. The out-of-plane coercivities as well as the anisotropies decreased by 45 and 20%, respectively, in these samples. A significant result was obtained when the second FePt layer was deposited at room temperature ($T_{dep}=25$ °C) where partial ordering in the second FePt layer was induced from the first FePt layer through homo-epitaxy [8, 9]. Consequently, it displayed enhanced magnetic properties, but little improvement in the surface roughness.

The growth dynamics of the second FePt layer over the first FePt layer was studied employing transmission electron microscopy. The variation in in-situ deposition temperature led to change in the grain growth from columnar ($T_{dep}=25$ °C) to encapsulating model ($T_{dep}=75, 150$ °C). The grain growth process then switches to growth by nucleation (Fig. 2) at even higher temperatures ($T_{dep}=250, 350$ °C) due to high surface mobility of the Fe and Pt atoms. These further provided a better understanding of the variation in topographical properties of the two-step temperature-deposited FePt media.

Furthermore, by this method the magnetic properties of FePt can also be tuned via interplay of factors such as induced ordering, new grain nucleation, surface mobility, and difference in thermal expansion coefficients of the underlayers. This study clearly shows the potential application of FePt bilayer stacks in HAMR and BPM. Further improvements are possible by systematic variation of parameters like addition of phase segregants, deposition temperatures, layer thicknesses, deposition pressures etc.

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Figure 1: Atomic force microscopy images of sample surface and root mean square (Rq) roughness of all samples.

Figure 2: TEM (top view) of reference sample A (with only first FePt layer) and sample E (T_{dep}=250 °C).

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INVESTIGATING THERMAL COUPLING EFFICIENCY OF FePt GRANULAR MEDIA FOR HEAT-ASSISTED MAGNETIC RECORDING

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I. INTRODUCTION

Heat assisted magnetic recording (HAMR) is a future generation magnetic recording technology that can enable higher data storage density by reducing the magnetic grain size and by increasing the effective write field gradient. Among the various recording metrics, jitter is an important performance indicator that governs the achievable linear down track storage density of the media layer. In HAMR recording media, jitter is dominated by the grain to grain distributions of Tc (\(\sigma_{Tc}\)), distributions of thermal coupling and resistivity (which produce \(\sigma_T\)), and to a lesser degree by distributions of Hk. Though both \(\sigma_{Tc}\) and \(\sigma_T\) have the same effect on jitter [1], the former is caused by variations in intrinsic grain properties, whereas the latter is caused by extrinsic variations in the coupling efficiency to the heat source and by thermal coupling variations from the grain to the underlayers.

A well-established technique for measuring \(\sigma_{Tc}\) in HAMR granular media has been demonstrated using Thermal Remanence Measurement tool [2], which uses far field laser heating to measure thermal remanence as a function of laser power. However, no approach to measure \(\sigma_T\) in HAMR media has been reported so far. In this poster, we present an approach to quantify the impact of thermal coupling efficiency variation of the media grains with the underlayer below the grain, which is one of the contributors to \(\sigma_T\).

II. RESULTS

Our \(\sigma_T\) measurement techniques is based on designing a series of underlayer structures which, during far field laser heating, have different heat fluxes between the magnetic grains and the underlayer. In the first case (shown in Fig. 1(a)), the FePt layer absorbs energy from the heated absorbing-metallic underlayer. The temperature of the FePt layer is in thermal equilibrium with the MgO layer, thus masking any effects of interfacial thermal conductance variations at their interface. This is evident in Fig. 1(c), which shows modeling results of the FePt temperature versus time following illumination with short far field laser pulse for media with different thermal interface conductivities G. The peak temperature of FePt does not vary with G, indicating that the measured TRM switching temperature distribution is therefore solely attributed to \(\sigma_{Tc}\). In the second case, the metallic underlayer is replaced with a high thermal conductivity transparent layer (Fig. 1(b)). As shown in Fig 1(c), the peak grain temperature under the same illumination has a strong dependence on G for the transparent underlayer media. Thus a variation in this coupling shows up as an increase in the measured TRM switching temperature distribution. By measuring \(\sigma_{T,\text{total}}\) for different underlayer samples with identical magnetic and seed layers we can extract \(\sigma_T\). We used this approach for FePtX granular media deposited on MgO seed layers. We found that the sample with the smallest heat flux had a measured \(\sigma_{T,\text{total}}\) of 2.3\% of Tc which increased to 2.6\% of Tc for the highest heat flux sample (Fig. 2(a)). We attribute the increase in \(\sigma_{T,\text{total}}\) to an increase in \(\sigma_T\), reflecting the grain to seed coupling variations in the media. Detailed experimental and modeling results will be presented.

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Figure 1. (a) and (b) show the two stack layers with different types of underlayers, either absorbing or transparent. (c) shows the simulated temperature profile of the FePt peak temperature for the two cases shown in (a) and (b), for same external laser power, as a function of different interfacial thermal conductances between FePt/MgO interface. The temperature rise of the media for G=100 is over twice that of G= 700 when the underlayer is transparent and negligible when it is absorbing. Higher laser power will be required to bring the transparent underlayer media to Tc, but the temperature ratios will be the same.

Figure 2. (a) shows the experimental switching temperature distribution plots of FePt for both absorbing and transparent underlayers. Broadening of the switching temperature distribution for transparent underlayer, is attributed to the increased contribution of $\sigma_T$ in the measurement, stemming from FePt-MgO interface conductivity variations. The FePt granular media on both the underlayers had similar structural properties, as indicated in (b).
A STUDY ON READ/WRITE PROCESSING FOR TDMR SYSTEM AS MULTILEVEL SIGNALING

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I. MOTIVATION

Since the shingled-write magnetic recording (SMR) was proposed in [1], a study of two-dimensional magnetic recording (TDMR) has become hot-topics for realization of higher capability HDD. By the SMR assumption, we have become to be able to study a system which has narrower track pitch independent from core width of writer element. The narrower track pitch brings, however, inter-track interference (ITI) as dominant noise in read-back processing. Therefore, it is considered that two or three reader elements are considered to be adopted to avoid corruption from ITI in almost of the TDMR discussions. Here, a main purpose of the ITI canceling is to ideally derive read-back signal corresponding to a desired track. Hence, the TDMR system does not use the ITI effectively on the read-back signal processing to realize the higher density.

In this discussion, we propose a read/write (R/W) processing of which two or three tracks are simultaneously detected as multilevel amplitude signaling with fully ITI corruption by one reader. To consider the R/W processing, we assume that a desired track includes two or three tracks as sub-tracks, each of which has 1/3 track width such as micro-track model. Each of sub-tracks is operated in bipolar as same as conventional perpendicular magnetic recording. In the case of using two sub-tracks, we can use 3-ary amplitude levels at one writing symbol where the 3-ary levels can be derived from writing conditions as \((-1,-1) = -2\), \((-1,+1) = 0\), \((+1,+1) = +2\) by the adjacent sub-tracks. As same fashion, 4-ary amplitude levels can be managed in the case of using three sub-tracks as \((-1,-1,-1) = -3\), \((-1,-1,+1) = -1\), \((-1,+1,+1) = +1\), \((+1,+1,+1) = +3\). By these fashions, we can easily consider a multilevel amplitude signaling in read-back signal. Furthermore, we propose mapping rule from binary bits to M-ary symbols in writing sequence to keep robustness against higher down-track density. Here, we consider mapping rules as follows, ‘3-bit to 2-symbol’ on 3-ary signaling, ‘5-bit to 3-symbol’ or ‘7-bit to 4-symbol’ on 4-ary signaling. These mapping rules effectively work as relaxing the down-track density. On the ‘3-bit to 2-symbol’ mapping, for example, down-track density on medium can be lower by 2/3 under condition of same density from conventional binary signaling. Likewise, as same, the writing density on medium can be relaxed by 3/5 or 4/7 in other cases, respectively. Moreover, we consider to adopt nonbinary LDPC (NB-LDPC) codes[2] as ECC which is suitable for multiple bits interval operation, namely, we can naturally recognize that a block as 3-bit, 5-bit or 7-bit can correspond to a symbol in a GF(8), GF(32), or GF(128), respectively. We will present the system, which employs the multilevel signaling with sub-tracks constructed by assuming SMR, optimum mapping rule on binary bits to M-ary symbols, and NB-LDPC codes, has effectiveness for realization of higher density recording.

