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Temperature Induced Near-field Transducer (NFT) Failure in Heat-assisted Magnetic Recording (HAMR)

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We have studied the reliability of a near field transducer (NFT) embedded in a magnetic recording slider used for heat-assisted magnetic recording (HAMR) in hard disk drives with a linear velocity of 20 m/s. The NFT head structure and the disk are separated by an air film of 2 nm thickness. In this work, the magnetic write width and amplitude of the written magnetic signal on the disk are used as a "health-monitor" for the reliability of the NFT under long-term thermal exposure. The results show that the reliability of the NFT head structure decreases sharply with increasing temperature of the near field transducer but depends only slightly on the media temperature.

***Index Terms*—Heat-assisted magnetic recording (HAMR), Laser optical power, Near-field Transducer (NFT) Life-time, Signal-to-Noise ratio**

I. Introduction

HARD disk drives (HDDs) are the most widely used storage devices in the world for data storage. Over the last few decades the HDD industry has tremendously increased the areal density by moving from longitudinal magnetic recording (LMR) to perpendicular magnetic recording (PMR) technology. As a result, areal densities of up to 1Tb/in^2 have been demonstrated [1, 2]. Due to basic physics limitation, it is difficult with conventional magnetic recording technology to achieve substantially larger areal densities. To realize higher areal densities, two requirements must be met, i.e., the volume for each individual bit must decrease while the signal-to-noise ratio must remain constant. Expressed differently, the number of magnetic grains within each bit must remain the same. Thus, greater areal densities require smaller magnetic grains. As the volume of magnetic grains decreases, a limit is reached where the magnetic orientation of the individual grains becomes thermally unstable. This phenomenon is generally termed the "superparamagnetic" limit. To overcome the superparamagnetic limit, magnetic materials with high magnetic anisotropy, such as L10-FePt, must be used [3, 4]. However, these materials require a much larger magnetic field to switch the magnetic direction of the grains in the media, i.e., to write data, the field available from conventional recording heads is too small. Clearly, a further increase in areal density requires a new recording technology.

Heat-assisted magnetic recording (HAMR) overcomes this writing challenge by raising the temperature of the recording media momentarily to near its Curie temperature in order to reduce its magnetic coercivity [5, 6]. The recorded bit is then quenched to the high anisotropy state by cooling to ambient temperature. HAMR technology has the potential to enable areal densities in the range of several terabits per square inch [7, 8]. HAMR uses a near field transducer (NFT) coupled with a laser diode to confine optical energy to a small region on the rotating disk media that is an order of magnitude smaller than the optical wavelength of the laser light used [9]. Confining light using an NFT structure has found several other applications such as optical lithography, surface enhanced Raman spectroscopy and bio-medical devices [10-13]. However, the challenges for the NFT in HAMR are more difficult than in other applications. In particular, in addition to the smaller spot size requirement, HAMR hard disk drives (HDD) have the following three extra challenges: (1) a higher energy density is required leading to increased temperature on head and media; (2) elevated temperatures are encountered on the media (500 - 600˚C) and head (200 - 300˚C); and (3) nano-gap spacing (1-2 nm) between the NFT and the rotating disk (Figure 1(a)) [14] are required. Understanding the dominant mechanism that governs the reliability of the NFT is critical for HAMR hard disk drives.

In this paper, we use HAMR disk media and a fully integrated HAMR head to investigate the effect of the NFT temperature on the reliability of the head disk interface. The reliability of the NFT is quantified by measuring the time at which the HAMR recording degrades, generally described as the "NFT lifetime". We show that the temperature at the head-disk interface is critical to NFT lifetime. As the optical energy in the HAMR system is increased, the resulting increase in the temperature of the head and the media reduces the NFT lifetime significantly. Comparing the NFT lifetime at the same disk temperature for different media, we observe that the head temperature is the dominant parameter causing failure of the NFT.

