TITLE: Materials Development for Thermally-Assisted Magnetic Recording Media

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Materials Development for Thermally-Assisted Magnetic Recording Media

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ABSTRACT

We have carried out a combined experimental and computer simulation study to specify and identify candidate films to support high areal density, thermally-assisted magnetic recording. The motivation of this work is to utilize the enhanced writability of very high coercivity materials that thermal assistance can provide. Media with high coercivity (and anisotropy K_u) are known to be essential to achieve a sufficiently high ratio of K_uV/k_BT necessary to maintain magnetic stability at temperature T in media switching units (grains; single domains) of volume V. Nominally, we expect $V \propto D^{-3/2}$, where D is the medium bit density per unit area in recording. A micromagnetic recording simulation tool with a capability of representing realistic grain size distributions, temperature-dependent magnetic properties, and spatially-varying imposed temperature distributions was employed to study the interplay of thermal and magnetic field gradients in the recording process. In addition, a simple LLG-based thermomagnetic switching model supplemented the micromagnetics model. We fabricated improved Co/X multilayer media for recording evaluation, and performed standard materials characterization.

RATIONALE FOR HYBRID RECORDING

Data storage technology has been advancing rapidly for several decades, with magnetic recording in particular having accelerated its rate of advancement several times in the past dozen years. With annual compound growth rates of areal density (count of "bits" per unit area on the recording medium's surface) rising above 100% in the last few years, magnetic recording technology in rigid disk drives (RDD's) appears to be approaching fundamental physical limits for the first time in its one hundred year history [1]. This situation has prompted accelerated research and development to modify the course of the technology's evolution, spurring renewed interest in perpendicular recording, and more recently drawing attention to novel approaches of patterned media and hybrid recording [1].

This paper deals with storage media materials development for hybrid recording. We define "hybrid recording" as an alternative approach to conventional magnetic recording in which thermal-assistance of the record and/or playback processes is invoked to improve system performance. Sometimes optical irradiation of media has been used to impart heating, but other means of introducing thermal energy can be envisioned. Nevertheless, the term hybrid recording has most often been understood to mean a merging of aspects of magnetic and optical recording.

The writing process in hybrid recording is essentially thermomagnetic recording very similar to that employed in magneto-optic recording [5]. One uses the temperature-dependence of the recording medium's magnetic properties to advantage for enabling high quality magnetic recording in a situation where the magnetic writing head is incapable of supplying a sufficient magnetic field to the medium to switch its magnetization at the ambient temperature of the storage device. Specifically, elevating the medium's temperature generally lowers its coercivity so that the magnetization can be switched with a more modest head field. A second, equally important benefit accrues when the medium immediately cools back to the ambient temperature, since the coercivity rises markedly and thereby stabilizes the recorded magnetization against unwanted reversal. Such reversal can occur due to either the influence from sufficiently strong internal or external magnetic fields, or from spontaneous decay under the influence of ambient temperature (or both) over long periods of time [2].

Magnetic recording engineers have become interested in hybrid recording for both of these reasons, although initially it was concern over media thermal decay in conventional longitudinal recording that prompted serious consideration of thermally-assisted recording. The specter of media thermal decay in RDD's arose as the areal density of recorded information continued its relentless exponential rise. Most magnetic recording media (particulate or thin film) is composed of assemblies of (ideally) independent magnetic particles, and a zone of such "particles" representing a recorded bit of binary data should contain of the order of several hundred of them. The medium signal-to-noise (power) ratio (SNR) performance scales proportionally to this number [3]. A rising areal bit density implied that the bit sizes were shrinking, and to hold SNR constant required shrinking the particle sizes proportionally with the bits. The theory of superparamagnetism establishes a minimum magnetic particle volume for stability of the particle's magnetization at temperature T – specifically, the ratio K_uV/k_BT representing the particle's magnetic anisotropy energy relative to its characteristic thermal energy should exceed ~25. When this ratio falls below 25, the particle's magnetization can spontaneously reorient under thermal agitation, and the particle ceases to be a stable ferromagnet – it is "superparamagnetic" with zero time-averaged magnetic moment in any particular direction due to thermal fluctuation. Superparamagnetism is thus a mechanism for spontaneous decay of recorded information if individual magnetic particles comprising the bit undergo magnetic reorientation under the influence of ambient thermal energy.