II. PROPOSED R/W SYSTEM MODEL

In our proposed M-ary R/W processing, user data sequence is encoded by NB-LDPC coding., The encoded sequence is fed into the ‘binary to M-ary symbol mapper’. The symbol mapper generates writing sequence is generated on M-ary, then The binary sequences for sub-tracks are re-arranged from the M-ary sequence on the ‘M-ary symbol to sub-track mapper’. We assume that all sub-tracks can be synchronously written as one desired track on medium. At read-back, all sub-tracks are simultaneously read by one reader with fully ITI. Therefore, the basic read-back signal becomes to M-ary signaling in amplitude if it has no inter-symbol interference. Here, a reference PR signal can be assumed by is derived from the M-ary signal. After equalizing read-back signal to the assuming PR target, likelihood information of the written sequence are calculated at Viterbi equalizer which is operated based on M-ary symbol is based. Here, furthermore, let us consider a detection scheme as following. Now, writing bits are assigned to M-ary symbols with block-wise by the mapping rule. Thus, we can regard the block-wise M-ary symbols as one detection interval on the VA as [3]. From the mapping rule, we can understand that the detected interval includes likelihood information of block-wise binary bits. Therefore, the likelihood information corresponding to the block-wise symbols directly also means a likelihood information of the block-wise binary bits. The likelihood information of the block-wise binary bits is suitable for decoding of NB-LDPC codes and...
can be directly fed into the decoder. At last, estimated binary user data are derived by the decoder without de-mapping from M-ary symbols to binary bits.

III. SIMULATION AND RESULT

In our simulation, we assume the R/W system model with the proposed M-ary signaling as shown in Fig. 1. A step response of each sub-tracks is given by waveform based on erf()). We also assume that all sub-tracks have independent jitter-like medium noise in each other independently, but writing synchronization for all sub-tracks is perfect. No ITI from out of range of the desired track is also assumed. PR target has been defined by Generalized PR corresponding to each M-ary signaling. System noise has been added to be 25[dB]=20log_{10}(maximum output level of read-back signal by random sequence/σ) in read-back signal. ECC frame length is assumed 2KB sector. Coded bit error rate (BER) performance of NB-LDPC over GF(8) on coding rate R=0.88 with 2-symbol over 3-ary signaling, NB-LDPC over GF(8) on R=0.88 with 3-symbol over 4-ary signaling and NB-LDPC over GF(128) on R=0.80 with 4-symbol over 4-ary signaling have been evaluated as our proposal. BER of LDPC over GF(4), GF(8) and GF(128) in R=0.88 with conventional binary signaling have also been evaluated for performance comparison. Coding rate of ECC has been selected to get the best performance under each conditions.

The BER performance of each signaling conditions are is shown in Fig. 2. In Fig. 2, a horizontal axis shows a down-track density which is normalized by user binary bit sequence, namely it is not ordinary SNR. As shown in Fig. 2, our proposed R/W systems assuming the multilevel signaling have gain for down-track density compared with binary signaling. The density gain is never get achieved even if ECC has had higher coding gain such as NB-LDPC over GF(128). For fair comparison under ECC condition, that is case of NB-LDPC over GF(128), our proposal shows 8% gain on user density. The density gain by our proposal has also become 13% from NB-LDPC over GF(4) on binary signaling. From our results, we can understand that the system, that issaying several number of sub-tracks are simultaneously detected by one reader, has density gain when the sub-tracks are perfectly controlled to operate the multilevel signaling. Besides, we should remember that the multilevel signaling may be derived by another magnetize method that is no sub-track construction by the SMR in future work.

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MODULATION CODES WITH TWO-DIMENSIONAL RUN-LENGTH LIMITED CONSTRAINTS FOR BIT-PATTERNED MEDIA MAGNETIC RECORDING

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I. INTRODUCTION

In this research, it proposes a new modulation code with a two-dimensional run-length limited (2D RLL) constraint for a signal processing scheme in bit-patterned media magnetic recording (BPMR). This signal processing scheme uses multitrack recording and simultaneous detection techniques for one of future high areal density recording technologies. In this signal processing scheme, the proposed modulation code with the 2D RLL constraint for multitrack recording is useful to be decoded by a single and simple one-dimensional maximum likelihood (1D ML) detector which detects the several recorded symbols in adjacency parallel tracks at each time slot. As a result, simultaneous detection for the proposed modulation code leads to an increase in the effective transfer rate over 1.0.

II. MODULATION CODES WITH TWO-DIMENSIONAL RUN-LENGTH LIMITED CONSTRAINTS

It is known that a binary 1D sequence satisfies the \((d,k)\)-RLL constraint if the run of 0’s have length at most \(k\) and the runs of 0’s between successive 1’s have length at least \(d\) \((0 \leq d < k \leq \infty)\). The conventional 1D \((d,k)\)-R constraint is naturally applied to the 2D constraint. Namely, the 2D constraint must be satisfied for each row and column of a given 2D array if a codeword is recorded by the predetermined 2D array [1]. Then, it is called the 2D binary array satisfies the \((d_1,k_1,d_2,k_2)\)-RLL constraint if it satisfies a \((d_1,k_1)\)-RLL constraint for the horizontal (down-track) direction and a \((d_2,k_2)\)-RLL constraint for the vertical (cross-track) direction independently. In this research, if the 2D binary array is considered as a codeword of a given modulation code, it defines the modulation code with the \((d_1,k_1,d_2,k_2)\)-RLL constraint and code rate \(\eta_c\).

III. TWO-DIMENSIONAL MAGNETIC RECORDING SYSTEM USING BIT-PATTERNED MEDIA

Fig. 1 shows the block diagram of the read/write system for BPMR. This read/write system uses 2D generalized partial response (GPR) equalization for three-track recording and 1D ML detection. In Fig. 1, a raw data sequence \(\{a_k\}\) of the with bit rate \(f_0\) is inputted into the modulation encoder with the 2D \((d_1,k_1,d_2,k_2)\)-RLL constraint and rate \(\eta_c\). The 2D RLL constraint sequence outputted from the modulation encoder is the codeword sequence \(\{b_{i,k}\}\) with the rate \(f_0\eta_c\) and is recorded on the \(i\)-th track. The sequence \(\{b_{i,k}\}\) with additional symbols which terminate a trellis diagram of the targeted 2D GPR system is transformed into the recording sequence \(\{c_{i,k}\}\) at the sequence converter output. The rate of the sequence \(\{c_{i,k}\}\) is nearly equal to \(f_0\eta_c\). Each sequence converter output sequence \(\{c_{i,k}\}\) is NRZ-recorded on islands made of the discrete double layered perpendicular magnetic medium with a soft under layer. These islands are arranged on a rectangular grid in the surface of recording medium.

For the readback BPMR channel, the readback signal of bit-patterned media is represented by the 2D Gaussian pulse response given by [2] and the normalized peak amplitude of this pulse is \(A_P\). In this readback process, the parallel readback signal sequence \(\{r'_{i,k}\}\) is obtained by combining readback signal sequences from the adjacent three tracks. In Fig. 1, \(r'_{i,k} = (r_{i+1,k}, r_{i,k}, r_{i-1,k}) + (n_{i+1,k}, n_{i,k}, n_{i-1,k})\), where the sequence \(\{r_{i,k}\}\) is the readback signal sequence from the \(i\)-th track with the rate \(f_0\eta_c\) and the noise sequence \(\{n_{i,k}\}\) is added at the reading point. The sequence \(\{n_{i,k}\}\) is additive white Gaussian noise (AWGN) with zero mean and variance \(\sigma^2_n\). The rate of the sequence \(\{r'_{i,k}\}\) is \(f_0/3\eta_c\). The reproducing waveform corresponding to the recording sequences readback by the reading head is inputted into the equalizer which consists of a 2D low-pass filter (LPF) and the 2D transversal filter (TVF). The equalization is performed so that the overall characteristic between the input of recording head and the output of the equalizer is equal to the aimed 2D GPR targets. By using this equalizer, the equalizer output sequence \(\{y'_{i,k}\}\) is obtained which sums equalizer output sequences from several adjacent tracks. In Fig. 1, \(y'_{i,k} = y_{i+1,k} + y_{i,k} + y_{i-1,k}\), where the sequence \(\{y_{i,k}\}\) is the equalizer output sequence from the \(i\)-th track with the rate \(f_0/3\eta_c\). In the equalizing process, tap-gain coefficients in the 2D TVF are evaluated by minimizing the expectation of the mean square error

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$E\{e_{i,k}\}$, where the sequence $\{e_{i,k}\}$ is the equalized error sequence between the ideal GPR target output sequence $\{d_{i,k}\}$ and the sequence $\{y_{i,k}\}$. The signal-to-noise ratio (SNR) at the reading point is defined as the ratio of $A_p$ and the noise power of AWGN. In decoding process, the equalizer output sequence $\{y_{i,k}\}$ is decoded by the 1D ML detector and the estimated sequence $\{b_{i,k}\}$ is given as the detector outputs $b_{i,k} = (b_{i-1,k}, b_{i,k}, b_{i+1,k})$. The estimated output data sequence $\{a'_{i}\}$ is obtained after demodulation. The bit error rate (BER) performance of this read/write system is evaluated by computer simulation between the sequences $\{a_{i}\}$ and $\{a'_{i}\}$.