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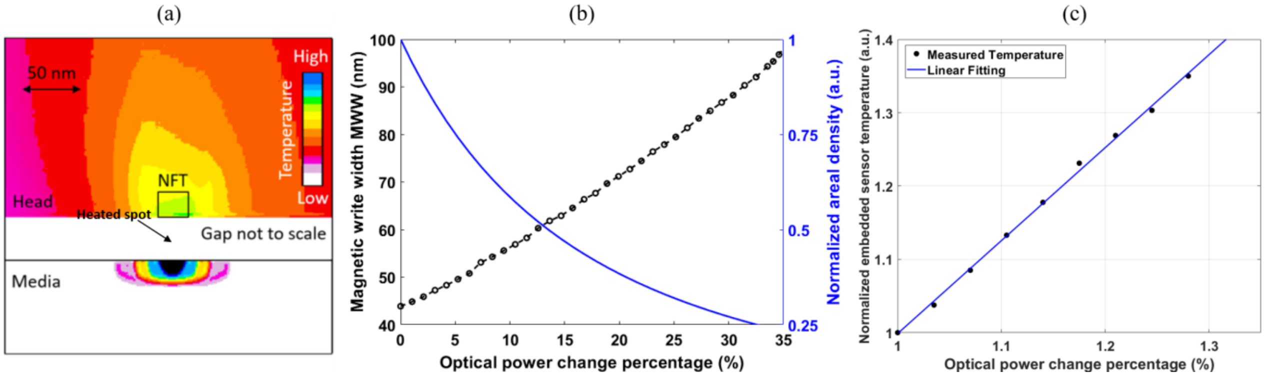

Figure 1. (a) Illustration of temperature distribution on head and disk due to HAMR heat source. (b) Percentage change in optical power of laser diode (left) and normalized areal density (right) as functions of magnetic write width MWW (c) Normalized temperature of an embedded temperature sensor as a function of percentage change in optical power of laser diode

II. Experimental Setup and Procedures

The HAMR head-disk interface setup used in this study consists of the recording head with integrated on-chip optics, including a laser, a waveguide and the NFT head structure flying on the disk. The disk is fabricated by sputtering a magnetic L10-FePt multilayer film structure onto a glass substrate, then coating it with a thin amorphous carbon thin film (protective overcoat layer), and finally lubricating it with a molecularly thin layer of perfluoropolyether lubricant (1 nm thick). The head is coated with a diamond-like carbon overcoat of approximately 1nm in thickness for wear protection. The disk-facing air bearing surface of the slider creates the air bearing pressure that supports the head over the disk. A 3.5 inch (95 mm) HAMR disk is rotated at an angular velocity of 7200 rpm and the head is flying at the middle diameter of the disk such that the linear velocity of the head in the experiments described in this paper is set to 20 m/s. When the head is not used for reading or writing operations, the flying height is typically on the order of 15 to 20 nm, depending on the air bearing design. To reduce the head disk spacing to the order of 1-2nm during read/write operations, a micro-heater is embedded in the slider. Upon energizing the heater, the slider will deform thermally and bring the read/write elements in close proximity to the disk surface [15]. This technology is described as thermal flying height control technology.

The micro-heater can also be used to evaluate and measure other protrusions that develop inside the head structure. For the “laser-off” condition, contact between the head and the disk is detected using a piezo-electric acoustic emission sensor, which detects elastic waves generated during head-disk contact events [16]. To set the desired spacing between the head-disk interface, we use the Wallace magnetic spacing loss equation which relates the exponential decay of the readback signal R from a random data pattern to the head-media spacing h as

$$R(f,h)=\alpha(f).e^{-2\pi fh} \quad (1)$$

, where $\alpha(f)$ is the readback signal amplitude at the spatial frequency f.

For the “laser-on” condition, several thermal protrusions develop on the head structure. During the writing process, optical power from the laser diode is delivered through the optical waveguide and couples to the NFT. A fraction of this optical energy gets absorbed inside the NFT leading to an increase in temperature and material protrusion. This protrusion is generally called the 'near-field' transducer protrusion (NFTPtr). Here, we note that [18] describes a contact-based touchdown scheme to measure the clearance between the protruded NFT structure and the disk. Due to the sharp and small radius of curvature of the “protrusion bulge” for the energized NFT structure compared to the “micro-heater bulge”, in this study we rely on an alternative non-contact recording based scheme to set the desired clearance (~2 nm) between the head and disk [19].

