

Heat-assisted magnetic recording

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The conventional magnetic recording has approached its physical limits. Further growth of the areal density is limited by the superparamagnetic effect and by the limited possibilities to further improve write heads design and pole materials in order to enhance the writing field. New technologies are needed to surpass these limits. Such an alternative is the *heat-assisted magnetic recording* (HAMR), which promises areal densities of more than 1 Tb/in². HAMR allows use of very small-grain media, required for recording at ultra-high densities, with a larger magnetic anisotropy, thus assuring a sufficient thermal stability, while the local optical heating leads to a temporary magnetic softening of the medium. The principle of HAMR and the structure of a HAMR system are discussed, as well as the requirements for the materials needed for this type of recording. An important aspect of HAMR is then analyzed: laser assisted writing provides an additional degree of freedom during writing, but it could lead to an increased thermal relaxation rate of the magnetization on the just written track or on the adjacent tracks. The possible write methods, a proposed head design, and the effects of the temperature distribution in the medium are then presented. An analytical prediction of the transition parameter on the basis of a modified Williams–Comstock model is presented. The last section summarizes the up-to-date results and the foreseeable challenges of the HAMR technology.

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1. Introduction

With the longitudinal magnetic recording, the maximum attainable areal recording density has been assessed as physically limited to about 100 Gb/in². Further growth of this density is limited, firstly by the superparamagnetic effect, but, also by the limited possibilities to further improve writing heads design and pole materials in order to enhance this field.

Perpendicular magnetic recording has also made significant progress, recently resulting in high-density commercial disk drive products, with areal density of about 300 Gb/in². But there still remain some important factors limiting its performance, as, for instance, jitters that lower the signal-to-noise ratio (SNR). The anisotropy field of the granular media, the saturation induction of existing materials, the head-medium spacing, and the geometry of the magnetoresistive (MR) heads are the main factors that determine the jitter configuration [1]. With the current values of these parameters, the conventional perpendicular recording seems to be limited to a maximum areal density of about 500 Gb/in².

Obviously, an alternative technology is needed to overcome this limit. Such an alternative is the *heat-assisted magnetic recording* (HAMR), which is a combination of magnetic and optical recording technology and promises areal densities of more than 1 Tb/in². HAMR allows the use of very small-grain media, required for recording at ultra-high densities, with a larger magnetic anisotropy, assuring a sufficient thermal stability, while the local optical heating of the medium leads to its temporary magnetic softening [2].

Firstly, the principle of HAMR and the structure of a

HAMR system are discussed, as well as the requirements for the materials needed for this type of recording (Section 2). An important aspect of HAMR is then analyzed (Section 3): whereas laser assisted writing provides an additional degree of freedom during writing, it could lead, on the other hand, to an increased thermal relaxation rate of the magnetization which has just been written on the recorded track or on the adjacent tracks.

Sections 4 and 5 give an overview of the possible writing methods and a proposed head design, whereas the effects of the temperature distribution in the medium are summarized in Section 6. Section 7 contains an analytical prediction of the transition parameter on the basis of a modified (thermal) Williams–Comstock model. The last Section summarizes the up-to-date results and the foreseeable challenges of the HAMR technology.

2. Principle of HAMR

The principle of HAMR is not too different from that of the magneto-optical (MO) recording. It is based on the fact that the intrinsic magnetic properties of the medium (saturation magnetization M_s , anisotropy field $H_K = 2K / \mu_0 M_s$, and coercive field H_c) decrease drastically as the temperature T of the material increases. Thus, heating the medium locally to a temperature T_w sufficiently elevated, close to the Curie point T_C , decreases the coercive field $H_c(T_w)$ of the medium below the writing field H_w and the magnetization of the grains situated in the heated area becomes oriented along the writing head field. But then the locally heated region must be rapidly

cooled to the room temperature T_{amb} , in order to ensure again a high $H_c(T_{\text{amb}})$ coercive field that freezes this orientation of the media grains.

The main difference between HARM and MO recording is the method used for reading back the recorded information: In the latter case, MO methods are used whereas in HAMR one uses MR heads. The immediate issue is that HAMR can ensure higher SNRs and thus, higher areal recording densities. The novelty of the HAMR technology consists thus in the extreme reduction of spatial and temporal scales.

Taking into consideration the aforementioned observations, it results that a HAMR system must add to a conventional magnetic recording system the potential to heat rapidly extremely small regions of the medium, where the grain magnetization will be easily oriented along the head writing field. This heating source is usually a highly focalized light spot: a laser delivered into a special shaped waveguide.

Materials used for HAMR must have the highest uniaxial anisotropy constant K_u possible and also a large dependence on temperature of the switching field. Some materials have been known for a long time as having large values of their anisotropy constants ($7 \cdot 10^5 \text{ J/m}^3$ for the FePt alloy) at operating temperature, due to their chemically ordered structure. Or, the maximum recording density attainable is roughly proportional to the value of K_u [3]. To operationalize these high values of anisotropy, the grain size must be lowered below 50 nm.