IV. PERFORMANCE EVALUATIONS

Fig. 2 shows the BER performances of the coded GPRML systems. In Fig 2., the solid line shows the BER performance of the proposed 2D modulation coding scheme using the single 1D ML detector for three track recording. In this system, the modulation code satisfies the (0,4,0,4)-RLL constraint and each codeword is recorded on the adjacent three tracks. This proposed modulation code has $\eta = 6/9$ and the effective transfer rate $\eta_e = 2.0$. The dashed, dotted lines show the BER performances of the compared 1D modulation coding schemes with the single 1D ML detector for the desired single-track recording [3], the three-track recording, respectively. These modulation codes satisfy the (0,8) constraint for each track and each codeword sequence is precoded by the precoder which has polynomial $(1+D)^{-1}$ (mod 2) where the symbol $D$ represents an unit shift in the down-track direction. These compared modulation codes have $\eta = 64/65$ and $\eta_e = 0.9846$ for each track. Therefore, the compared coding scheme has $\eta_e = 2.9538$ in the case of simultaneous three-track detection. The recording condition corresponds to the areal density of 4.0 Tbit/in$^2$ given by [2]. In this simulation, the SNR is defined as $\text{SNR} = 20 \log_{10} A_p/\sigma_n$[dB]. As can be seen in Fig. 2, the performance of the BPMR system with 2D modulation coding scheme outperforms that of 1D modulation coding scheme using a single track by about 7.0 dB of SNR gain at a BER of $10^{-5}$. The performance of the BPMR system with 2D modulation coding scheme is slightly superior to that of 1D modulation coding scheme using three tracks at a BER of less than $10^{-5}$.

V. CONCLUSION

In this research, a modulation code with a 2D RLL constraint is proposed for the BPMR system. In this BPMR system, a codeword is recorded on the adjacency three tracks and parallel readback signals from these tracks are read back by a single reading head. Research results imply that the modulation code with the 2D RLL constraint for both of down-track and cross-track directions and simultaneous detection of recorded data on collected parallel tracks are effective to improve the areal density of the BPMR system.

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Fig. 1 Block diagram of the read/write system for BPMR.

Fig.2 BER performances.
A STUDY ON ROTATION OF READING SENSITIVITY IN SMR R/W CHANNEL

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I. INTRODUCTION

The two-dimensional magnetic recording (TDMR) by shingled magnetic recording (SMR) draws attention as a next generation technology to increase recording densities in hard disk drive (HDD) [1]. In the SMR R/W channel, we detected the fact that the distribution of reader sensitivity was not matched with inclined magnetization pattern due to the curvature of the effective write field [2],[3]. In this study, we evaluate the effect of rotated reading distribution in an SMR R/W channel under a specification of 4 Tbit/inch\(^2\) by the computer simulation.

II. READ/WRITE CHANNEL AND BIT RELIABILITY

We simulate a granular medium with non-magnetic grain boundaries using a discrete Voronoi model [4]. In computer simulation, the discretized granular medium based on Stoner-Wohlfarth switching mechanism [3]-[6] is recorded by the realistic head field calculated by the finite element method (FEM) [3]. The average grain size, the standard deviation of grain size and the averaged non-magnetic grain-boundary are set to 5.0 nm, 1.0 nm and 1.0 nm, respectively. The anisotropy magnitude and angle of grain are variable. Magnetostatic and exchange interactions are also considered. A shingled written magnetization pattern for the discretized granular medium is illustrated in Fig. 1. The channel bit length \(l_c = 7.3\) nm and the track pitch \(l_{tp} = 22.1\) nm are assumed, which corresponds to an areal channel density of 4 Tbit/inch\(^2\). In the figure, the pattern is written in shingled writing direction shown in the figure by the writer which consists of a triangle main-pole and a one side shield.

Figure 2 shows the bit reliability for both recording patterns of “010” and “101”. It is obtained by counting correct and incorrect magnetizations by pixel. As can be seen from the figure, the high reliability area is inclined at an angle of about -30 degrees due to the curvature of the effective write field. Figure 3 shows the non-rotated (0 deg) and rotated (-30 deg) readers for cross-track direction a full-shielded magnetoresistive (MR) reader is employed in reading process, and its sensitivity is calculated by FEM [7], where the width between side shields, the shield gap of the reader are set to 30 nm and 22 nm, and the width and thickness of the MR element are set to 17 nm and 2 nm, respectively. The rotated reader of sensitivity fits in well with the inclined magnetization pattern shown in Fig. 2.

A channel bit response from the intended track \(l\) is equalized to the partial response class-I (PR1) target by the equalizer composed of the low-pass filter (LPF) having cut-off frequency \(f_c\) normalized by the channel bit rate \(f_c\) and the transversal filter with \(N_t\) taps. The PR1 channel output is decoded by Viterbi detector.

Figure 4 shows the BER performance of PR1ML system without the system noise. The horizontal axis shows the scanning offset in cross-track direction of reader from the center of intended track \(l\). The symbols square and circle show the cases of the non-rotated and -30 degrees rotated reader, respectively. The result shows that the BER performance is improved by rotating reading sensitivity at -30 degree angle.
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Fig. 1 Shingle-written granular medium.

Fig. 2 Bit reliability for both recording patterns of “010” and “101”.

Fig. 3 Rotation angle of reading sensitivity.

Fig. 4 BER performance of PR1ML system (w/o system noise).
SYNTHESIS, STRUCTURE AND MAGNETIC CHARACTERISTICS OF NANOCRYSTALLINE NiFe₂O₄ – A POTENTIAL MAGNETIC RECORDING MATERIAL
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I. INTRODUCTION
Because of its soft-magnetic feature and superior mechanical performance such as high-temperature resistance, high rigidity and strength, as well as excellent thermostability, NiFe₂O₄ is regarded as a potential magnetic recording material. Among several magnetic parameters, coercivity (Hc) and saturation magnetization (Ms) are two critical ones determining the performance of a magnetic head material. A small Hc would reduce the energy loss and signal noise, while a high Ms could intensify the magnetic field at the head gap. It is well known that the magnetic properties of NiFe₂O₄ are closely related to its microstructure. For the traditional NiFe₂O₄ material, with decreasing of grain size, Ms decreases while Hc increases. Consequently, the nano-sized NiFe₂O₄, although exhibiting enhanced mechanical characteristics, is usually not a good candidate for magnetic head application. Investigating novel NiFe₂O₄ nanomaterials with desirable magnetic properties is therefore of great significance. In this work, we report investigations on hydrothermal synthesis, structure and magnetic characteristics of novel NiFe₂O₄ nanocrystals with regular octahedral morphology.

II. EXPERIMENTAL DETAILS
Powder X-ray diffraction (XRD) patterns of the samples were recorded by RIGAKU-DMAX2500 X-ray diffractometer. The morphologies and microstructures of the as-synthesized samples were observed by FEI Sirion scanning electron microscope (SEM) at 5KV and JEOL-2010 transmission electron microscope (TEM) at 200KV, respectively. Magnetic properties of the as-synthesized sample were measured using a physical property measurement system (PPMS).