Increasing the laser current or the optical power leads to increased heat dissipation in both the NFT and the disk. This leads to an increase in temperature of both the head and the media. While temperature on the media surface is estimated based on the Curie temperature of the magnetic layer, the head temperature can be monitored using an embedded calibrated temperature sensor located near the NFT [20]. Turning on the laser and the writer allows a magnetic pattern to be written on the media surface and the written track amplitude of the media and its width can be used to estimate this temperature. Figure 1(b) shows an increase of the percentage change in optical power of the laser diode as a function of the measured magnetic write width (MWW) signal on the media. As the magnetic write width increases from 45 nm to 100 nm, the optical power increases by 35% (Figure 1(b)). An increase of the temperature of an embedded sensor, that is located near the NFT, is also proportional to an increase of the laser optical power (Figure 1(c)). It is important to mention that as the magnetic write width increases from 45 nm to 100 nm, the areal density of the hard disk drives decreases by approximately 4 times (Figure 1(b)).

The read back signal of a hard disk drive can be used for in-situ “health monitoring” of the NFT. Signal amplitude and write width of a HAMR drive signal (HAMR writing quality) depend on several parameters including the dimensions and efficiency of the NFT. The Figure 2(b) shows a typical written cross-track profile at constant magnetic write width (MWW) for both a pristine and a degraded NFT. We observe that the amplitude of the magnetic readback signal is reduced

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significantly as the NFT degrades, leading to a significant decrease of the read back amplitude and signal-to-noise ratio (SNR). Clearly, NFT "health" and reliability can be monitored by continuously tracking the change in the quality of the written track (amplitude and width) on the media.

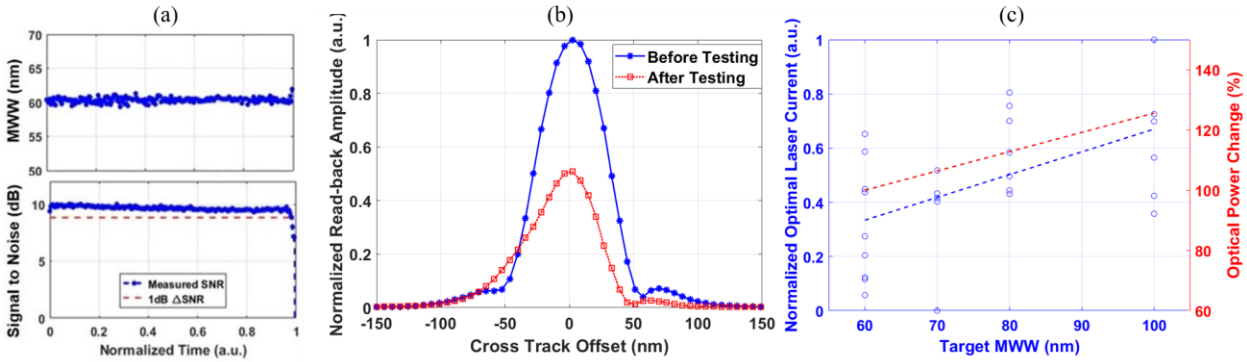

Figure 2. (a) In-situ monitoring of parameters like magnetic write width and signal-to-noise ratio on written track on media during lifetime testing. (b) Normalized read-back amplitude before and after the lifetime testing (c) Optimal laser current and optimal laser power as a function of magnetic write width (MWW) for lifetime testing.