Another advantage of HAMR is the fact that writing on the media with high K_u and with very low grain size allows the use of field gradients much steeper than in the case of conventional perpendicular recording. The total writing field gradient for HAMR represents a difference of two terms: the head field gradient, dH_h/dx , and the temperature gradient dT/dx times the variation of the coercive field H_c with temperature,

$$\frac{dH_{\text{tot}}}{dx} = \frac{dH_h}{dx} - \frac{dH_c}{dT} \frac{dT}{dx}. \quad (1)$$

Then, a large temperature gradient dT/dx is suitable for both the down and cross-track directions, which was proved experimentally [1].

3. Comparison of HAMR with Conventional Magnetic Recording

One considers the writing of a single track of a thin-film medium which consists of single-domain particles, not exchange coupled; also, it is supposed that grains switch by coherent rotation. It is assumed that the maximum possible areal recording density D is determined by the SNR of the medium, which is limited, in turn, by thermal relaxation effect. The minimum volume of the grain, V_{min} , is imposed by the requirement that the recorded signal can be found again with an acceptable error after a sufficiently long time t_s . The medium has at the writing temperature T_w

a coercive field much smaller than the one at the operating temperature T_s . At the frequencies presently used ($< 1 \text{ GHz}$) and for the current values of the anisotropy field of the media in use today, the coercive field H_c equals H_K .

To make a correct comparison between recording densities in the case of HAMR (index h) and conventional perpendicular magnetic recording (index c) we suppose:

- all the geometrical parameters of the recording system (medium film thickness, track width, head–medium spacing, etc.) scaled linearly by the same ratio;
- the same SNR of the medium.

The best measure of this comparison is the ratio of the highest possible areal recording densities of the two recording modes [4]:

$$Q_{h/c} = \frac{D_h}{D_c} = \left(\frac{V_{\text{min},c}}{V_{\text{min},h}} \right)^{2/3}, \quad (2)$$

named *relative density advantage*.

Thermal relaxation of the magnetization in the presence of a demagnetizing field H_{dm} is expressed in terms of the Arrhenius–Néel–Brown mode

$$M(t) = M_s \{ -1 + 2 \exp[-f_0 t \cdot \exp(-\Delta W_b / k_B T)] \}; \quad (3)$$

f_0 is the standard reversal frequency and

$$\Delta W_b = KV \left(1 - \frac{H_{\text{dm}}}{H_K} \right)^2 \quad (4)$$

is the reversal energy barrier. The minimum grain volume required for a correct retrieval of the recorded signal after the time t is:

$$V_{\text{min}} = \frac{k_B T}{K} \ln(f_0 \tau q) \left(1 - \frac{H_{\text{dm}}}{H_K} \right)^{-2}, \quad (5)$$

where $q = \left(\ln \frac{2}{p+1} \right)^{-1}$ and p is the fraction of the

saturation magnetization M_s that should remain before SNR of the medium becomes too small due to thermal relaxation. One makes the comparison expressed by $Q_{h/c}$ under the following constraints concerning the properties of the media:

- (i) $H_{K,h}(T_w) = H_{K,c}(T_s)$;
- (ii) $M_{s,h}(T_w) = M_{s,c}(T_s)$;
- (iii) $\max(M_{s,h}(T')/H_{K,h}(T')) \leq M_{s,h}(T_w)/H_{K,h}(T_w)$, for $T_s < T' < T_w$.

Assuming the same head field, (i) and (ii) assure the same writing conditions and, therefore, equal transition lengths at T_w . The transition length is roughly equal to half the grain diameter plus a term proportional to M_s/H_K ratio [5]. Condition (iii) assures that the transition does not widen after writing.

The three conditions lead therefore to the assumption of equal transitions at the temperature T_s ; besides, conditions

(i) and (ii) imply $K_h(T_w) = K_c(T_s)$ and (i) assures a coercive field equal or proportional to the anisotropy field. (This last conclusion is not valid if the *coefficient of thermal stability* $\kappa = K_u V / k_B T < 30 \dots 50$ at T_w and at the same time the writing pulses are high as compared to $1/f_0$ [6].)

For most recording media, M_s decreases with increasing T_{amb} , so that, if the three constraints are satisfied, we have

$$M_{s,c}(T_s) < M_{s,h}(T_s) \leq \frac{H_{K,h}(T_s)}{H_{K,h}(T_w)} M_{s,c}(T_s). \quad (6)$$

The good value of the $Q_{h/c}$ ratio is then accompanied by another important advantage: a much larger saturation magnetization at the temperature T_s ; this fact is useful when the SNR of the system is due to the read head and to the electronic parts of the system, not only to medium.

For conventional perpendicular magnetic recording the largest demagnetizing field occurs near transitions and at half the distance between two successive transitions, respectively. In both points this field H_{dm} is proportional to M_s , the proportionality factor depending only on the geometry of the system [5] and, therefore, remaining the same.