A natural means of suppressing superparamagnetism is to maintain the energy ratio K_uV/k_BT at sufficiently high levels, in spite of the technological pressure to drive V downward. Since the operating temperature of data storage devices is unlikely to be a parameter that the design engineer has much leverage in changing significantly, one is left with only the option of elevating the media's magnetocrystalline anisotropy K_u. This intrinsic material parameter is intimately connected with the extrinsic media design parameter coercivity, the mean switching magnetic field of the material. Raising K_u has therefore become a primary materials strategy to preserve thermal stability of media [4]. But since coercivity H_c rises more or less in proportion to K_u, eventually a concern develops as to whether the recording medium can be switched with available recording heads at ambient temperature. The output fringe field of writing heads for switching magnetic media is proportional to the saturation magnetization M_s of the head's pole tip material at the gap. There is a strict upper limit on values of M_s for head materials ($4\pi M_s \sim$ 25 kilogauss), largely imposed by the ferromagnetic elements found in the periodic table – Fe, Co, Ni. Engineers today cannot envision writing fields ever exceeding this limit. And yet, one can envision medium coercivity rising toward 100 kilo-oersted using known materials [4]. Thus, a writability crisis in magnetic recording has arisen from the effort to preserve the essential performance requirements of SNR and media stability, and hybrid recording is thus logically established as a candidate method to address this issue.

It has been established in prior work that heating a magnetic medium during readout, particularly using light, can offer some benefits to this phase of the recording process [5]. Optical readout of MO media is a well-developed technology in optical storage, and use of an

MO process to read in RDD's is a possible future benefit of hybrid recording. This is particularly true in view of challenging technological issues surrounding continued extendibility of magnetoresistive readout that has been so prevalent in the past decade. For optical readout to be viable at tomorrow's areal densities necessarily implies that we work beyond the diffraction limit that governs the localization (focusing) of electromagnetic energy in the far-field of the radiation pattern, since bit lateral dimensions will lie in the range of tens of nanometers at areal densities approach 1 Tb/in^2. This means that only near-field optics will be a useful ingredient in hybrid recording.

Previous work in Japan [5] considered another potentially important aspect of future hybrid readout in RDD's, namely manipulation of data track widths using a combination of localized heating imparted to the medium with multilayer interaction between magnet films. More broadly, this could introduce to RDD's a potential strategy of using multiple film layers to attempt to jointly optimize media design for both writing and reading, a technique common in MO recording.

MEDIUM MATERIALS DEVELOPMENT

In this work, we consider means of improving the materials engineering of Co/X multilayer films previously considered for perpendicular recording [6]. If the technology of hybrid recording emerges into products, it is fairly certain that the magnetic medium will exhibit perpendicular anisotropy, since the advantages of vertical recording are reasonably well established for future high areal density recording [7]. Media for hybrid recording presents additional challenges and opportunities beyond conventional perpendicular media. Thermal design of the film and substrate structure will clearly be necessary to set thermal response times and possibly heat flow control (axial and lateral) [8]. If optical means are used to impart heating, then optical reflectance and absorbance of the medium surface must be designed to insure efficient energy transfer from the heating transducer to the disk. On the other hand, hybrid recording may allow the media designer to avoid use of the often onerous "soft underlayer" that appears essential for perpendicular media [7], or if necessary, have it also function as a heat sink. In hybrid recording, most of the writability assistance is provided by heat, and a conventional inductive ring writer may provide vertical fields of adequate quality with heated media.

The ideal recording material for our hybrid recording experiments must satisfy not only certain magnetic performance requirements but also demanding technical requirements for application in high areal density hard disk drives. Key magnetic property requirements are high perpendicular anisotropy, high coercivity, high magnetization, and appropriate temperature dependence of these properties for thermally assisted magnetic recording. Key technical requirements are small and uniform physical grain size, controllable exchange coupling between grains, and environmental stability adequate for drive applications with vanishingly thin (< 50 Å) protective overcoats.