III. RESULTS AND DISCUSSION
XRD pattern (Fig.1a) reveals the synthesized product being the fcc NiFe₂O₄ phase (PDF#100325). SEM observation (Fig.1b) shows clearly the morphology and high yield of NiFe₂O₄ octahedrons sized around 60 nm. HR-TEM images (Fig.2) exhibit various structural features of NiFe₂O₄ octahedrons when observed along different directions, demonstrating high geometric symmetry of the nanocrystal. The consistent lattice orientation of the octahedral particles reveals their single crystalline nature. Based on TEM analysis, a structure model of the nano-crystalline octahedron enclosed by {111} planes is established (Fig.1c). It is believed that, in the hydrothermal process, NiFe₂O₄ nano-crystals precipitate in a way with much faster growth rate along <100> over that along <111>, due to the lowest energy of the {111} surfaces.

Magnetic measurement (Fig.3) indicates that the NiFe₂O₄ nano-octahedrons are soft-magnetic material with much lower coercivity (Hc<300e) and higher saturation magnetization (Ms=49.7emu/g) than the NiFe₂O₄ nanocrystals (Hc=500Oe, Ms=37.6emu/g) with similar size but irregular shapes reported earlier [1]. Ms of 49.7emu/g is comparable to, while Hc of <300e is remarkably smaller than that of the micro-sized NiFe₂O₄. Generally, the number of magnetic domains in a magnetic particle diminishes with decreasing particle size, and the particles turn into single domain ones when their size are under a critical value (for NiFe₂O₄, it is about 100nm [2]), resulting in the increase of coercive force due to vanishing of magnetization caused by movement of domain walls. The result that NiFe₂O₄ nano-octahedrons exhibit such a small Hc is therefore quite interesting, which is probably ascribed to their unique faceted octahedral structure. The excellent characteristics imply that the nano-octahedral NiFe₂O₄ might be a potential magnetic recording material.

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Fig. 1 (a) XRD pattern revealing the synthesized product being NiFe$_2$O$_4$;(b) SEM micrograph of NiFe$_2$O$_4$ nanocrystals; (c) structure model of a NiFe$_2$O$_4$ octahedral crystal.

Fig. 2 HR-TEM images and schematic structural illustrations of the NiFe$_2$O$_4$ octahedrons observed along different directions: (a, b) along [110]; (c, d) along [001]; (e, f) along [111]. Insets are the corresponding FFT patterns.

Fig. 3 Magnetization curve of NiFe$_2$O$_4$ nano-octahedrons at room temperature.
MICROMAGNETIC MODEL ANALYSIS OF INTEGRATED SINGLE-POLE-TYPE HEAD WITH SPIN-TORQUE OSCILLATOR

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I. INTRODUCTION

Some requirements for the spin-torque oscillator (STO) in microwave-assisted magnetic recording (MAMR [1]) heads are: 1) the high-frequency field from the STO should be stable and as large as possible, 2) the STO should oscillate with a low injected current, 3) an oscillation frequency that excites the medium to resonance is preferable and 4) high-frequency switching following the head coil current is necessary. In this work a micromagnetic analysis of write heads with integrated STOs, including all interactions, was performed [2], to find head designs which satisfy these requirements.

II. CALCULATION MODEL

Finite element method (FEM) – boundary integral method (BIM) based micromagnetic software [3] was used to investigate the MAMR heads. The equation solved was

\[
(1 + \alpha^2) \frac{dM}{dt} = -\gamma M \times (Heff - \alpha Hst) - \frac{\gamma}{M_s} M \times \{M \times (\alpha Heff + Hst)\}
\]

with reflected and transmitted spin-torques; the so-called g-term was not considered.

\[
H_{st}^{FGL} = -\frac{P_o J h}{e M_s \delta} M_{RL}, \quad H_{st}^{RL} = +\frac{P_o J h}{e M_s \delta} M_{FGL}
\]

In Fig. 1, a perspective view of the write head model and an air-bearing surface (ABS) view are shown. Unless stated otherwise the field generating layer (FGL) material properties were: \(4\pi M_s = 16 \text{ kG}, H_k = 31.4 \text{ Oe}, A = 2.0 \times 10^{-6} \text{ erg/cm} \) and \(\alpha = 0.02\). The reference layer (RL) had: \(4\pi M_s = 8 \text{ kG}, H_k = 20 \text{ kOe}, A = 1.0 \times 10^{-6} \text{ erg/cm} \) and \(\alpha = 0.02\). The write head had: \(4\pi M_s = 24 \text{ kG}, H_k = 31.4 \text{ Oe}, A = 3.0 \times 10^{-6} \text{ erg/cm} \) and \(\alpha = 0.02\). The antiferromagnetic coupling (AFC) constant in the soft magnetic underlayer (SUL) was -0.2 erg/cm². The applied coil current was 0.6 A_Tp; side shields were not considered; and the STO was placed on the main pole center line. A 2 nm non-magnetic interlayer was assumed between the FGL and RL in the STO. The electrons flowed from the FGL into the RL and the FGL oscillation arose from the reflected spin-torque at the RL interface. The whole space including the write head, STO and SUL was treated micromagnetically. The STO was divided into cubes with 2.5 nm sides and the remaining material was divided into tetrahedra. In this work the STO was oriented perpendicular to the medium plane.

III. RESULTS AND DISCUSSION

In Fig. 2 STO oscillations for various write head models with throat height (TH) = 30 nm are shown and it is clear that stable oscillation was not obtained. Fairly stable oscillation was obtained when TH = 60 nm, as shown in Fig. 3: the larger in-plane field in the TH = 30 nm models was presumed to be the cause of the unstable oscillation.

In the TH = 60 nm models the optimum current density was \(J = 1.65 \times 10^8 \text{ A/cm}^2\) for all three main pole widths (MPWs). The oscillation frequencies were 36 GHz for the 20 nm wide pole and 37 GHz for the others. Note that models with larger gap fields were considered and stable oscillation was not obtained, i.e. a large gap field is not always preferable. In Figs. 4 and 5, oscillation characteristics, optimum injected current densities and oscillation frequencies were determined for various FGL

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saturation magnetizations ($4\pi M_s = 16, 20, \text{ and } 24 \text{ kG}$) with integrated and quasi-integrated models. Main pole widths of 30 and 60 nm were considered: MPW = 20 nm was not considered as it had a large in-plane field and the STO oscillation was unstable. It was found that the optimum injected current density increased by 50% from the quasi-integrated model to the integrated model due to the STO – write head interactions. To reduce these interactions and to lower the injected current density, model calculations will be presented for various write head structures and material characteristics. 


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REDUCTION OF BIAS CURRENT DENSITY USING HEUSLER ALLOY CoO$_2$Fe(Ga$_{0.5}$Ge$_{0.5}$) SPIN INJECTION LAYER IN A MAG-FLIP SPIN-TORQUE OSCILLATOR DEVICE FOR MICROWAVE-ASSISTED MAGNETIC RECORDING

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I. INTRODUCTION

In the last couple of years the increase in areal density in hard disc drives (HDD) slowed down due to the technical limit of the perpendicular recording method. To increase the areal density to a higher level exceeding 2 Tbit/in$^2$, the industry must shift to a new recording technology that can overcome the so-called trilemma problem, which arises from the trade-off relationship among signal-to-noise ratio, thermal stability, and writability in the recording media. In order to overcome the writability problem of nanosized ferromagnetic grains with high magnetocrystalline anisotropy energy, energy-assisted recording techniques [1] such as heat assisted magnetic recording (HAMR) and microwave assisted magnetic recording (MAMR) has recently been proposed. MAMR is based on the principle where an ac magnetic field ($H_{ac}$) is applied to the recording media to excite large angle precessions for lowering the switching field of magnetic grains. The main challenges of MAMR for next generation high areal density magnetic recording are development of a mag-flip spin torque oscillator (STO) [2] consisting of in-plane magnetized field generating layer (FGL) and perpendicularly magnetized spin-injection layer (SIL) that is able to generate a large $H_{ac}$ from FGL with a frequency over 20 GHz at small bias current density $J_C < 1.0 \times 10^{12}$ A/m$^2$ [3]. Moreover, solid understanding of underlying mechanism of the large angle out of plane (OPP) mode uniform precession is equally essential.