Let be $Q_{h/c}$ the ratio corresponding to a linear decrease of the temperature just after writing:

$$\begin{aligned} T(t) &= T_w + (T_s - T_w) \frac{t}{t_c}, & t < t_c; \\ T(t) &= T_s & t > t_c, \end{aligned} \quad (7)$$

where t_c is the *cooling time* up to the operation temperature T_s . The minimum volume V_{min} of a grain is the solution of the implicit equation

$$M(t_s, V_{\text{min}}) / M_s = p, \quad (8)$$

using also the differential form of equation (2). At $t = t_s$, the magnetization becomes then pM_s . For instance, assuming $T_w = 450$ K, $T_s = 300$ K, $t_s = 10$ years and $f_0 = 10^9$ s⁻¹, with $p = 0.8$, it results the curves represented in Figure 1, if $H_{K,h}$ and M_s decrease linearly with temperature with a factor $H_{K,h}(T_s)/H_{K,h}(T_w) = z = 2 \dots 10$ [4]. If t_c is a few nanoseconds and if $H_K(T_s)$ is at least 5 times larger than $H_K(T_w)$ (or $K_h(T_s) \approx 25K_h(T_w)$), it is obtained $Q_{h/c} > 8$.

The curves prove the existence of two possible regimes. The best $Q_{h/c}$ results from the *fast cooling regime* [4]. The cooling time t_c to T_s is so short that no significant thermal relaxation occurs and $Q_{h/c}$ is independent on t_c . During the rest of the storage period only the relaxation at ambient temperature occurs. According to equation (5), V_{min} is smaller by a factor $K_h(T_w)/K_h(T_s)$ than in the case of the best possible conventional medium. In the limit $t_c \rightarrow 0$, we have then:

$$Q_{h/c} = [K_h(T_s)/K_h(T_w)]^{2/3} = z^{4/3}, \text{ with}$$

$$K \propto H_K M_s \propto H_K^2. \quad (9)$$

In the other regime, the *slow cooling regime*, the $Q_{h/c}$ ratio decreases with increasing cooling time t_c . The value of t_c above where relaxation takes place during cooling depends on factors p, z and f_0 . In this case, it follows [7]:

$$Q_{h/c} = \left[\frac{T_s}{T_w} \frac{\ln(qf_0 t_s)}{\ln(qf_0 t_w)} \right]^{2/3}, \quad (10)$$

where t_w is the effective time after writing during which relaxation takes place if $T = T_w$. Consequently, $T = T_w$ for $0 < t < t_w$, while for $t > t_w$ relaxation is negligible.

The dashed curve in Figure 1 proves that if $t_w = t_c$ equation (10) underestimates $Q_{h/c}$.

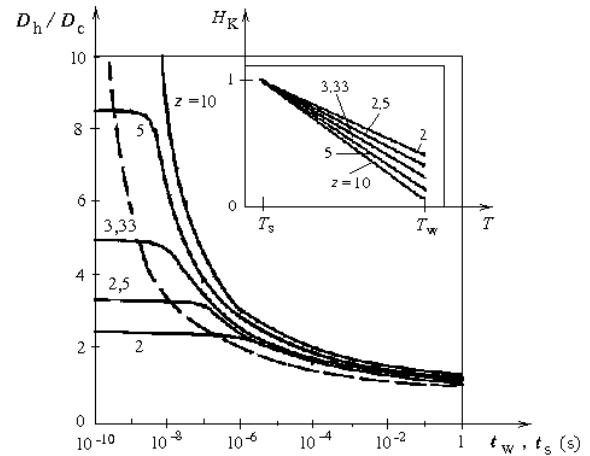


Fig. 1. Density ratio $Q_{h/c}$ for values of the medium parameters as specified in the text, and for linear cooling after writing within a time t_c . The dashed curve, corresponding to equation (10), is a function of the effective time during which the medium is at the writing temperature T_w .

The value of t_c at which the two regimes crossover decreases with increasing f_0 . So, if $H_K(T_w)/H_K(T_s) = 5$ and if f_0 is increased from 10^9 s⁻¹ to 10^{10} s⁻¹, it results a change by a factor equal to about 10. For $t_c = 1 \dots 10$ ns, the $Q_{h/c}$ ratio decreases drastically. In fact, the estimate $f_0 \approx 10^9$ s⁻¹ [8] is based on the expression $f_0 \approx \alpha \gamma H_K$ [9], used in the case of current Co-based longitudinal media ($\alpha \approx 0.01$ is the damping constant for magnetic precession, γ is the gyromagnetic ratio and $H_K \approx 480$ kA/m). The use of media with a much higher product $H_{K,h}(T_w)$ is then not suitable for HAMR. The prediction concerning $Q_{h/c}$ ratio can be improved if one considers the dependence on the temperature T of the standard frequency f_0 , according to $\alpha(T)H_K(T)$.

4. Writing Methods

If diode laser sources and conventional optics are to be used for the writing process of HAMR, there is an important problem to overcome: the diffraction limit. Subdiffraction limit optics suggests near-field (NF) optical approaches. For areal density beyond 1 Tb/in², HAMR requires optical spot sizes less than 50 nm. Lenses, apertures, antennas and waveguides were all been successively considered, as possible solutions for light confinement with high efficiency (see [10]).

There are several ways to realize HAMR. Some of these methods are shown schematically in Figure 2.