III. Experimental Results and Discussions

In this investigation, we perform a systematic NFT lifetime testing protocol where the reliability of the NFT is tracked through continuous monitoring of the written tracks on the media (stress writing) and comparing these measurements with reference measurements (performance check). The performance check and stress writing were done on separate locations on the media denoted as reference and stress-writing tracks, respectively. On the stress-writing tracks, the NFT underwent prolonged exposure with the laser diode turned on continuously for 120s before moving to the reference track. On the reference track, the performance of the NFT was evaluated by monitoring the magnetic write width (MWW) and the signal-to-noise ratio (SNR) of the written track. This measurement was repeated until the decrease of the signal-to-noise ratio was larger than 1 dB, i.e., until the NFT was degraded to the point that it cannot write with the same quality as at the beginning of the test. Figure 2(a) shows the behavior of a typical lifetime head tested where the NFT was stressed at a constant magnetic write width of 60 nm. For most of the lifetime, the MWW and SNR remain unchanged at the target values.

After prolonged usage, both MWW and SNR begin to deviate from the initial target, indicating failure of the NFT to perform heat-assisted magnetic recording. We have performed similar lifetime tests with multiple heads at different MWW conditions. Figure 2(c) shows the normalized optimal laser current (left y-axis) and power change (right y-axis) required for different heads to write a magnetic signal on the media with MWWs of 60 nm, 70 nm, 80 nm and 100 nm, respectively. We note that the optimal laser current required to attain the same target MWW signal on the media varies from device to device. This is primarily attributed to the alignment variation among optical components such as the laser diode, the waveguide and the NFT, which are all integrated inside the head structure. Figure 3 shows the normalized lifetime of heads stressed at different target MWW conditions on the media. Clearly, as the MWW increases from 60 nm to 100 nm, the NFT lifetime is reduced by approximately 10 times. It is apparent that the reduction in lifetime at larger MWW is related to the higher temperature of the head and the media. Heads tested under higher stress conditions (MWW = 100 nm) require approximately 25% higher optical power than heads writing with a lower target MWW of 60 nm.

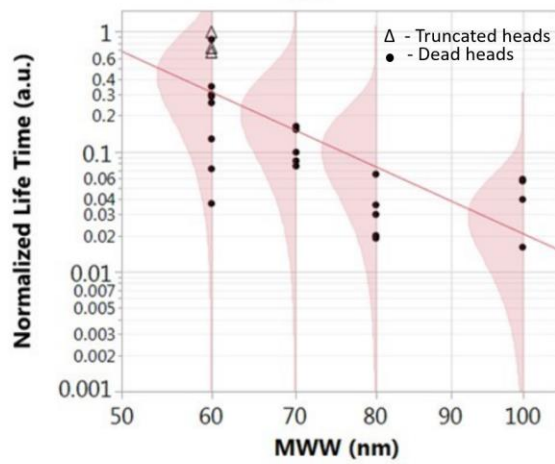

Figure 3. Normalized lifetime as a function of magnetic write width (MWW)

To further investigate the effect of media and head temperature, we performed a lifetime study on a different media (Media B) having higher optical power requirements (~21%) than the previous media (Media A) for the same magnetic write width of 60 nm (inset Figure 4). Since the magnetic materials and the heat sink layer on both types of media were the same, it is justifiable to assume that the temperature of the two media is the same keeping the same magnetic write width. Figure 4 shows the normalized NFT lifetime as a function of the change in optical power on media A at different MWW conditions (filled circle) and on media B at MWW of 60 nm (open circle). The reduction in NFT lifetime at higher optical power on media A is attributed to the higher temperature of both the head and the media. We note that the NFT lifetime on media B at a constant MWW of 60 nm is much lower than the NFT lifetime on media A at the same MWW of 60nm. In addition, lifetime on media B at 60nm MWW is similar to the lifetime on media A with MWW of 100 nm for which the optical power requirements are similar. This clearly demonstrates that the increase in head

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temperature is the dominant mechanism for the writing quality failure in HAMR recording. The increase of the NFT temperature is likely to cause thermal reliability issues at the head-disk interface [21]. An increase of NFT temperature also affects formation of write-induced contamination on the slider surface [22]. The formation of so-called "smear areas" over a long period of time will have a negative impact on the flying stability of the slider and the head-media interface.

