Optically-Assisted Magnetic Recording

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Abstract- Thermally-assisted magnetic recording experiments on high-coercivity, perpendicular anisotropy, multilayer Co/Pt media are reported. High performance writability is demonstrated on media that could not be written at ambient temperature. Simulations help to clarify the physical phenomena involved in the thermally-assisted writing process.

Key words: magnetic recording, optically-assisted magnetic recording, thermal assistance, writability, micromagnetic simulation

1. Introduction

As recently discussed^{1,2)}, the current rapid increase in hard disk drive areal density will soon pose very challenging problems for conventional longitudinal magnetic recording. In order to maintain sufficient media signal-to-noise ratio, *SNR*, while increasing the areal density, one needs to reduce the average media grain size. Consequently, it becomes necessary to increase the grain anisotropy in order to limit data thermal decay to an acceptable level. Due to severe limitations in the maximum recording field an inductive head can deliver to the media, particularly at high data rate, it becomes increasingly challenging to maintain good writeability and overwrite performance. Recently demonstrated antiferromagnetically exchange coupled multilayer media structure are believed to be one way to postpone the onset of the decay problem for longitudinal recording³⁾ by allowing a better trade off between thermal stability, media *SNR* and writeability. As a more drastic solution, perpendicular magnetic recording on keptered media⁴⁾ allows for an increase in the available field at the recording layer level, and is likely to increase significantly the areal density limit of magnetic recording. However, even in this case it is estimated that the writeability issue will prevent recording beyond 300-500 Gb/in²²⁾. Optically-Assisted Magnetic Recording (OAMR) schemes, combining a local and transient increase in media temperature provided by an optical spot with the application of the recording head field, have been previously described for both longitudinal⁵⁾ and perpendicular⁶⁾ geometries as a possible solution to the writeability problem. Here we report for the first time detailed performance measurements of OAMR on perpendicular Co/Pt multilayers, a class of media that is believed to have a strong potential for stable recording at high densities⁷⁾.

Carbon overcoat
(Co/Pt) x 16
Seed layers
AR coat, diffusion block
Glass-ceramic substrate

Fig. 1 Structure of the media studied in this report.

2. Experiment

2.1 Sample preparation and magnetic properties

Single-sided disk media samples were fabricated in a multiple-cathode dc-magnetron sputtering system with 3×10^{-8} torr base pressure and ambient temperature processing. Film structures as shown in Fig. 1 were deposited with no vacuum break on 84 mm diameter glass ceramic disk substrates which had been previously etched in selected regions. An antireflection underlayer was utilized to reduce the through-substrate reflectance from about 60% to the 5-12% range. Additional underlayers were used to control the magnetic properties of the Co/Pt multilayer⁸⁾. The multilayer, consisting of 16 bilayers of 0.35 nm Co/1.0 nm Pt, was co-sputtered from elemental targets in Kr gas⁹⁾ onto a rotating disk substrate with a baffle to prevent intermixing. The final vacuum deposited layer was a hard carbon overcoat, after which conventional liquid lubricant was applied for flying head testing at glide heights as low as 12.5 nm.

Fig. 2 In-plane and out-of-plane VSM hysteresis loops of the media studied in this report. The perpendicular coercivity of the media is approximately 7kOe.

The magnetic properties of the multilayers were varied over a considerable range by controlling the thickness and sputtering parameters of the seed layers. Coercivity H_c varied up to 11.1 kOe, squareness $S = M_r/M_s$ ranged between 0.8 and 1.0, coercive squareness S^* varied from 0.3–0.9, with a remanent moment-thickness product $M_r t$ of typically 0.5 memu/cm². For this study, a disk with low S^* and mid-range H_c was selected; in-plane and perpendicular hysteresis loops for this sample, measured by Vibrating Sample Magnetometry (VSM), are shown in Fig. 2. Low S^* , an indication of reduced exchange coupling between magnetic grains, was induced by increasing the sputter pressure and thickness of the underlayer.