The first method uses a combination of a focused laser spot with a coil that supplies the writing field (fig.2,a), as in the case of MO recording. The track width is then the same as the spot diameter. The solution was deeply investigated, using perpendicular amorphous rare-earth (RE) – transition-metal (TM) multilayered media; the readout uses the magnetic flux (and not the Kerr effect). The main disadvantage of this solution is that the recorded bits are crescent shape and therefore are less adequate for readout with MR heads.

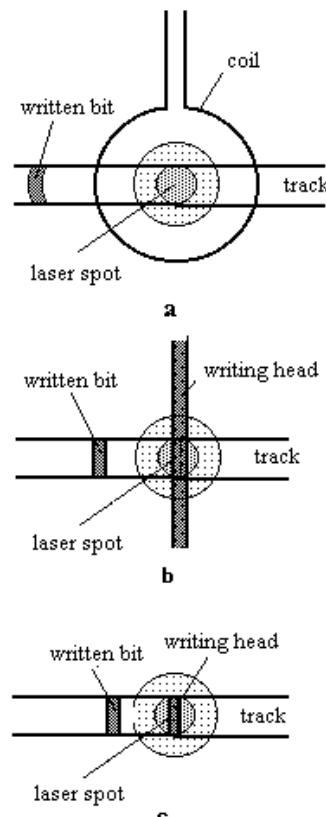


Fig. 2. Schematic representation of some methods to realize HAMR.

This disadvantage disappears when a conventional magnetic writing head is used (fig.2,b) [11]. If the light spot is correctly focused, its width will determine the track width.

The track width can be magnetically determined (fig.2,c). This is a very advantageous solution if track widths below 100 nm are required. Or, normally, even a NF optical recording using a blue light ($\lambda \approx 400$ nm) and a planar solid immersion mirror with a good numerical aperture (of value 2.0) does not assure a spot diameter below 120 nm. Fortunately, one can reduce the poles size below 100 nm using focused ion beam patterning.

The analysis allows the definition of the following requirements for the writing device [4]:

i. The head and the light source must be on the same side of the disk. This configuration would result in a smaller total volume of the system, would make possible the NF optical recording and would permit a permanent alignment of the head with the light spot.

ii. The light spot does not extend over the adjacent tracks, because their strong and frequent heating is dangerous from the viewpoint of the thermal relaxation.

iii. The writing field must cover only the track to be recorded, because its extension to the adjacent tracks can enhance the thermal relaxation effect added to the weak (but repeated) heating due to thermal diffusion out of the recorded (directly heated) track. It is preferable that the diameter of the spot and the magnetic pole size be equal.

iv. The light spot should not heat the already recorded bits. From this viewpoint, the center of the spot must be localized near the trailing edge of the pole tip and its length must be as small as possible, maximum the double of the spot shift. Thus it is obtained a reduction of the time between heating and writing. It becomes then possible to use media with large thermal diffusivity, resulting in a short cooling time and an enhanced $Q_{h/c}$ ratio.

So it is convenient to design a HAMR system made up by a slider carrying an integrated configuration of a NF light source and a magnetic writing/reading head. The widths of the spot and of the writing head must be equal to the track width (see figures 2,b and 2,c), with a slight shift of the spot toward the trailing edge of the head.

5. Integrated Head for HAMR

Taking into consideration the previous conclusion, a possible option for the integrated head is as follows [4].

The simplest form of the device is a multilayered structure that consists of a central dielectric layer with a high refractive index, framed by two adjacent dielectric layers with a lower refractive index. The adjacent layers can also be metallic, although this solution is less convenient, because it leads to a decrease of the transmission efficiency. The planar wave-guide is connected to a laser by an optical fiber. A practical possible configuration is represented in Figure 3 [4].

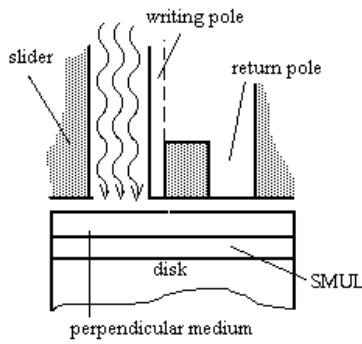


Fig. 3. A possible configuration of a perpendicular HAMR head. The pole-type head is integrated with a light guide adjacent to the writing pole.

The device assures a much higher $Q_{h/c}$ ratio than in the case of longitudinal recording. For perpendicular recording the thermal instability limits the areal density to maximum 500 Gb/in² [12]. Assuming a bit aspect ratio of 4, at this density the distance between two neighbor transitions is less than 20 nm and the thickness of the writing pole along the track is of (20...50) nm. The pole acts as a metallic cladding layer, partially transparent.

An optical modeling of a configuration in which the pole layer is combined with a very thin second layer, made from Ag, [4] proves that the highest heating of the Ag layer is obtained at less than 80 nm from the trailing edge. This result is very convenient, because it becomes possible the use of media with cooling time of maximum (3 ... 5) ns, while the heating of the writing pole allows the use of materials with high saturation magnetization M_s and an anisotropy field H_K much smaller at the operating pole temperature (higher than the room temperature). (At room temperature H_K of the presently available high M_s materials is too high.) At the same time, the use of the Ag layer, which is a good thermal conductor, allows a better control of the temperature of the pole.