We consider Co/Pt and Co/Pd multilayer media as promising material candidates for thermally assisted recording. In prior hybrid recording experiments [9], we utilized perpendicular Co/Pt multilayer media that was fabricated without special attempts to control intergranular magnetic exchange coupling, or to minimize irreversible physical changes upon thermal cycling of the film structure. Not surprisingly, the playback of recorded patterns

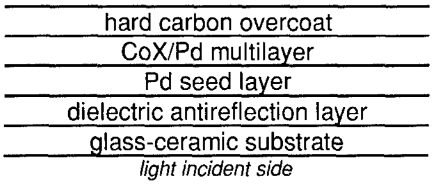

Figure 1. Typical structure of the hybrid media fabricated in this study.

exhibited considerable media noise, and recording performance could depend on the thermal history of the media. In the engineering of granular, thin film, longitudinal magnetic media for hard disk drives, materials strategies for producing decoupled grains along with the full suite of other desired (room temperature) properties are well-developed. We adopted similar approaches, by choosing Cr and other Co dopants in the multilayer system CoX/Pd, and by employing substrate temperature during and/or after deposition of the multilayer to induce dopant diffusion to grain boundaries.

Single-sided disk media samples were fabricated in a multiple cathode dc-magnetron sputtering system with 3 x 10^{-8} torr base pressure, rotating disk holder, and radiant infrared heating of the disk substrate during deposition. Disk temperature was monitored using an infrared pyrometer imaging the uncoated side and calibrated using an identical disk substrate instrumented with a chromel-alumel thermocouple. Film structures as shown in Figure 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 (e.g. reactively sputtered Si_3N_4) was utilized to reduce the through-substrate reflectance from about 60% to the 10 – 30% range. A Pd seed layer was used to enhance the coercivity and minimize initial layer disorder in the multilayer. Substrate heating could be applied before, during, and/or after the multilayer deposition. The multilayer was co-deposited from 5.1 cm. diameter Co-alloy and Pd targets at a target-substrate separation of 6.4 cm in Ar or Kr gas. The individual layer thicknesses were controlled by the deposition rate and rotation speed (20 rpm typical) of the substrate. The final vacuum deposited layer was a hard amorphous carbon overcoat, to which conventional liquid lubricant was applied for flying head testing at glide heights as low as 12.5 nm.

Media Film Characterization

The magnetic properties of the multilayers were controlled over a considerable range by adjusting the thickness and processing parameters of the seed layer and the temperature treatment of the multilayer. 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 to 0.9, with a remanent moment-thickness product M_rt of typically 0.5 memu/cm^2. For perpendicular media another parameter gaining favor is $\alpha = 4\pi(dM/dH_{appl})|H_c$, i.e. the slope of the hysteresis loop evaluated at the coercive point, which provides an indirect but useful indication of the degree of exchange coupling in the media (S* also gives a measure of slope, but, unlike α, is a function of H_c). High α (>5) indicates strong exchange, an extreme example of which would be the rectangular hysteresis loops observed for continuously exchange coupled TbFeCo-based magneto-optic films [14]. At the other extreme, a completely exchange decoupled media would exhibit a sheared loop with slope determined by the sheet demagnetizing field, $4\pi M_s$, for which the limiting value of $\alpha = 1$. Multilayer properties can easily be adjusted over a large range of α, examples of which

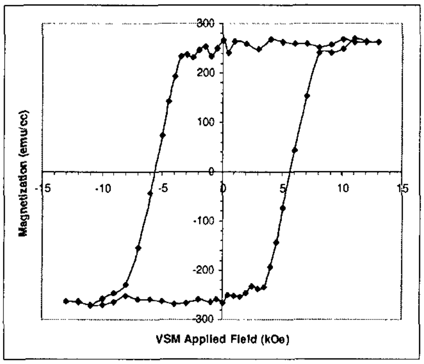

Figure 2. Perpendicular VSM hysteresis loop for a (CoX/Pd:2.6Å/8Å) x 17 multilayer sputtered at ambient temperature, then exposed to room air and annealed in vacuum at 250-300°C for 15 minutes. Slope parameter $\alpha = 1.5$.