IV. SUMMARY

A study of the reliability of a near field transducer at high head and disk temperatures was performed in a heat-assisted magnetic recording disk drive. The reliability of the NFT structure was found to depend on the dissipation of heat inside the head structure. Head and disk temperatures were monitored by using an integrated thermal sensor and the width of the magnetic signal on the media, respectively. Operating the NFT with a higher target magnetic write width (increased head and media temperature) reduced its lifetime by a factor of ten. Comparing the NFT lifetime with a media with higher optical power requirement for the same media temperature, we found that the head temperature is the dominant factor determining NFT failure.

A thorough understanding of the failure mechanism of the NFT structure is important for the understanding of drive reliability, and holds great economic value to the computer hardware industry. The results presented in this work demonstrate the importance of optical heat management in the near field transducers of HAMR hard disk drives.

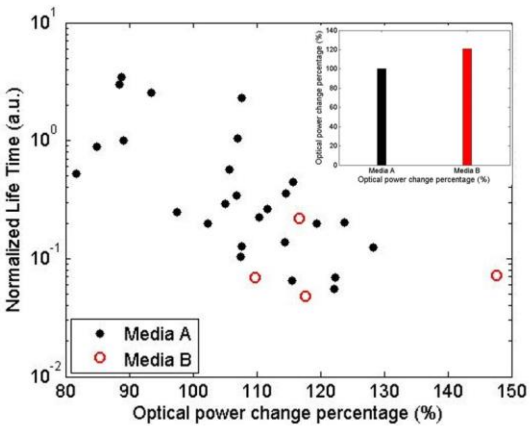

Figure 4. Normalized lifetime as a function of change in optical power for media A (filled circle) and media B (open circle). Inset shows the optimal optical power comparison of the two media.

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REFERENCES

[1] R. Wood, M. Williams, A. Kavcic, J. Miles, "The Feasibility of Magnetic Recording at 10 Terabits Per Square Inch on Conventional Media," *IEEE Transactions on Magnetics*, vol. 45, issue 2, 2009.

[2] B. Marchon, T. Pitchford, Y. T. Hsia, S. Gangopadhyay, "The Head-Disk Interface Roadmap to an Areal Density of 4 Tbit/in^2", Advances in Tribology, vol. 2013, 2013.

[3] D. Weller, A. Moser, "Thermal Effect Limits in Ultrahigh-Density Magnetic Recording", IEEE Transactions on Magnetics, vol. 35, pp. 4423-4439, 1999.

[4] K. O'Grady, H. Laidler, "The Limits to Magnetic Recording – Media Considerations", Journal of Magnetism and Magnetic Materials, vol. 200, pp. 616-633, 1999.

[5] R. E. Rottmayer, S. Batra, D. Buechel, W. A. Challener, J. Hohfeld, Y. Kubota, L. Li, B. Lu, C. Mihalcea, K. Mountfield, K. Pelhos, C. Peng, T. Rausch, M. A. Seigler, D. Weller, X. M. Yang, "Heat-Assisted Magnetic Recording", IEEE Transactions on Magnetics, vol. 42, pp. 2417-2421, 2006.

[6] W. A. Challener, A. V. Itagi, "Near-Field Optics for Heat-Assisted Magnetic Recording (Experiment, Theory, and Modeling)", Modern Aspects of Electrochemistry, vol. 44, Springer, NY, 2009.

[7] W. A. Challener, C. Peng, A. V. Itagi, D. Karns, W. Peng, Y. Peng, X. Yang, X. Zhu, N. J. Gokemeijer, Y. T. Hsia, G. Ju, R. E. Rottmayer, M. A. Seigler, E. C. Gage, "Heat-Assisted Magnetic Recording by a Near-field Transducer with Efficient Optical Energy Transfer", Nature Photonics, vol. 3, pp. 220-224, 2009.

[8] B. C. Stipe, T. C. Strand, C. C. Poon, H. Balamane, T. D. Boone, J. A. Katine, J. L. Li, V. Rawat, H. Nemoto, A. Hirotsune, O. Hellwig, R. Ruiz, E. Dobisz, D. S. Kercher, N. Robertson, T. R. Albrecht, B. D. Terris, "Magnetic Recording at 1.5 Pb m-2 using an Integrated Plasmonic Antenna", Nature Photonics, vol. 4, pp. 484-488, 2010.