It is of special importance to realize a suitable shape of the spot along the track width direction. For this purpose it has been proposed a planar waveguide configuration with mode index lens, but one should also explore a possible convenient patterning of this part of the waveguide that is near the air bearing surface of the head – the combined solution assuring a very good alignment. Another approach can be the use of a laser of very small aperture mounted on the slider [4]. Nevertheless, in this case one must study the problem of the smallest possible distance between the head and the aperture, to obtain a small cooling time, as well as the effect of power dissipation of the laser on the temperature of the slider.

6. Effect of Temperature Distribution on the Recording Medium

An important problem to address is if cooling times of

maximum few nanoseconds are possible for realistic media, because such times are required to obtain good values of the $Q_{h/c}$ ratio. Calculus performed concerning the temperature distribution in the case of perpendicular recording media of RE-TM – type [4] proves that:

i. In the spot middle, the increase of the temperature during the exposure to the spot action depends on the disk speed; about half of the power spot is dissipated into the disk, while the rest is reflected.

ii. The anisotropy has not a significant effect.

iii. When one use glass substrate (thermal conductivity 1 W/mK, calorific capacity 1.3 MJ/m³K), the curves $T(t)$ are 3 times broader than when an Al substrate (thermal conductivity 237 W/mK, calorific capacity 2.38 MJ/m³K) is used.

iv. The effect of the substrate is reduced, due to the presence of the soft magnetic underlayer (SMUL) lying under the recording layer, which is a good thermal conductor.

Therefore, the proposal cooling times are perfectly possible.

For HAMR with an areal density at least 2 times higher than the forecast accepted for the conventional perpendicular recording, the bit length will be of maximum 18 nm.

7. Modeling the HAMR Writing Process

An important advantage of HAMR is the chance to enhance writing resolution as the areal recording density is increased. The current measure of this resolution is the minimum bit size l_{bit} that can be reliably recorded, but only if the bit frontier is sharply defined as well. In other words, the transition length parameter a must be much smaller than the minimum bit length, $a \ll l_{bit}$. Associated with the ability to reduce the parameter a is a small variance on the location of the transition center x_0 . That is why, the ratio l_{bit}/σ is often considered a good measure of SNR. Therefore, it is reasonable to expect that $\propto a$.

In classical recording theory [2], on a continuous medium, the transition parameter a is related to $(dH_w/dx)^{-1}$. But this theory must be seriously amended if one takes into consideration the variable heating of the medium, with the corresponding dependences of the intrinsic magnetic parameters on temperature.

Indeed, in the classical Williams-Comstock (W-C) model, only the knowledge of the $M \propto H$ loop of the medium is needed to calculate the transition parameter a , because one assumes that the behavior of the medium is everywhere described by this loop. In the case of the HAMR system the situation is rather different, because the heating of the medium during writing modifies its magnetic properties. This is represented in figure 4, where two idealized $M \propto H$ loops of the same medium are drawn: (1) corresponding to a lower temperature T_1 and (2) corresponding to a higher temperature T_2 , where remanent magnetization M_r and coercive field H_c are lower. As a result, compared with the classical model W-C, in equation

$$\begin{aligned} \frac{dM(x)}{dx} &= \frac{dM(H)}{dH_{\text{tot}}}\bigg|_{H_c} \cdot \frac{dH_{\text{tot}}(x)}{dx}\bigg|_{x_0} = \\ &= \frac{dM(H)}{dH_{\text{tot}}}\bigg|_{H_c} \cdot \left[\frac{dH_w(x)}{dx}\bigg|_{x_0} + \frac{dH_{\text{dm}}(x)}{dx}\bigg|_{x_0} \right]; \quad (11) \end{aligned}$$

the temperature must be taken into account explicitly. In equation (11) the total field H_{tot} is written as a sum of the applied field (of the head) H_w and of the medium demagnetization field H_{dm} . Instead of the loops $M \propto H$, the loop $M \propto h$ (fig.4, b) can be considered, with

$$h(x) = \frac{H_{\text{tot}}(x)}{H_c(T(x))}, \quad (12)$$

where the coercive field H_c depends on the position x by means of the temperature T . The medium is now saturated to an *effective field* $h = 2 - S^*$, where S^* is the dimensionless rectangularity factor of the loop $M \propto H$.

According to equation (5), it is then possible that:

- either, at a given coercive total field H'_c , the medium be saturated at a total field $H_{\text{tot}} = (2 - S^*)H'_c$,
- or, vice versa, at a total field H'_{tot} , the coercivity be reduced by heating the medium at the value $H_c = H'_{\text{tot}}/(2 - S^*)$.