2.2 Recording measurements

A custom spindrive, similar to the one described by Cumpson et al., was built for the purpose of conducting thermally-assisted recording measurements³⁾. Heat was delivered to one surface of the media using a far-field optical spot, while recording measurements were performed using a conventional recording head on the opposite surface of the media. The relevant recording parameters and dimensions of the optical spot and recording head are given in Table 1. Both the optical source and the recording head could be moved independently in order to facilitate alignment of the optical spot and the write gap for optimum recording. Actuators allowed positioning of the heads in increments of less than 0.05 μm . The heads were aligned using 100 nm deep pits that were etched into the glass-ceramic substrate prior to deposition of the magnetic layer.

Magnetization divergence in the pits produced a readback signal for magnetic head alignment, while diffraction of the optical source incident at the pit edges produced a reflectivity variation used to align the optical spot. The pit patterns were designed so the heads could be aligned in both the downtrack and crosstrack directions.

In Fig. 4, we show an oscilloscope trace of a series of data bursts written to the media at varying levels of optical incident power, P_{inc} . The write current in the recording head, I_w , was held fixed at 10 mA. During

Fig. 3 Schematic diagram of the tester built for conducting thermally-assisted recording experiments. Heat is delivered optically through the transparent substrate, while recording measurements are performed on the bottom surface.

Fig. 4 A series of 10 μsec bursts written with varying levels of incident optical power, P_{inc} . The write current in the recording head I_w was held fixed at 10 mA. The written signal frequency was 20 MHz.

recording, the write gate for the magnetic recording head was enabled continuously, while the laser diode was enabled for a series of 10 μsec intervals. The various values of P_{inc} used for recording are indicated in the figure next to the respective data bursts. Below an optical power threshold of approximately 8 mW negligible writing occurs, above which the signal amplitude monotonically increases as P_{inc} increases.

Due to the high coercivity of the sample used here, in the absence of thermal assistance it was virtually impossible to write data to the media. This is clearly indicated by the data of Fig. 5, where crosstrack profiles of thermally-assisted and conventionally-written data are shown. Even when using the maximum possible value of write current amplitude, $I_w = 49$ mA, it is seen the maximum crosstrack profile amplitude of conventionally-written data is negligible as compared to the thermally-assisted value. In Fig. 6 we see a trace of relatively isolated pulses written with thermal assistance. The pulses look like typical readback signals from perpendicular media, as expected.

In Fig. 7, we show the narrow-band power of a low frequency (LF) tone (11.5 MHz) vs. write current for thermally-assisted and conventional recording. Consistent with the data above, it is seen that negligible writing occurs in the absence of thermal-assistance, even

Table 1 Basic recording parameters used in this work.

Writer width	1.2 μm
Reader width	0.90 μm
Write gap length	0.30 μm
Flying height	25 nm
Optical spot size (FWHM)	0.70 μm
Head-media relative velocity	12.5 m/sec
Optical source wavelength	680 nm
Maximum optical power	30 mW

Fig. 5 Crosstrack profiles of tracks written conventionally and with thermal assistance. The written signal frequency was 20 MHz.

at the highest levels of write current. Figure 8 shows overwrite, OW , as a function of write current. For this measurement, the OW frequencies were 11.5 and 69.1 MHz. It is seen that even though the coercivity of this sample is in excess of 7 kOe, thermally-assisted recording yields OW values of approximately -35 dB. On the other hand, the OW value for conventional recording was only -10 dB.

In Fig. 9, we show "rolloff" curves - signal amplitude vs. recording density, for both conventional and thermally-assisted recording. Due to the large differences in amplitude, the data is plotted on a logarithmic scale here. We note the lines in this graph are guides for the eye, and should not be taken to imply the signal amplitude should be a monotonic function of recording density.

In Fig. 10, we show the auto-correlation signal-to-noise ratio, $ACSNR$, as a function of linear recording density for thermally-assisted recording. This time-domain measurement was made on single-tone signals written to the media. We note that when this measurement was performed on media written without thermal assistance, the measured $ACSNR$ value was consistently < -5 dB at all recording densities. This is readily understood in light of the fact that at room

Fig. 6 A time-domain trace of isolated pulses written with thermal assistance.

Fig. 7 Low-frequency signal amplitude vs. write current for conventional and thermally-assisted recording.

temperature, this media is virtually unwritable as was shown above. Although the data of Fig. 10 show a rapid decrease in SNR with recording density, one needs to keep in mind that the sample studied here was deposited at room temperature, and no extensive effort was made to reduce the exchange coupling of the media.