II. PURPOSE OF THIS STUDY

The main aim of this study is to use highly spin polarized SIL material with perpendicular magnetic anisotropy (PMA) to verify the effect of SIL spin polarization for reduction of $J_C$. We have selected well established Co-based ferromagnetic (FM) Heusler alloy, Co$_2$Fe(Ga$_{0.5}$Ge$_{0.5}$) (CFGG) for SIL/FGL because of the recently observed large MR ratio over 50% in CFGG-based CPP-GMR device, which is attributed to the half-metallicity of CFGG[4]. Therefore, in this study we have investigated the oscillation behavior of a mag-flip STO device with 100 nm diameter circular pillar using highly spin polarized CFGG as SIL, perpendicularly magnetized with FePt, and also compared with a typical ferromagnetic alloy CoFe SIL. We investigated the STO behavior by slightly tilting the external magnetic field $H_{ex}$ at an angle $\theta \sim 7^\circ$ from the film plane normal since $\theta \sim 0^\circ$ does not give any electric rf output for OPP mode oscillation,

II. RESULTS AND DISCUSSION

Figure 1 shows the schematic diagram of a mag-flip STO device structure with 100 nm circular pillar consisting of perpendicularly magnetized SIL CFGG (or CoFe) (3 nm) with FePt (10 nm), and CFGG (7 nm) FGL separated by Ag (5 nm) spacer. Here we have used CFGG as FGL as well to achieve higher MR ratio for the detection of RF signals since the RF output power is proportional to the square of MR ratio. $\Delta R-H_{ex}$ curves for CFGG and CoFe SILs, for various negative dc bias currents $I_{dc}$ with $H_{ex}$ applied perpendicular to film plane ($\theta \sim 0^\circ$) are shown in Fig. 1 (b) and (c), respectively. Maximum MR ratios observed are $\sim 0.9\%$ for CFGG SIL and $\sim 0.5\%$ for CoFe SIL including the contact resistance of a 2-terminal measurement. A sudden jump to an intermediate resistance state at high $H_{ex}$

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region in the $\Delta R-H_{ex}$ curves for CFGG SIL when $|I_{dc}| \geq 5.5$ mA indicates excitation of magnetization dynamics by the reflected spin current from the SIL interface. On the other hand, for CoFe SIL the intermediate resistance state appears at comparably higher $|I_{dc}| \geq 13$ mA than CFGG. Such differences in MR ratios and $I_{dc}$ for magnetization precession can be attributed to the higher spin polarization of CFGG than CoFe. Figures 1(d) and (e) show $\Delta R-H_{ex}$ curve for $|I_{dc}| = 9$ mA and the corresponding rf signals for CFGG SIL, respectively, with $H_{ex}$ slightly tilted $\sim 7^\circ$ from the film normal. A maximum precession frequency of $f \sim 12$ GHz has been observed for $H_{ex} \sim 10$ kOe, which systematically decreases with the reduction of $H_{ex}$ following Kittle’s equation. Moreover, the blue shift of $f$ with $I_{dc}$ in Fig. 1(f) also confirms detection of the OPP mode excitation for the bias current density $J_C \sim 0.95$ to $1.15 \times 10^{12}$ A/m$^2$, which is close to the desired $J_C$ for application. Understanding of the large angle OPP mode oscillation with higher $f$ is still under investigation. Finally, our results suggest that half-metallic Heusler compounds could be effective as the SIL to reduce $J_C$ for development of mag-flip STO devices for practical MAMR application.

Acknowledgements

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References:
STUDY OF DIRECTION OF MICROWAVE CHIRALITY EFFECT ON RECORDING PROPERTY IN MAMR

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I. INTRODUCTION

Microwave-assisted magnetic recording (MAMR) is one of the candidates to realize future high density HDD. Many numerical studies were reported such as magnetic recording ability improvement[1]. Important experimental studies such as coercive field reduction in granular film[2] were also reported. Considering a circular polarized microwave field, the same rotation as medium magnetization precession could be easy to reduce medium switching field. Microwave field generated from spin torque oscillator (STO) is ellipsoidal polarized field, which includes both CW and CCW rotation[3]. In this study, the direction of microwave chirality effect on magnetic recording property is discussed by dynamic magnetic recording simulation.

II. SIMULATION MODEL

Dynamic medium magnetization behaviors in the recording process were simulated by solving the Landau-Lifshitz-Gilbert equation. The medium has exchange coupled control (ECC) structure and averaged-Hk=16.0kOe, averaged-Ms=700emu/cc and averaged-α=0.03. Fig. 1 shows the on-track effective write field distribution and the circular polarized microwave field components generated from STO in this model. This field distribution is calculated along the track center direction at a depth of medium center position. As mag-flip type STO is used, the major microwave chirality direction below the main pole is always assists magnetization reversal and its direction of chirality is represented as positive or ‘+1’ in Fig. 1. The other direction is represented as negative or ‘-1’. The amplitude of the circular polarized component is set to 580 Oe.

III. RESULT AND DISCUSSION

To discuss each direction of microwave chirality effect separately, the read/write performances at 1000kfcf and 166kfcf were simulated applying three types of microwave field, (A)all components, (B)only positive chirality component and (C)only negative chirality component, individually. Fig. 2 shows the applied microwave frequency dependence of SNR at 1000kfcf. The dashed line shows the result with no microwave field as reference. SNR is significantly improved around 20GHz in case (A). In case (B), there is no remarkable difference of SNR gain throughout the microwave frequency from that of case (A). In contrast, SNR gain is not observed in case (C). These results show that SNR gain at 1000kfcf is dominantly determined by a positive chirality. The influence of a negative chirality is negligibly small on a write resolution property around the optimum frequency.

Fig. 3 shows the applied microwave frequency dependence of track averaged amplitude (TAA) of readout signal at 166kfcf when the same three types of microwave field are assumed. TAA is degraded over 20GHz in case (A). Furthermore, this TAA degradation is also observed in case (C). Fig. 4 shows the recording patterns at 166kfcf. The oscillation frequency is set to (a) 20GHz, (b) 24GHz and (c) 32GHz with respect to case (A), (B) and (C). As shown in Fig. 4(c), magnetization is partially erased on the track center excluding the trailing-side near the transition position. On the other hand, such a partial demagnetization is not observed as shown in Figs. 4(a) and (b). Considering a recording process in MAMR, there exist two microwave assist situations. At First, medium grains are reversed with assist effect by a positive chirality of microwave on leading side, which is near main pole, of field generation layer (FGL) of STO. Second, a part of these grains are reversed again on trailing side, which is near write shield, of FGL because a negative chirality matches the precession direction of these grains. This partial demagnetization is return field partial erasure (RFPE) assist effect as shown in Fig. 4(c). Furthermore, as shown in Fig. 3, frequency range occurring RFPE assist is higher than that with positive assist because internal medium fields including anisotropy, demagnetization and write head fields are different on two assist situations. Demagnetization
field on positive assist situation is smaller than that on RFPE assist situation. On the other hand, write head field on positive assist situation is much larger than that on RFPE assist situation, and the difference of frequency range is dominantly determined by this write head field difference. So, we can design optimum microwave frequency to understand the direction of microwave chirality effect in MAMR.

REFERENCES


Fig.1 Effective write head field and circular polarized microwave field distributions. Write head field is calculated using FEM and defined as effective field based on Stoner-Wolfarth model.

Fig.2 SNR at 1000kfcI versus microwave frequency of STO applying three types of microwave field (A) all components, (B) only positive chirality and (O) only negative chirality component.

Fig.3 TAA at 166kfcI versus microwave frequency.

Fig.4 Recorded magnetization patterns at 166kfcI applied three different components of microwave at (a) All components 20GHz (b) Positive component at 24 GHz (c)Negative component at 32 GHz
ULTIMATE SOLUTION FOR ULTRA-THIN FILM SYSTEMS

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I. INTRODUCTION

Reliable measurements of the Elastic Modulus of the thin films is particularly challenging due to the so called substrate effect. The prevalent rule of limiting indentation depth to the 10% of the coating thickness to avoid the substrate influence in the mechanical properties is challenging to assure especially when the film thickness goes below 200nm. The tip radius can be one of the many factors limiting the application of Oliver-Pharr model [1] on the elastic modulus calculation so as the surface roughness.

With the newly developed ultra-low noise xProbe transducer combined with the intrinsic thin film property solution iTF [2] (Figure 2), quantitative mechanical properties from nanoindentation tests on 2nm thin film systems are possible.