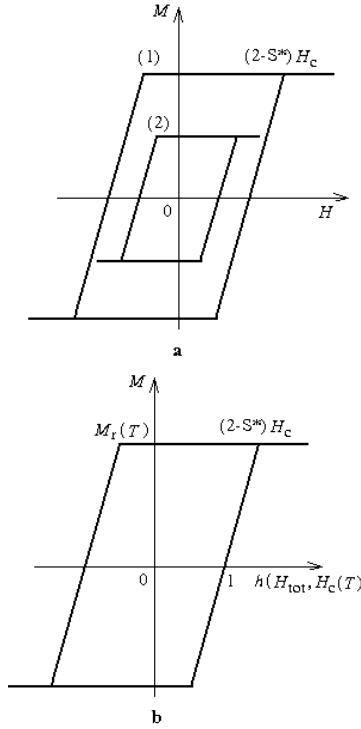


Fig. 4.a. Loops $M \propto H$ of the medium at two different temperatures, $T_2 > T_1$. b – Loop $M \propto H$ normalized with H_c ; both M and h depend on the temperature.

The equation of the classical model W-C,
 $M(x) = M[H_{\text{tot}}(x)] = M[H_w(x) + H_{\text{dm}}(x)]$
must now be written as

$$M(x) = M[h_{\text{tot}}(x)]. \quad (13)$$

Noting with $T_0 = T(x_0)$ the temperature of the medium in the transition centre x_0 , where $H_w(x_0) + H_{\text{dm}}(x_0) = H_c(T_0)$, by deriving the equation (13) we obtain:

$$\frac{dM(x)}{dx}\bigg|_{x_0} = \frac{dM(h)}{dh}\bigg|_{H_c} \cdot \frac{dh(x)}{dx}\bigg|_{x_0}. \quad (14)$$

For the idealized loop $M \propto h$ it results

$$\frac{dM(h)}{dh}\bigg|_{H_c(T_0)} = \frac{M_r(T_0)}{1 - S^*(T_0)} = H_c(T_0) \cdot \frac{dM(H)}{dH_{\text{tot}}}\bigg|_{H_c(T_0)} \quad (15)$$

And

$$\begin{aligned} \frac{dh(x)}{dx}\bigg|_{x_0} &= \frac{1}{H_c(T_0)} \times \\ &\times \left[\frac{dH_w(x)}{dx}\bigg|_{x_0} + \frac{dH_{\text{dm}}(x)}{dx}\bigg|_{x_0} - \frac{dH_c(T)}{dT}\bigg|_{T_0} \cdot \frac{dT}{dx}\bigg|_{x_0} \right]. \quad (16) \end{aligned}$$

Then, the new form of the equation W-C of the slope is obtained [13]:

$$\begin{aligned} \frac{dM(x)}{dx}\bigg|_{x_0} &= \frac{dM(H)}{dH_{\text{tot}}}\bigg|_{H_c(T_0)} \times \\ &\times \left[\frac{dH_w(x)}{dx}\bigg|_{x_0} + \frac{dH_{\text{dm}}(x)}{dx}\bigg|_{x_0} - \frac{dH_c(T)}{dT}\bigg|_{T_0} \cdot \frac{dT}{dx}\bigg|_{x_0} \right]. \quad (17) \end{aligned}$$

In the absence of any thermal gradient, (17) is reduced to the classical formula. The magnetization and demagnetizing field gradients do not appear explicitly, but they contain implicitly a term dependent on the temperature gradient.

To solve the equation (17) a form of transition must be supposed a priori. Traditionally, it was considered the *arctangent* function which follows closely the head field (the Karlqvist' proposal), although other functions were also used (see [14], p.100). In the case of HAMR it is not necessarily required that the transition should follow exactly the form of the head field; in certain conditions, it can follow even the thermal profile. But, if the thermal gradient is not too sharp, compared with that of the head field, the transition takes the form in *arctangent* of the head field. During recording, magnetization is reduced by heating and this is an issue to take into account when the transition is formed. Thus, in the case of a large spot, when the head field gradient is dominant, the transition during recording can be described by equation

$$M(x) = \frac{2}{\pi} M_r(T(x)) \cdot \tan^{-1} \frac{x - x_0}{a}. \quad (18)$$

Just as in the classical model, the transition described by equation (18) is centered in x_0 , its length being roughly equal to πa . The equation (18) describes the transition only in the recording stage, after the transition is recorded the magnetization going back to the value corresponding to the room temperature, so that M_r of (18) must be $M_r(T_{\text{amb}})$ everywhere; thus, parameter a returns to the value corresponding to the classical model, which does not take into account any mechanism that takes into consideration magnetization losses, that is the transition broadening during cooling and removal of the field.

The value of the derivative of equation (18) in the transition center $x = x_0$ is:

$$\left. \frac{dM(x)}{dx} \right|_{x_0} = \frac{2}{\pi a} M_r(T_0). \quad (19)$$

The slope of the hysteresis loop in the coercivity point results from equation (15):

$$\left. \frac{dM(H)}{dH} \right|_{H_c(T_0)} = \left| \frac{M_r(T_0)}{H_c(T_0)(1 - S^*(T_0))} \right|. \quad (20)$$

Whatever the orientation (sign) of H_c , expression (20) is positive, because the slope of the loop in this point is always positive (fig.4).