3. Modeling

3.1 Introduction

In simulating optically-assisted magnetic recording, there are optical, thermal, and magnetic aspects of interest. We have employed stand-alone thin film optical and thermal conduction models, as well as two types of integrated thermomagnetic recording simulations. The stand-alone optical and thermal models are the same as those used in the design of optical recording media and systems¹⁰⁾. The recording simulations essentially solve numerically for the time evolution of the magnetic state of a magnetic film structure which falls under the influence of externally applied magnetic fields (from a recording head or coil) and imposed heating due to optical absorption and thermal conduction. The magnetic state solvers employ either energy minimization or rigorous solution of the dynamical equation governing the local magnetization vector (for example, the Landau-

Fig. 8 Overwrite vs. write current for conventional and thermally-assisted recording.

Fig. 9 Signal amplitude vs. recording density for conventional and thermally-assisted recording.

Lifshitz-Gilbert [LLG] equation). Both of these approaches have been called “micromagnetics” calculations (although the spatial dimension over which variation in the magnetic state occurs is about 10 nanometers).

The simulation results reported in this section were obtained for the perpendicular film structure used in the experiments.

3.2 Optical and thermal calculations

To simulate heating with an optical beam in OAMR, we must quantify the optical interaction of the light beam with the disk medium. Figure 11 shows the geometry of the second-surface illumination with a normally incident, diffraction-limited, focused laser beam. We are interested primarily in the reflectance from and distribution of absorbance in the films on the disk. The distributed absorbance, proportional to the local derivative of the radiation’s Poynting vector in the film normal direction, represents the source power for film heating¹⁰.

We show in Table 2 the optical and thermal properties and optical absorption for an example disk structure as shown in Figure 11. This film stack, involving a perpendicular anisotropy Co/Pt multilayer, is made with an anti-reflection (AR) structure, since without it the

Fig. 10 Auto-correlation signal-to-noise ratio vs. linear recording density for thermally-assisted recording.

Table 2 Optical and thermal properties of the media. c is the specific heat [$J/(cm^3 \cdot ^\circ K)$], k_{th} is the thermal conductivity [$W/(cm \cdot ^\circ K)$], and $Abs.$ is the absorbance.

Layer	n	k	c	k_{th}	$Abs.$
Substrate	1.5	0	1.98	0.02	0
AR coat	3.17	0.352	2.0	0.10	0.4067
Seedlayer	2.49	4.40	2.86	0.25	0.1967
Co/Pt	2.49	4.38	2.86	0.25	0.2668
Carbon	1.82	0.02	2.74	0.015	0.00025

the metallic film coating results in a reflectivity in the 50-60 percent range, making the optical heating efficiency too low. The AR structure drops the reflectivity to about 8%, and yields the distributed absorbance in Table 2.

Figure 12 shows the temperature rise through the film stack corresponding to the absorbance distribution of Table 2. This temperature rise results from 1 mW optical power incident on a disk moving under the beam at 10 m/s. This temperature distribution is captured at track center at the x -position where the temperature peaks in the magnetic layer 100 ns after the laser beam is switched on. We see that temperature elevation is fairly uniform through the thin film stack, reflecting the balanced optical absorbance and relatively low thermal resistivity normal to the films.

Two other aspects of the simulated thermal response of the disk are depicted in Figure 13. Fig. 13(a) shows the spatial distribution of temperature along the track center of the moving disk $\Delta T(x, t_0)$ at an instant of time t_0 when the laser power has been on long enough to produce a steady-state profile. Such a distribution has been confirmed experimentally on our spindown by sequentially measuring readback signals resulting from OAMR writing with the separation between the centers of the optical spot and writing head gap varied. To our knowledge, this is the first reported direct measurement

Fig. 11 Geometry of through-substrate illumination.

Fig. 12 $\Delta T(x_o, y_o, z, t_o)$ per mW through film depth for the geometry of Fig. 11.

of a locally temperature-dependent property showing the temperature distribution on the surface of a moving recording medium.

Figure 13(b) shows the modeled dynamic behavior of the temperature in the magnetic layer at various positions along track center reflecting the maximum temperature rise at times of 10 and 100 ns after the laser pulse is switched on. The quantity $\Delta T(x_o, t)$ gives information on the rate of warm-up at a fixed point on the disk as it passes under the laser. This measures both the physical spread of the focused spot and the temporal thermal response of the film structure. The curve for 100 ns also shows both of these responses, but in a more readily separated form, since the laser is switched off at $t = 100$ ns. The cool-down rate is readily apparent for $100 \text{ ns} < t < 110 \text{ ns}$.