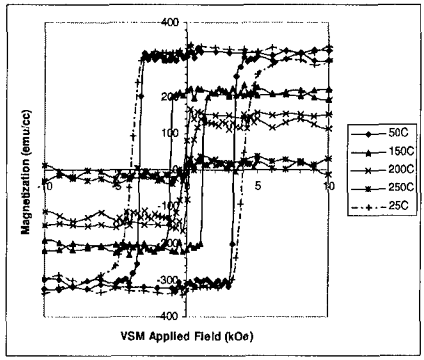

Figure 3. Perpendicular VSM hysteresis loops measured at temperatures from 25°C to 250°C for a (CoX/Pd:2.6Å/8Å) x 17 multilayer sputtered at 300°C substrate temperature. The 25°C loop was the last loop measured in this series. A 25°C loop was also measured at the beginning of the series, but for clarity is not plotted.

are shown in Figures 2 and 3, for which α ranges from 1.5 to over 20. Strong decoupling (low α) can be achieved using processing conditions which likely result in physical separation of grains to break exchange, e.g. ambient temperature deposition and high sputter pressure to reduce surface mobility, and rough seed layers to create incoherent nucleation sites. TEM images of films grown under such conditions typically exhibit a network of voids and rough surface morphology, supporting a picture of physically isolated grains. The multilayer in Figure 2, although sputtered at ambient temperature, was subsequently exposed to room air and then annealed in vacuum at 250-300°C for 15 minutes. Although unconfirmed, it is likely that oxide formation, e.g. at grain boundaries, is also playing a role in the decoupling mechanism for this sample. In contrast, an example of strong coupling is shown in Figure 3 for a multilayer grown at 300°C substrate temperature. The higher M_s for this sample compared with that in Figure 2 can be explained by an increase in film density, consistent with enhanced temperature induced surface mobility of depositing species. A possible explanation for the resultant strong coupling is that film densification dominates over any dopant segregation effects.

A requirement unique to hybrid recording is that the media must also be stable against thermal cycling under the action of the thermal assist heat source. Porous sub-dense films typically suffer irreversible physical change upon heat cycling. It is not unusual to observe a 50% reduction in VSM coercivity upon annealing at 300°C and re-measuring at room temperature. Both films corresponding to Figures 2 and 3 show marked improvement in thermal stability compared to films processed entirely at room temperature. The film in Figure 3 is remarkably stable against annealing at 300°C for 15 minutes in flowing N_2. H_c and M_s are virtually unchanged, and α remains high, as shown in Figure 4. We note that α is extremely sensitive to small changes in coupling for these highly rectangular loops. Similarly, the film of Figure 2 has been re-annealed in vacuum at 300°C with virtually no change in room temperature hysteresis properties, within the precision of the measurement. Thus, films with much improved

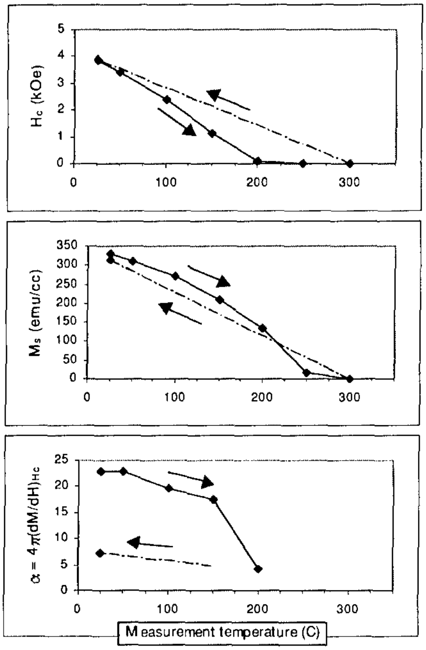

Figure 4. Temperature dependence of H_c, M_s, and $\alpha = 4\pi(dM/dH_{appl})|H_c$, corresponding to the temperature dependent hysteresis loops of Figure 3. After the sequence of measurements up to 300°C (solid lines, right hand arrows), the film was returned to room temperature and a final measurement made (dashed lines, left hand arrows).

thermal stability have been achieved, with resultant α in the range 1.5 - 5, through substrate heating either during or after deposition, and, in the case of Figure 2, an intermediate air exposure.