Adopting, just as in the classical W-C model, Karlqvist's expression for the longitudinal component of the head field, it results:

$$\left. \frac{dH_w}{dx} \right|_{x_0} = -\frac{Q}{y} H'(T_0), \quad (21)$$

where [15]:

$$Q = \frac{1}{\pi} \frac{x_0}{g} \frac{H_g}{H'(T(x_0))} \sin^2 \frac{\pi H'(T(x_0))}{H_g} \quad (22)$$

and to $x = x_0$, $H' = H_c - H_{\text{dm}}$. In the case of a symmetrical transition, $H_{\text{dm}} = 0$, it results $H' = H_c$.

The demagnetizing field of a step-transition located in the origin is:

$$H_x^{\text{tr}}(x) = \frac{1}{\pi} \tan^{-1} \frac{\delta}{2x}, \quad (23)$$

δ is the medium thickness. For any shape of the transition, the demagnetizing field can be found using the method of the transitory response to the step-unit function [13]:

$$H_{\text{dm}}(x) = -\frac{\partial M(x)}{\partial x} \otimes H_x^{\text{tr}}(x), \quad (24)$$

where \otimes signifies the convolution integral.

In the case of large spots, the thermal gradient is low, and the approximate expression of the demagnetizing field gradient in the transition centre is:

$$\left. \frac{dH_{\text{dm}}(x)}{dx} \right|_{x_0} = -\frac{2}{\pi} \frac{\delta}{a \left(a + \frac{\delta}{2} \right)} M_r(T_0). \quad (25)$$

Location of the transition centre x_0 . In the classical model, there were no thermal gradients, $dT/dx \equiv 0$, and the demagnetizing field is antisymmetrical relative to the transition centre, $H_{\text{dm}}(x_0) = 0$. The location of the transition results by determining the point in the medium where the head field is equal to the remanent coercive field $H_{c,r}$, typically approximated by H_c , $H_w(x) = H_{c,r} \cong H_c$.

Including the thermal term $dT/dx \neq 0$ interferes with the antisymmetry of the demagnetising field about the transition centre. Indeed, the heating of the medium results in a decrease of magnetization and thus of the demagnetizing field. If the thermal profile is shifted from the transition centre, the decrease of the magnetization is no longer symmetrical and the demagnetizing field will be non-zero in the transition centre, its zero being slightly shifted. In the case of HAMR, the location x_0 of the transition results, then, from condition:

$$H_c(T(x_0)) = H_w(x_0) + H_{\text{dm}}(T(x_0)). \quad (26)$$

For a recording with large spot, the thermal gradient is small and for transitions recorded at temperatures much below the Curie temperature T_C of the medium, the effects of the demagnetizing field can be neglected,

$$H_c(T(x_0)) \cong H_w(x_0), \quad (27)$$

equation that can be solved numerically for x_0 , if the profile of the thermally induced coercive field of the medium is known. With (27), it results $H' \cong H_c$. Without this simplification, the transition location depends as well on the parameter a through the demagnetizing field.

The thermal W-C model. By replacing the precedent results in (17) we obtain:

$$\frac{2}{\pi a} M_r(T_0) = \left| \frac{M_r(T_0)}{H_c(T_0)(1 - S^*(T_0))} \right| \times \left[-\frac{\beta}{y} |H_c(T_0)| - \frac{\delta}{\pi a \left(a + \frac{\delta}{2} \right)} M_r(T_0) \right], \quad (28)$$

where the parameter

$$\beta = -\frac{H_c}{|H_c(T_0)|} Q - \frac{y}{|H_c(T_0)|} \left. \frac{dH_c}{dT} \right|_{x_0} \cdot \left. \frac{dT}{dx} \right|_{x_0} \quad (29)$$

takes into account both the effect of the head field gradient and that one of the thermal gradient.

From equation (28) it results:

$$a = -\frac{\delta}{4} + y\alpha + \left[\left(-\frac{\delta}{4} + y\alpha \right)^2 + \left(\frac{\delta y}{\pi\beta} \frac{M_r(T_0)}{H_c(T_0)} + \delta\alpha \right) \right]^{1/2} \quad (30)$$

with $\alpha = \frac{1 - S^*(T_0)}{\pi\beta}$. At the limit of the very thin media ($\delta \ll a$) and in the absence of the thermal gradient ($dT/dx = 0$), equation (30) is reduced to the classical W-C expression for the parameter a .

The transition parameter a depends on some parameters which depend all on temperature. On the basis of the equation (30), the following observations can be made [13]:

i. S^* parameter may lead either to the increase or decrease of the transition parameter depending on the temperature. The increase with temperature of S^* results in narrower widths of the transitions and consequently in a lower value of the PW_{50} recording parameter (pulse width at half height).

ii. If the coercivity ratio M_r/H_c decreases/increases with temperature, the parameter a decreases/increases at the room temperature.

iii. The thermal gradients can increase or decrease parameter a depending on the part of the thermal gradient where the transition is recorded. This effect is taken into account by the behavior of parameter β ; an accurately positioned thermal gradient may result in a very high value of β and thus, in very low values of the parameters a and PW_{50} .

iv. Curvature of the transition leads to a widen transition, because it leads to a higher value of PW_{50} .

Experiments confirmed the validity of the thermal W-C model [13] and proved that the alignment, writing current intensity and the power of the laser spot must be upgraded simultaneously to obtain the most powerful signal, ensuring the highest recording density possible.