Fig. 13 (a) $\Delta T(x_o, y_o, z_o, t_o)$ per mW along track center. (b) Temporal dependence $\Delta T(x_o, y_o, z_o, t)$ per mW.

Fig. 14 Simulated optically-assisted writing of a constant frequency tone during laser power burst of 100 ns duration. "Racetrack" contours are cumulative history isotherms (ΔT_{max} contour is 275°K , and interval = 50°K), while grouping of nearly vertical lines on the right side show write head H_y contours at $t = 100 \text{ ns}$ ($\Delta H_y = 1 \text{ kOe}$)

3.3 Magnetic simulation

We simulated a typical OAMR recording sequence with the result shown in Figure 14. A laser pulse is switched on for 100 ns as the disk moves below the beam at 10 m/s. During the same time interval, a finite-width, infinite pole length "Lindholm" writing head with the parameters shown in Table 1 is activated with a square wave current of alternating polarity. The writing head can be positioned arbitrarily relative to the heating light spot, but these two transducers are at rest relative to one another. The magnetic field component of the inductive "ring head" that is perpendicular to the disk films is the primary writing field. With the simulator, one learns about the criticality for optimal writing of both the relative positioning of the write head and the heated spot, and the proper setting of the relative media heating and applied magnetic field strength. This is how one gains understanding of the relative importance of thermal and magnetic field gradients in the OAMR recording process. In thermomagnetic recording, a key physical parameter is the temperature dependence of medium coercivity, $H_c(T)$. $H_c(T)$ as measured on a VSM is shown in Figure 15, and we use this data in the modeling. As in the experiment, we can demonstrate with the model the feasibility of

Fig. 15 $H_c(T)$ of recording film measured by VSM.

Table 3 Temperature-dependent properties used for the results of Fig. 16; Gilbert damping coefficient $\alpha = 0.10$; grain volume = 4860 nm^3 .

T (°K)	M_s (emu/cm ³)	K_u (10 ⁶ erg/cm ³)	H_k (kOe)	$K_u V/k_B T$
298	447	2.24	10.0	265
373	436	1.74	8.0	164
448	410	1.33	6.47	104.6
523	316	0.84	5.29	56.6
598	205	0.42	4.12	24.7
673	82	0.10	2.35	5.0
773	0	0	0	0

using optical assistance to perform good saturation recording on media with coercivity beyond the reach of the writer working at ambient temperature.

The media magnetic switching model used in Fig. 14 was a simple square loop scheme in which a writing criterion of $|H_w| \geq |H_c(T)|$, ignoring demagnetizing effects, was used. A more sophisticated writing model is available in which a Voronoi grain structure is implemented reflecting rigorous LLG dynamic switching with correct treatment of demagnetization and thermal effects¹¹⁾. The simpler model is just as useful as the more detailed model in studying the basic physics of implementing OAMR recording.

A final magnetic simulation of relevance to OAMR recording is a representation of the dynamics of magnetization switching¹²⁾. By inputting temperature-dependent magnetic properties for the granular (particulate) film material (Table 3), one can compute the full dependence of $H_{cr}(t, T)$. A more rigorous simulation of dynamic coercivity can be performed on a realistic granular medium with a distribution of magnetic properties and anisotropy axes using ARM¹¹⁾. The key point is that the medium material can be tailored to have a steep falloff of $H_c(T)$, even at writing times of ~ 1 ns. Figure 16 shows a comparison of results using properties

Fig. 16 Dynamic coercivity $H_{cr}(t, T)$ from models^{5,6)}.

derived from measurements on the medium used in our experiments.

4. Conclusions

We have fabricated Co/Pt multilayer media with $H_c > 8$ kOe and performed optically-assisted recording experiments on a two-headed spindrive. Good writeability was demonstrated on media that could not be written at ambient temperatures with current product recording heads, confirming the potential of OAMR to increase the areal density limit. Computer simulations have been used to help explain the recording physics in OAMR, and provide insights into paths to further optimize this new recording technology.

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