Recording measurements and simulation (see below) indicate that noise is correlated with α, i.e. noise decreases (transition sharpness increases) with decreasing α. The challenge alluded to in Figures 2 and 3 is to engineer a film which at the same time is not only properly decoupled and thermally stable, but also smooth to minimize head-to-media spacing and chemically receptive to the protective overcoat (which argues against surface oxide formation). We continue to explore methods combining physical (with minimal void space and reduced roughness) and chemical (e.g. dopants, oxygen) grain separation for media optimization.

MODELING OF HYBRID RECORDING

Two types of recording simulations were used to explore hybrid media materials design and recording performance. The first was a micromagnetics model structured for recording medium design and recording process assessment [10]. The second was an extension of a much simpler model reported by Ruigrok [11] which considers the magnetization reversal of a single particle on short time scales as described by a modified Landau-Lifshitz-Gilbert (LLG) equation. One of us (tm) added to the Ruigrok model time-dependent heating and incorporation of temperature-dependent magnetic properties to more fully investigate the predictive power of this model for hybrid recording.

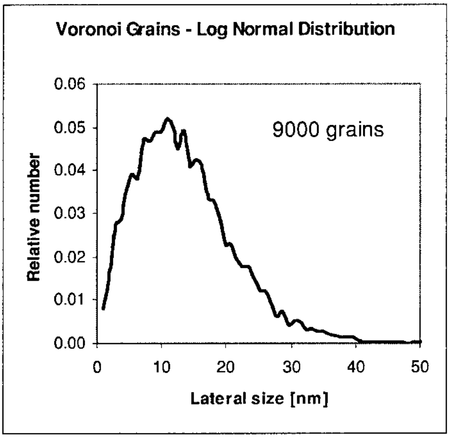

Figure 5. Medium grain size distribution from micromagnetics simulator. Mean size is ~10 nm.

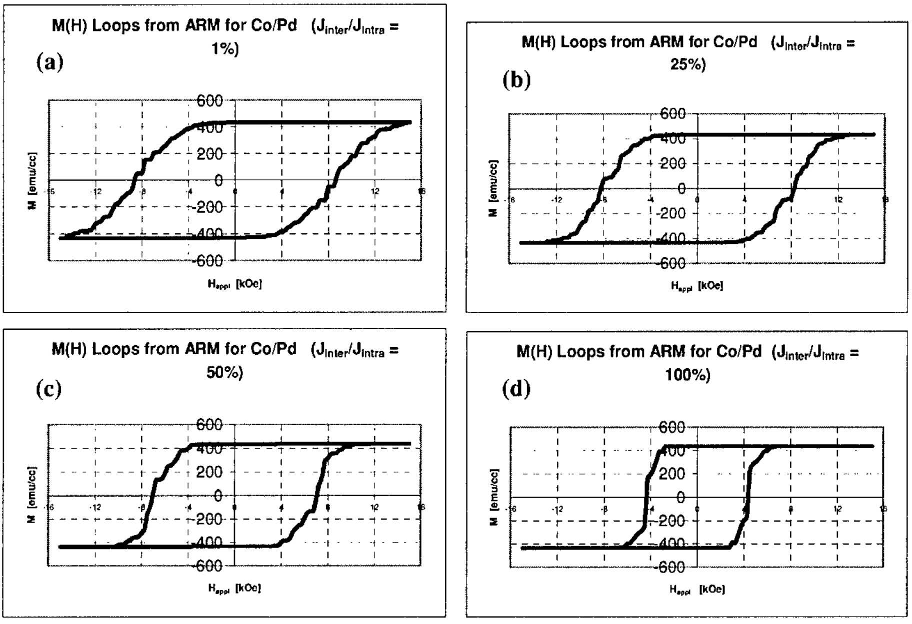

Figure 6. Modeled M(H) hysteresis loops for cases of the ratio of inter- to intra-granular exchange coupling equal to 1, 25, 50, and 100%. Medium grain size distribution for these loops is shown in Figure 5.