II. PROCEDURE

The experiment was conducted using the Hysitron Triboindenter equipped with xProbe and Cube Corner probe in quasi static mode. xProbe is a MEMS based transducer with a noise floor similar to that of contact mode Atomic Force Microscope (AFM). The linear actuation allows for the direct and fully quantitative measurements without the need of the modeling which leads to more precise mechanical properties estimation and faster analysis throughput. Nanoindentation (Figure 3) was performed on the ultra-thin film sample using load control feedback mode.

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III. RESULTS

Unloading segments of each indentation are analyzed using the Oliver-Pharr model [1], where the stiffness is calculated from the unload segment. Based on that, as well as probe calibration, the elastic modulus of nanoindentation can be directly calculated with non-linear substrate effect to the thin film based on the equation

\[ E_r = \frac{S\sqrt{d}}{2\sqrt{A}} \]  

(1)

Reduced elastic modulus and hardness are plotted in a function of contact depth (Figure 4). The initial increase in the mechanical properties can be related to the surface roughness and the interfacial surface layer on the surface.

Applying iTF analysis to the stiffness, depth and load profile the intrinsic elastic modulus of the film will be calculated almost instantaneously. iTF analysis utilizes the known area function, the contact geometry and the load and stiffness as an input for the three equations between the elastic deflection and the contact radius.

Unlike finite element analysis the model does not need any presumed modulus for the thin film. By numerically solving these equations, the film modulus (Figure 3) and plasticity parameter are calculated.

![Figure 4. Reduced elastic modulus and hardness are plotted in terms of nanoindentation penetration depth. The interface between the film and substrate can be seen in the graph shown as dash dot line. The Estimated film modulus analyzed by iTF analysis is 44 GPa.](image)

IV. CONCLUSIONS

By combining the ultra-low noise xProbe transducer and analytical intrinsic thin film solution (iTF), we quantitatively estimate elastic properties of the ultra-thin film systems of 2 nm or below.

REFERENCES


CORRELATING IN AND EX SITU NANOMECHANICAL MEASUREMENTS FOR HARD DISC DRIVES

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I. Introduction

Nanomechanical measurements, particularly nanoindentation and nanoscratch, have transitioned from a purely academic research instrument into a tool for examination of complex industrial processes. These, typically ex situ measurements can generate an enormous amount of statistical information, which can then be examined in terms of the degree of failure. However, the actual deformation mechanisms can sometimes be difficult to determine for complex engineering materials such as the multilayers in a hard disc film stack. For these complex cases both statistical information and data on the failure mechanisms are required.

II. Experimental

Initially, a MEMS based transducer with a noise floor similar to that of contact mode AFM is used for large data set accumulation for statistical analysis. This system is actuated linearly, so avoids the rocking, bending, or sliding modes typical of AFM indentation. Indentation depths range from 0.5 to 10 nm, figure 1, with the analysis utilizing both the approach and retract curves to describe the crack growth/separation between the diamond indenter and the carbon film. Additionally, the elastic-plastic transition is thoroughly explored in an effort to understand the effects of a protective coating on a substrate. The data is presented in the format of the measured material properties of interest; yield stress, hardness, and elastic modulus.

Nearly a decade ago Hysitron introduced the first in situ TEM nanomechanical test instrument, which is used to test the same film stack as that tested ex situ, but co-deposited on a silicon wedge, figure 2. Here, the information of a few tests can be used in a correlative manner that describes the failure of the individual layers under both 1 and 2-D stress fields that is backed by statistical evidence.

Figure 1: Five indents up to 1.4nm in displacement on a DLC overcoat/Glass wafer substrate.

Figure 2: A post in situ TEM indentation image, showing the complexity of the film stack interaction.
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Cu-BASED NON-LOCAL SPIN VALVES FOR ROOM TEMPERATURE FIELD SENSOR APPLICATIONS

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The non-local spin valve (NLSV), in which ferromagnetic injector and detector contacts are separated laterally by a non-magnetic nanowire channel (Fig. 1), is a model system for understanding spin transport, enabling separation of charge and spin currents. From the applied perspective, such devices have low RA product (in the absence of tunnel barriers), while the elimination of charge current in the detector provides a potential means to realize a scaled read sensor with a small footprint at the air-bearing surface, and low spin torque noise [1, 2].

Many recent studies on metallic NLSVs have focused on the anomalous temperature dependence of the spin accumulation signal, \( \Delta R_{NL} \), which unexpectedly decreases at low temperatures. We (O’Brien et al.) recently advanced an explanation for this effect, based on interdiffusion-induced local magnetic impurity moments in the non-magnetic channel, suppressing injected spin polarization via a manifestation of the Kondo effect [3].

![Co/Cu NLSV](image)

**Fig. 1** Co/Cu NLSV. Current is driven through the injecting Co pad on the left resulting in a diffusive spin current in the channel and a spin accumulation under the detector on the right.

Here we extend this work to devices based on Co/Cu, a technologically relevant combination for which the Kondo temperature exceeds 300 K. Non-magnetic channel thicknesses, \( t_N \), from 50 to 200 nm have been explored, along with annealing temperatures up to 500 °C. The decrease in spin diffusion length in the Cu from 300 nm for \( t_N = 200 \) nm to 90 nm for \( t_N = 50 \) nm, and its change with annealing will be discussed in detail. Most importantly we find that, despite the limited miscibility of Co in Cu, a significant decrease in \( \Delta R_{NL} \) and in the injected current polarization occurs with cooling as the Cu channel thickness is reduced. In the thinnest channels, we find that the maximum in \( \Delta R_{NL} \) and the onset of significant spin current depolarization occurs even at room temperature. This result implies that local moment formation and the associated Kondo physics can impact the performance of spin transport devices even at ambient temperature in such common and technologically important materials systems.

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STUDY OF SPIN TORQUE OSCILLATOR AS A POTENTIAL MAGNETIC READ SENSOR

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Spin torque oscillator (STO) has been extensively studied due to its various potential applications, such as tunable microwave oscillators [1]-[4]. It utilizes the torque applied by a spin polarized current to generate persistent magnetization precession. STO has been demonstrated experimentally in giant magnetoresistive (GMR) spin valve [1] and MgO-based magnetic tunnel junction (MTJ) [2]. The magnetic layer precession leads to a microwave oscillatory component of the resistance and thus an oscillatory component of output power. Compared to traditional oscillators, the nanoscale spin torque oscillators have their unique advantages. They are small, frequency tunable, have wide working temperature, and are also compatible with VLSI CMOS [2-3]. For applications, the microwave signal is desired to have high power, narrow linewidth, and tunable frequency. A narrow linewidth is good for high quality factor (Q-factor) Q=f₀/Δf. Here, f₀ is the peak frequency of the power spectrum, and Δf is the linewidth. Theoretically, the linewidth is caused by nonuniform magnetization oscillation due to the thermal effect. Experimentally, it has been demonstrated that the spectral linewidth depends on the temperature, current, and inplane magnetic field angle [5]. In this work, we have investigated the effect of current, magnetic field, and the energy barrier, which is created by the device shape anisotropy, on the linewidth of the spin torque oscillation. Figure 1(a) shows the device structure and the measurement setup. The layer structure is seed layer/PtMn(15)/CoFe(2.5)/Ru(0.85)/CoFeB(2.4)/MgO(0.8-0.82)/CoFeB(2)/capping layer (units in nm.) The thin films were patterned into nanopillars with different aspect ratios to tune the energy barriers of MTJ. The magnetization precession is induced by spin transfer torque in the top CoFeB layer, and the bottom CoFeB layer acts as the fixed layer using a synthetic antiferromagnetic (SAF) structure. If the device is biased by a direct current, its resistance changes as a function of time through the TMR effect, and the signal is measured by a high frequency spectrum analyzer or a real time oscilloscope. Figure 1(b) shows the magnetoresistance as a function of current. The current switching happens at -0.2 to -0.25 mA in both current directions. However, the switching is unstable from -0.2 to -0.27 mA, and the free layer magnetization bounces back and forth between the parallel and the antiparallel state. This indicates that there is thermal effect at the onset of switching, and the energy barrier plays an important role in the switching and precession of the magnetization. Figure 1(c) is the power spectra at 180 Oe and different currents. As the current changes from 0.3 to 0.5 mA, the linewidth decreases and then increases. The decrease of linewidth is associated with decrease of thermally excited ferromagnetic resonance noise, while the peak broadening can be explained by the strong impact of the nonlinearity. Figure 1(d) is the power spectra at 0.4 mA and different external fields. The magnetic field varies from 180 to 364 Oe. As the field increases, the linewidth also increases from 269 to 381 MHz. This is because thermal fluctuations strongly influence small amplitude dynamics. Narrow linewidth and high Q factor can be achieved by tailoring the anisotropy and the bias current of the device for HDD reader application.
Fig. 1 (a) Schematic of the stack structure and measurement circuit. (b) STT switching of the MTJ nanopillar. (c) The STO linewidth at 180 Oe and different currents. (d) The STO linewidth for a current of 0.4 mA at different fields.