8. Challenges

The paper reviews the most important present results of a new recording technology, the heat assisted magnetic recording, HAMR, capable to extend the areal recording density beyond the physical limits of conventional magnetic recording. The presentation tried to highlight also some challenges addressed by this very promising technology that can be summarized as follows:

i. Obtaining a very low grain size for different types of media used in current products (below 5 nm). This objective is especially important in the case of composite media, as FePt/FeRh bilayers [16], recently proposed to obtain a strong reduction of the required switching field at temperatures much below T_c . This task is so more difficult as, at such reduced grain size, some finite size effects may lead to a significant decrease of the anisotropy constant K_u .

ii. The thermal design of HAMR media must assure a reduced broadening of the temperature profile during writing. Or, this can be obtained by an extremely fast cooling due to vertical heat diffusion in different layers situated under the magnetic recording layer. A good choice of the interlayer separating the recording layer from the underlayer is crucial from the viewpoint of the thermal design of HAMR media so more as this design must take into consideration the magnetic, structural and even mechanical properties of the media configuration.

iii. To obtain recording densities above 500 Gb/in², the diffraction limits of visible light prevent the achievement of the small spot size required. In order to realize densities surpassing 1 Tb/in², spot sizes of less than 50 nm and an efficient coupling to lossy metallic media are needed. Such small spots can be produced by NF transducers with various design (circular, rectangular or "C" shaped – see [1]). Dissipated spot sizes below 50 nm are possible with both antennas and apertures [17]. With the best transducers, NF power coupling efficiencies of (10...14)% become possible, if the transducers fly at less than 5 nm above the medium.

iv. Early estimates indicate than currently more than 50% of the energy incident on the slider is lost by thermal dissipation in the body of the slider [10]. Therefore, there are large temperature gradients that may concern the performance and the reliability of the HAMR system, because they cause the deformation of the slider and the damage of its components. The air bearing is expected to be an important way for limiting the effects of this thermal load. The analysis of the thermal characterization of the air bearing were carried out experimentally and compared to a simple conduction model [18]. Heat dissipation for the light source must be then a mandatory part of this integrated slider design.

v. Even if the different parts of a HAMR system are technologically achievable, the main obstacle to high densities seems to be the head-medium spacing.

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References

- [1] R. E. Rottmayer, S. Batra, D. Buechel, W. A. Challener, J. Hohlfeld, Y. Kubota, Lei Li, Bin Lu, C. Mihalcea, K. Mountfield, K. Pelhos, C. Peng, T. Rausch, M. A. Seigler, D. Weller, X. Yang, IEEE Trans. Magn. **42**, 2417 (2006).
- [2] H. Gavrilă, Magnetic Recording, Eds. Printech, Bucharest, 2005 (in Romanian).
- [3] A. Lyberatos, J. Hohlfeld, J. Appl. Phys. **95**, 1949 (2004).
- [4] R. Coehoorn, S. R. Cumpson, J. J. M. Ruigrok, P. Hidding, F. Zijp, A. H. J. Immink, H. P. Urbach, in: Magnetic Storage Systems beyond 2000 (G.C.

Hadjipanayis, Ed.), Kluwer Academic Publishers (2001); pp.571-583.

[5] H. N. Bertram, M. Williams, I.E.E.E. Trans. Magn. **36**, 4 (2000).

[6] H. J. Richter, R. Y. Rajan, J.M.M.M. **193**, 213 (1999).

[7] J. J. M. Ruigrok, R. Coehoorn, S. R. Cumpson, H. W. Kesteren, J. Appl. Phys. **87**, 5398 (2000).

[8] D. Weller, A. Moser, I.E.E.E. Trans. Magn. **35**, 4423 (1999).

[9] J. J. M. Ruigrok, Short-Wavelength Magnetic Recording: New Methods and Analyses, Elsevier, Oxford, New York, 1990.

[10] T. W. McDaniel, W. A. Challener, K. Sendur, I.E.E.E. Trans. Magn. **39**, 1972 (2003).

[11] H. Katayama, M. Hamamoto, J. Sato, Y. Murakami, K. Kojima, I.E.E.E. Trans. Magn. **36**, 195 (2000).

[12] S. H. Charap, P-L. Lu, Y. He, I.E.E.E. Trans. Magn. **33**, 978 (1997).

[13] T. Rausch, J. A. Bain, D. D. Stancil, T. E. Schlesinger, I.E.E.E. Trans. Magn. **40**, 137 (2004).

[14] H. N. Bertram, Theory of Magnetic Recording. Cambridge, Cambridge Univ. Press, 1994.

[15] H. N. Bertram, H. Zhou, R. Gustafson, I.E.E.E. Trans. Magn. **34**, 1845 (1998).

[16] J.-U. Thiele, S. Maat, E. E. Fullerton, Appl. Phys. Lett. **82**, 2859 (2003).

[17] W. A. Challener, E. Gage, A. Itagi, C. Peng, Jpn. J. Appl. Phys. **45**, 6632 (2006).

[18] E. J. Black, J. A. Bain, T. E. Schlesinger, I.E.E.E. Trans. Magn. **43**, 62 (2007).

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