Table I. Micromagnetics modeling parameters

Parameter	Units	Mean Value	σ
Saturation magnetization M_s	emu/cm^3	437	10 to 40
Anisotropy field H_k	Oe	10500	200 to 1050
Anisotropy axis perpendicular alignment	degrees	0	0 to 5
Intra-granular exchange coefficient A_x	erg/cm	10^{-7}	0
Inter-granular exchange coefficient A_x	erg/cm	10^{-10} to 10^{-7}	10^{-11} to 10^{-8}
Gilbert damping constant		0.1	0.1
Curie temperature	K	663	
Media grain size	nm	10 to 28	2 to 8
Ring head pole width	nm	1200	
Ring head gap length	nm	300	
Pole head length, width	nm	200, 200	
Head - medium spacing	nm	30	

Table II. M(H) hysteresis parameters for modeled loops such as those shown in Figure 6.

J_{inter}/J_{intra}	Hc [kOe]	Mr [emu/cc]	S*	α
0.001	8.83	434.00	0.583	1.48
0.01	8.63	434.00	0.651	1.81
0.05	8.81	434.01	0.667	1.86
0.25	8.22	434.05	0.789	3.14
0.5	7.04	434.08	0.855	5.34
1	4.35	435.50	0.92	15.73

In the first use of the micromagnetic model, we set up a hypothetical medium with film properties approximating those of our film samples. This model can construct a granular medium with Voronoi grains that match log normal size distributions such as those measured experimentally using transmission electron microscopy (TEM). Table I shows a set of film properties incorporated in the modeled medium in the micromagnetic model. Figure 5 depicts a typical grain size distribution in the model, while Figure 6 presents modeled M-H hysteresis loops (with demagnetization shearing present) for the perpendicular medium represented in Table I. The shape of the loop gives information concerning the degree of grain decoupling [12], which is a controllable parameter in this model. Inter-granular exchange was varied as a percentage of the intra-granular value, and the resultant effect on loop shape is evident in Figures 6(a)-6(d). Table II summarizes the hysteresis loop characterization.

The micromagnetic model provides for simulation of a thermomagnetic recording process by incorporating steady-state medium thermal profiles transcribed from a separate medium thermal model (see Ref. [14]), and by imposing writing fields from a specified recording head. The relative positioning of the two fields in the medium can be set to explore potential design issues for an integrated hybrid recording transducer. For the recording simulations that follow, a steady-state thermal profile in the medium is created by a 10 milliwatt laser beam focused to a spot of 700 nm FWHM. The peak temperature at the thermal field's center was 658K. The coercivity of the magnetic recording layer was simulated with a linear decrease versus temperature to match curves measured experimentally with a VSM. The aim of the recording simulations was to explore the apparent quality of the recorded domains and transitions, given a range of modifications in the magnetic design of the media films.

Recording system parameters incorporated in the model are listed in Table I. Given the perpendicular anisotropy and its dispersion built into the recording medium, we expect that the vertical magnetic field of the head, along with the thermal profile in the medium, are the most significant determinants of the global recorded domain shapes. Additionally, the detailed structure of magnetization transitions in the medium should be governed by the medium grain structure, intergranular exchange, and medium demagnetization effects.

Figure 7 shows simulated, statically recorded patterns using a single pole head on heated media with an SUL. For this combination of head field and medium heating chosen, the writing quality was excellent on this exchange-decoupled medium. Notice that the transition on the trailing (left) edge of the pole head (footprint shown in outline) is smooth and sharp, corresponding to low noise, high signal contrast recording.

Figure 8 illustrates a short sequence of simulated, recorded patterns using a Lindholm inductive ring head writing on moving perpendicular media without an SUL. For the chosen combination of head deep gap field and medium heating, the writing quality was poor on this highly exchange-coupled medium. The transitions are very ragged, with magnetic percolation from grain to grain being evident. We see curvature of reversed domain as observed in our spinstand experiments.