REFERENCES


FABRICATION OF METALLIC LATERAL SPIN VALVES FOR MAGNETIC READER APPLICATIONS USING AN ETCH BACK PROCESS

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I. INTRODUCTION

As magnetic recording densities are scaled, it is highly desirable to have small read heads. Recently, it has been proposed to use nonlocal lateral spin valves (NLSV) for read heads[1]. NLSVs provide a promising candidate to overcome some of the current challenges with magnetic read heads. Tunneling magnetoresistance (TMR) devices can be used to provide larger signal levels compared to giant magnetoresistnace (GMR) devices; however, TMR devices require a tunneling barrier resulting in a higher RA which is undesirable. Additionally, TMR devices require a pinning layer within the shielded region of the read head near the media which makes it difficult to reduce the overall thickness of the TMR device material stack and therefore limits the scalability of the read head device.

All metallic NLSVs do not require a tunnel barrier for operation and can be used to overcome the issue of high RA in TMR based devices. Additionally, NLSV devices utilize only two layers (magnetic and non-magnetic channel material) in this region which significantly reduces the material stack height and therefore size of the read head element and improves scalability. The NLSV design allows for the pinned ferromagnetic layer to be away from the recording head media and will have little impact on the read head scalability.

II. EXPERIMENTAL DETAILS

For our device fabrication film stacks are deposited in a Shamrock sputtering system with a structure of substrate / MgO (3 nm) / Cu (100 nm) / Co (20 nm) / Pd (3 nm). All of the patterning is done using e-beam lithography. After deposition, the channel is patterned using negative resist and ion milling to define the channel region. After resist removal, negative resist and ion milling were used again to pattern and define the pillars. Then, SiO2 is deposited using e-beam evaporation to isolate the pillars to prevent oxidation and to prevent shorting between top electrodes and the channel. The e-beam resist was then removed and SiO2 lifted off from the tops of the pillars to expose the tops of the pillars for electrical contact. An additional step of e-beam lithography was performed to pattern vias in order to make electrical contact to the channel region and the vias were etched using reactive ion etching. A final step of e-beam lithography was performed to pattern the top electrodes and e-beam evaporation is used to deposit the electrodes. A schematic of the fabrication process is shown in Figure 1.

III. RESULTS AND DISCUSSION

For our experiment, we fabricated ferromagnetic pillars of sizes 75 nm x 100 nm to 450 nm x 500 nm. SEM images of the fabricated devices are shown in Figure 2a,b. Using a nonlocal measurement set-up and sweeping an external in-plane field, we could detect the nonlocal voltage signal and observe switching events of the nanopillar structures. Results from a 75 nm x 100 nm and 100 nm x 125 nm ferromagnetic injector and detector combination are shown in Figure 2c. A 5 mA was applied at the injector site and the nonlocal voltage was measured at the detector using a nanovolt meter.

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We demonstrated a new fabrication approach for nonlocal lateral spin valve devices with applications for magnetic recording read heads and all-spin logic. We fabricated devices with pillar sizes ranging from 75 nm x 100 nm to 450 nm x 500 nm with various spacings. Room temperature results of the NLSV show correct operation. The fabrication process described in this paper allows for the entire material stack to be deposited under vacuum followed by a series of patterning, etching, and deposition techniques to form magnetic nanopillar structures on a defined channel. The process will allow for control of device dimensions and help improve scalability. This method also provides a fabrication process that is compatible with current industry methods and should allow for easier integration with today’s read head fabrication processes.

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Figure 2. a) SEM image of device electrical contacts, b) individual pillars, electrodes, and channel, and c) nonlocal spin valve measurement.
STT-RAM SWITCHES BY MAGNETOSTATIC INSTABILITY

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I. SUMMARY

1. STT-RAM (spin transfer torque random access memory) switching statistics have usually been fit with a single-macrospin model (i.e., assuming nearly-uniform switching). Fits can be quite good, but activation energy typically is << the expected value KV (anisotropy energy times volume).

2. However, no real STT-RAM (large enough to be stable) switches nearly-uniformly. It is often assumed[1] that local (edge) nucleation occurs.

3. Here, we argue that no real STT-RAM switches by local nucleation either: switching is by a global instability (normal mode). To calculate STT-RAM error rates, we must understand this mechanism.

Distinguishing between local nucleation and global instability is not trivial – the trajectory in the one-dimensional space (precession angle $\theta$) usually used for visualization is the same. We will describe a 2D visualization space in which they can be easily distinguished, and show that only the instability mechanism occurs.

II. VISUALIZING UNIFORM (SINGLE-MACROSPIN) SWITCHING IN 1D

In uniform switching, only one variable is important, which can be taken to be the precession angle $\theta$ (from the z axis). The energy in terms of this angle is shown in Fig. 1.

For small angles, the horizontal magnetic moment $m_h^2 = m_x^2 + m_y^2$ is an equivalent choice of variable for the uniform system and generalizes more naturally to the non-uniform case. It cannot be used beyond $\theta = \pi/2$ (the barrier in the case of zero current and field), but we don’t need to follow the system beyond this since (especially with spin torque) the system is almost certain to switch if it reaches this point. We will denote $m_h^2$ by $U$ to indicate that it is a measure of the uniform precession amplitude. The energy as a function of $U$ is shown in Fig. 2 (just a straight line; at zero field and current).

III. VISUALIZING NON-UNIFORM SWITCHING IN 2D

The moment $m_x$ can be written as an integral over the element: $m_x = \int M_x dV$. The next moment will be denoted $\Sigma = x(m_x^2 + m_y^2)$, and indicates non-uniformity – it vanishes for a uniform system. A measure of the overall (long-wavelength) non-uniformity is $\Sigma = x(m_x^2 + m_y^2) + ym_y^2$. It turns out that to avoid singularities in probability distributions it is convenient to use its square $NU = \Sigma^2$ as our measure of non-uniformity. Note that this is still zero for the “flowered” ground state of the disk (Fig 3 – only the next higher moment is nonzero for this state). Thus the nearly-uniform switching of a small element (in which exchange is strong enough that there are no instabilities) is represented in the U-NU plane (Fig. 3) by a straight trajectory along the U axis (i.e., NU = 0). A state with edge...
nucleation beginning, for example, would be represented by a point in the interior of the U-NU plane, with both U and NU nonzero.

Figure 4 shows the result of a stochastic simulation of a realistic STT-RAM model (radius 16 nm, thickness 4 nm, anisotropy field 1000 kA/m, saturation magnetization 500 kA/m, exchange constant $A = 10^{-11}$ J/m) with high damping $\alpha = 0.1$, with spin torque current $J = 0.8 J_c$, where $J_c$ is the critical current for switching[2]. Deterministic (without noise) uniform trajectories lie along the horizontal axis; for $J=0$, all deterministic trajectories on this axis would move left toward the origin; for $J = J_c$, all would move to the right. At $J = 0.8 J_c$, there is a critical precession angle (value of U) such that trajectories to its left move left, but trajectories to its right move right (i.e., switch), as indicated by the blue “Deterministic flux” arrows in Fig. 5 (this is on a larger scale than Fig. 4). Fig. 5 shows some deterministic trajectories, whose left-right motion is as expected. Their initial conditions were chosen to encourage edge nucleation, but the vertical motion is always downward (toward decreasing non-uniformity). This can be understood in terms of damping of short-wavelength (high frequency $\omega$) spin waves, since damping is proportional to $\alpha \omega$. Thus the edge nucleation disappears, and the system evolves nearly uniformly, switching only when it gets near an instability[2] near $U = 0.8$, at which NU grows exponentially.