[9] T. Matsumoto, F. Akagi, M. Mochizuki, H. Miyamoto, B. Stipe, "Integrated Head Design using a Nanobeak Antenna for Thermally-Assisted Magnetic Recording", Optics Express, vol. 20, pp. 18946-18954, 2012.

[10] L. Wang, S. M. Uppuluri, E. X. Jin, X. Xu, "Nanolithography using high Transmission Nanoscale Bowtie Apertures", Nano Letters, vol. 6, pp. 361-364, 2006.

[11] L. Pan, Y. Park, Y. Xiong, E. U. Avila, Y. Wang, L. Zeng, S. Xiong, J. Rho, C. Sun, D. B. Bogy, X. Zhang, "Maskless Plasmonic Lithography at 22nm Resolution", Scientific Reports 1, 175, 2011.

[12] D. P. Fromm, A. Sundaramurthy, A. Kinkhabwala, P. J. Schuck, G. S. Kino, W. E. Moerner, "Exploring the Chemical Enhancement for Surface-Enhanced Raman Scattering with Au Bowtie Nanoantenna", The Journal of Chemical Physics, vol. 124, 2006.

[13] A. Kinkhabwala, Z. Yu, S. Fan, Y. Avlasevich, K. Mullen, W. E. Moerner, "Large Single-molecule Fluorescence Enhancements produced by a Bowtie Nanoantenna", Nature Photonics, vol. 3, pp. 654-657, 2009.

[14] E. Schreck, D. Li, S. V. Canchi, L. Huang, G. P. Singh, B. Marchon, H. J. Richter, B. Stipe, M. Staffaroni, "Thermal Aspects and Static/Dynamic Protrusion Behaviors in Heat-assisted Magnetic Recording", vol. 50, issue 3, 2014.

[15] P. Machtle, R. Berger, A. Dietzel, M. Despont, W. Haberle, R. Stutz, G. K. Binnig, P. Vettiger, "Integrated Microheaters for In-situ Flying Height Control of Sliders used in Hard Disk Drives", IEEE International Conference on Micro Electro Mechanical Systems (MEMS), pp. 196-199, 2001.

[16] S. Rajauria, S. V. Canchi, E. Schreck, B. Marchon, "Nanoscale Wear and Kinetic Friction between Atomically Smooth Surfaces Sliding at High Speeds", Applied Physics Letters, vol. 106, issue 8, 2015.

[17] B. Marchon, K. Saito, B. Wilson, R. Wood, "The Limits of the Wallace Approximation for PMR Recording at High Areal Density", IEEE Transactions on Magnetics, vol. 47, issue 10, 2011.

[18] S. Rajauria, E. Schreck, "Tunable Contact Detection Sensitivity to Directly Measure Clearance of Protrusions in Magnetic Recording Heads", US Patent 9,595,281, 2017.

[19] S. Xiong, R. Smith, J. Xu, S. Nishida, M. Furukawa, K. Tasaka, K. Kuroki, Y. Yoon, N. Wang, S. Canchi, E. Schreck, Q. Dai, "Setting Write Spacing in Heat Assisted Magnetic Recording", IEEE Transactions on Magnetics, vol. 54, issue 8, 2018.

[20] J. T. Contreras, L. Huang, T. Matsumoto, S. Ren, E. Schreck, B. C. Stipe, "Dual Thermal Sensor for HAMR Waveguide Power Monitor and Integration with the Contact Sensor", US Patent 9,047,926, 2015.

[21] J. D. Kiely, P. M. Jones, Y. Yang, J. L. Brand, M. A. Dufresne, P. C. Fletcher, F. Zavaliche, Y. Toivola, J. C. Duda, M. T. Johnson, "Write-Induced Head Contamination in Heat-Assisted Magnetic Recording", vol. 53, no. 2, 2017.

[22] J. D. Kiely, P. M. Jones, J. Hoehn, "Materials Challenges for the Heat-Assisted Magnetic Recording Head-Disk Interface", MRS Bulletin, pp. 119-124, 2018.