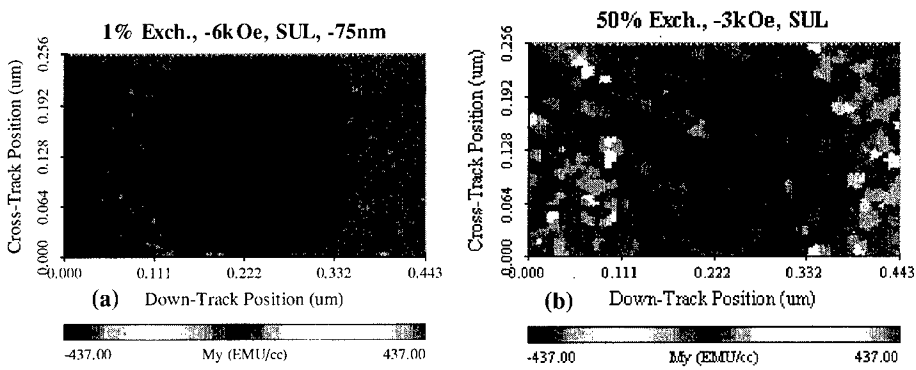

Figure 7. Simulated thermomagnetically written marks on perpendicular media with 10 nm mean grain size on an SUL, using a square footprint pole head of edge length 200 nm. Center of 700 nm FWHM heating spot is 75 nm to right of pole head center, and medium velocity is zero. (a) Medium with inter-granular exchange of 1% of the intra-granular value. Notice that the left edge of the reversed domain is written sharply and smoothly due to high field and temperature gradients. (b) Same situation, except with medium having 50% inter-granular exchange. Note the uncontrollable writing as the grain switching percolates beyond the edge of the pole head, and into the hotter zones toward the right. The transition zone on the left edge is ragged (noisy).

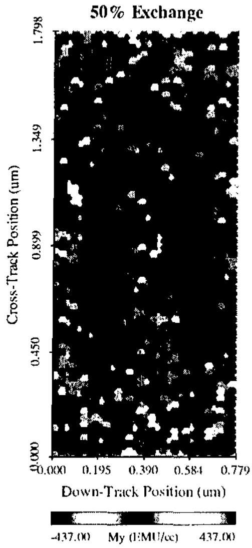

Figure 8. Simulated thermomagnetically written marks on perpendicular media with a rather large 28 nm mean grain size, using the Lindholm ring head in Table I. Center of 700 nm FWHM heating spot is in the gap center, and medium velocity is 10 m/s from right to left. The medium had inter-granular exchange of 50% of the intra-granular value. The writing quality is fairly poor since the head field strength was set very low (4kOe). Granular percolation is evident, and transition zone is ragged (noisy).

A single particle thermomagnetic model [11] was constructed to further investigate the interplay of temperature and head magnetic field, along with magnetization reversal dynamics. A modified form of the Landau-Lifshitz-Gilbert (LLG) with an added term to reflect finite temperature effects of the medium thermal bath was employed [15]. Magnetic parameters of the switching particle were allowed to be temperature-dependent, and the history of the thermal and writing (magnetic) fields at the site of the particle moving under a hybrid recording head were tracked. We simulated an assumed future high-density recording configuration in which a heating, near-field, Gaussian optical beam of 50 nm FWHM was used in conjunction with a magnetic head capable of producing field gradients on a similar length scale.

Figure 9(a) shows the thermal history of the particle as the heating beam moves over it, along with some assumed temperature-dependent magnetic parameters of the particle. We found in thermal modeling that the depicted temperature rise was achievable with an integrated optical

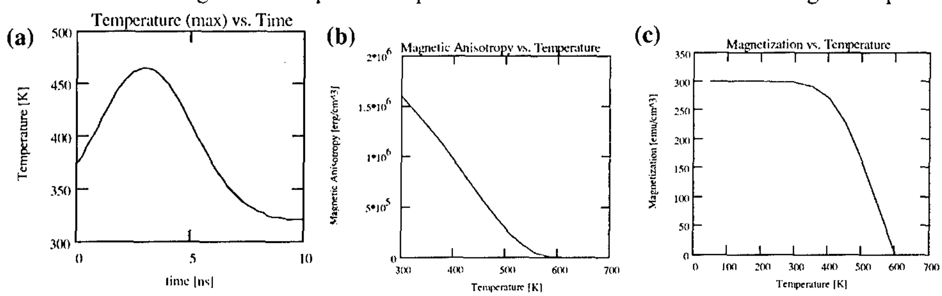

Figure 9. (a) Thermal history of a magnetic particle moving at 10 m/s below a 50 nm Gaussian heating beam on a well heat sunk medium. Ambient temperature is 320K. (b), (c) Assumed temperature dependence of the particle's magnetic anisotropy K_u and saturation magnetization M_s.