This magnetostatic instability is somewhat analogous to the stripe domain instability in thin films. We will show how to calculate a Lyapunov exponent to determine the position of this instability[2]. The instability reduces the effective energy barrier, bringing it closer to its experimental value; we will show how to estimate this reduction analytically. We will also show images of the instability.

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FIELD-LIKE SPIN-ORBIT TORQUE OPPOSING THE OERSTED TORQUE IN Fe/Pt BILAYERS

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ABSTRACT

Spin-orbit torques (SOTs) have been demonstrated to be an effective approach for electrical manipulation of the magnetization and are hold great promise for application in spintronic devices [1]. Despite the intensive experimental and theoretical studies on SOTs and exciting progresses, SOT phenomena are still not well understood and call for clarification of detailed mechanisms.

In this study, spin-torque torques in Fe/Pt bilayers have been characterized with spin-orbit torque ferromagnetic resonance (SOT-FMR) [2]. Alternating microwave current is injected into Fe/Pt bilayers to generate oscillating spin-orbit torques that induces ferromagnetic resonance in the Fe layer. The resonance behavior is further manifested by a dc voltage invoked through anisotropic magnetoresistance. The Oersted field-dc voltage spectra measured under excitation frequencies of 10 GHz are shown in Fig. 1(a)-(c). The FMR spectra could be fitted to the Lorentzian function to distinguish between the symmetric component induced by the anti-damping torque (ADT) and the asymmetric component induced by the field-like torque (FLT) and the Oersted field induced torque (OT), as shown by Fig. 1(a)-(c).

The SOT-FMR was originally proposed as a self-calibrated approach to characterize the spin Hall angle, assuming that the field-like spin-orbit torque is negligible. However, a significant field-like spin-orbit torque is observed in our thickness dependent study of SOT-FMR spectra for Fe/Pt bilayers. Fig. 1(a)-(c) show that with a fixed Pt thickness of 5 nm, as the Fe thickness is reduced from 10 nm to 2.5 nm the antisymmetric component of Lorentzian function reverses in sign while the sign of symmetric component remains the same. Since the antisymmetric component corresponds to the combined FLT and OT, the sign reversal implies that the FLT is not zero and has an opposite sign as that of OT. Aside from its own scientific and technological significance, the presence of FLT also renders the conventional estimation of SHA by SOT-FMR invalid or doubtable. Given the different dependence of the ADT, FLT and OT on the thickness of films, by plotting the ratio of different torques against film thickness, FLT and OT could be differentiated from each other, as shown in Fig. 1(d), and a more reliable estimation of SHA could achieved.

REFERENCES


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Preferred category: #5
Fig. 1. The SOT-FMR spectra for the bilayers (a) Pt(5)/Fe(2.5), (b) Pt(5)/Fe(5) and (c) Pt(5)/Fe(10) measured at excitation frequency of 10 GHz is shown. The thickness in brackets are in nanometers. The experiment data (black) is overlaid with the fitted symmetric Lorentzian (red) and antisymmetric Lorentzian (blue) curve, as well as their summation (green). A clear reversal in sign of the antisymmetric component is observed as the thickness of Fe is varied, suggesting that a FLT that opposes the OT becomes dominate at small Fe layer thickness. (d) The ratio $A(\tau_{\alpha} + \tau_{FL})/\tau_{AD}$ plotted against the Fe layer thickness, where $A$ is a constant.
THINNER GLASS SUBSTRATE DESIGNED FOR 95MM HDD AND HAMR APPLICATION

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I. Abstract

In response to the increasing demand for storage capacity, HDD development has concentrated on Areal Density improvement and disk platter count increases. As a Glass substrate maker, HOYA continuously supports these development directions. We have developed thinner (Ultra-Thin) 95mm substrates to support increasing HDD platter count HDD’s and high heat resistance glass to satisfy coming HAMR technology. New glass form factors of 95mm OD- 0.635mm (25mil) thickness and even thinner 95mm OD- 0.50mm (20mil) thickness are achieved. Our High heat resistance glass N105 and N105X has a Glass Transition temperature (Tg) of 676 deg.-C with CTE 79 x10E-7/k.

II. 95mm Thinner substrate

When considering adding platters in a one inch thick HDD, the concerns are decreased stiffness of the thinner substrate and the resulting fluttering and shock issues. Generally speaking, Glass materials are stiffer than AlMg substrates and have higher heat resistance.

Table 1 shows properties of Glass (current PMR substrate, high heat resistance N105/N105X) and AlMg. Young’s modulus (Stiffness) of Glass is higher than AlMg material by 118% and specific modulus is 120% higher. CTE (co-efficient of thermal expansion) of high heat resistance glass is close to N5H (current PMR substrate).

Fig 1 show indentation images of Glass (N5H) and AlMg surfaces. On both Vickers and Knoop indenter, Glass shows a smaller size depression. The measured Glass hardness value larger of Hv 620 is much higher than AlMg’s Hv 128. A harder surface contributes to preventing scratches or surface damage by external factors such as head slapping of the media surface by shock phenomenon during HDD operation.

Table 1 Property comparison (Glass vs AlMg).

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Glass</th>
<th>AlMg</th>
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<tr>
<td>Glass name</td>
<td>N5H</td>
<td>N105</td>
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<tr>
<td>Chemical Strengthening</td>
<td>Yes</td>
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<td>Glass Transition Temperature (Tg) °C</td>
<td>503</td>
<td>675</td>
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<td>CTE (150/700 deg.C)</td>
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<td>CTE (100/300 deg.C)</td>
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<td>Young’s Modulus (GPa)</td>
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<td>Density (g/cm³)</td>
<td>2.49</td>
<td>2.67</td>
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<tr>
<td>Specific Modulus</td>
<td>33.3</td>
<td>31.8</td>
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</table>

Fig 1, Hardness comparison (Vickers and Knoop indenter)
1) Anti-Shock resistance

Testing was done using a shock tester (Lansmont Model 23D) on two thicknesses of glass substrate 95-25-0.635t and 95-25-0.5t. (Young’s modulus 83GPa) Substrate was set horizontally on attachment.

Table 2. G-Shock test (Duration time: 2msec)

<table>
<thead>
<tr>
<th>Shock (G)</th>
<th>N105XT2 (w/o CS) 0.5mm</th>
<th>N105XT2 (w/o CS) 0.635mm</th>
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<tr>
<td>300</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>500</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>600</td>
<td>90%</td>
<td>100%</td>
</tr>
<tr>
<td>750</td>
<td>70%</td>
<td>80%</td>
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</table>

At shock levels from 300G to 750G, even with very thin 0.5mm thickness no damage is seen up to 500G and just 10% damage at 600G. In the case of 0.635 mm t, there is no damage up to 600G and just 20% damage at 750G. These shock levels are entirely sufficient for 3.5-inch HDD shock requirements which are typically 300G specification for non-operation shock. In this testing, duration time for shock was 2mili second and no substrates are chemically strengthened.

2) Flutter performance

Testing was done by LDV tester (Polytech Fiber OFV512) using 0.8t thickness substrate 95-25-0.8 of Glass and AlMg and 0.635t of Glass substrate. NRRO (Non Repeatable Run Out) peak was derived after FFT analysis.

95-25-0.8t Glass and AlMg substrate: AlMg substrate chart show higher peaks and lower frequency at each vibration mode. And when looking at 1k to 4k Hz, the difference is significant.

95-25-0.635t Glass substrate show also lower peaks than AlMg 0.8t at 1k to 4k Hz that is the usual disk fluttering region.

From these data, thin Glass substrates have the potential to reduce TMR (Track Miss Registration) allowing easy control of head suspension positioning.

III. High Heat Resistance and Summary

N105 and N105X show higher transition temperature (Tg) of 675deg.–C described in table 1. This temperature is enough for ordering L10 structure of Fe-Pt binary alloys. N105 and N105X glass is also designed to have a CTE of 79 x10E-7/k which is close to the current PMR glass substrate N5H CTE of 91 x10E-7/k.

We have developed 95mm OD thin glass substrates combined with high heat resistance material. With this thin 95mm Glass substrate higher storage capacity is possible in one HDD with a higher platter of 8 or more disks and HAMR media to achieve higher Arial Density.

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