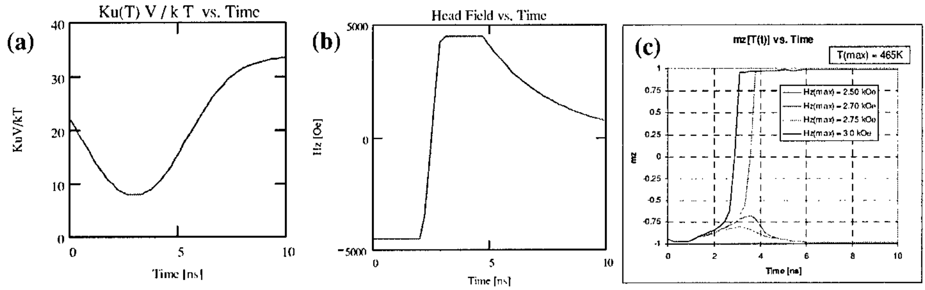

Figure 10. (a) Temperature dependence of magnetic particle's thermal stability parameter K_uV/k_BT. (b) An example of the head field experienced by the particle in the moving medium. (c) An example of the sensitivity of the particle's magnetization reversal to applied head field according to the LLG equation for a peak temperature of 465K during the switching sequence.

power of 1-2 mW in the 50 nm beam. Figures 9(b) and 9(c) show the assumed temperature dependence of the particle's magnetic anisotropy and magnetization.

Figure 10(a) gives the particle's thermal stability energy ratio K_uV/k_BT versus time for the thermal history of Figure 9(a), using $K_u(T)$ of Figure 9(b). An example vertical head field history in Figure 10(b) will induce particle switch when combined with a suitable magnetic "softening" due to particle heating. Finally, in Figure 10(c) we see an example of the onset of particle magnetization reversal as the applied head field becomes sufficiently strong at a peak medium temperature of 465K. With this model, one can study the tradeoffs of head field strength versus medium temperature for fast particle switch. Additionally, with the thermal decay term in the modified LLG equation, the impact of excess or prolonged heating on particle thermal stability during and immediately after writing is accessible.

SPINSTAND RECORDING TESTING

Previous hybrid recording experiments in a spinstand environment were reported [9,13]. Successful thermomagnetic recording on both longitudinal and perpendicular media was shown. The Co-alloy longitudinal media tested was well-engineered for product application, and showed excellent SNR performance due to its refined crystalline structure with low inter-granular exchange coupling. The Co/Pt multilayer perpendicular media evaluated consisted of laboratory samples which were fabricated to have relatively high coercivity, but which had not undergone extensive materials engineering to establish exchange decoupling among the crystalline grains. Consequently, this media was useful for demonstrating the principle of thermally-assisted writing, but it did not exhibit remarkable SNR performance due to the relatively large inter-granular exchange.

We anticipate future recording testing work on the materials reported in this paper, which is expected to yield improved SNR performance in hybrid recording. This prediction is supported by the recording simulations reported above.

SUMMARY AND CONCLUSIONS

We have undertaken experimental materials development of Co/Pd multiplayer samples for use in hybrid magnetic recording. We prepared coupon samples that met design targets for reduction of inter-granular coupling and improvement of magnetic stability in thermal cycling. Disk samples with these coatings were prepared to have mechanical and magnetic properties suitable for spinstand testing. Computer simulations of the Co/Pd material's magnetic hysteresis and thermomagnetic recording performance helped guide our materials development work. The recording simulations showed that reduction of inter-granular exchange coupling should result in excellent media SNR performance, since recorded transitions will be smooth and free of large, irregular magnetic clusters due to unwanted coupling. Modeling was helpful in illustrating the recording performance improvement enabled by reducing the breadth of the distributions of key media material magnetic and structural parameters, such as magnetic anisotropy strength, anisotropy axis alignment, and grain size. The simulations also clarified the importance of proper setting and co-location of the thermal and magnetic field gradients in the hybrid recording process.

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