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Achievement and expected issues in heat assisted magnetic recording

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Abstract. The main goals in magnetic recording are the continuous increase of the areal recording density and the highest possible signal-to-noise ratio (SNR). 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. The perpendicular magnetic recording (PMR) with pole head and perpendicular media is the best alternative, especially to defer the superparamagnetic limit. PMR is also better situated to face the challenging design *trilemma* of magnetic recording: To increase the areal recording density, smaller grain volumes are needed, but to ensure the thermal stability of recorded information, the anisotropy should be increased accordingly; or, the increased anisotropy asks for higher writing fields, which are unavailable with the saturation magnetization of the magnetic materials of the current heads. Obviously, an alternative technology is needed to overcome the physical limit of conventional perpendicular recording (CPR). The most promising successor of CPR is the *heat–assisted magnetic recording* (HAMR), which is a multidisciplinary technology, a combination of magnetic and optical recording technology that proved experimentally areal densities of more than 1 Tb/in^2. HAMR allows the use of very small-grain media, required for recording at ultra-high densities, with a larger magnetic anisotropy at room temperature, thus assuring a good thermal stability, while the local heating leads to a temporary magnetic softening of the medium. The realization of HAMR involved some challenges from both optical design and media properties. In the optical design the use of near-field transducers (NFT) represents an important advance. Regarding the media, a thermal design was used to produce the heating and cooling of the media within a very short time, about 1 ns, in order to achieve the desired data rate and generate a large thermal gradient for sharp bit edge definition. The structure of a HAMR system is briefly discussed, as well as the processes characterizing the writing process. A special attention is paid to the requirements for the materials needed for this type of recording: the granular $L1_0$-ordered FePt:X alloy sputtered on glass disk, the FePt-C and FePtC-Ag granular films and the bit-patterned media. Some important challenges of the HAMR technology are also summarized.

Keywords: heat-assisted magnetic recording; thermal stability; recording media.

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1. Introduction

The main goals in magnetic recording are the continuous increase of the areal recording density and the highest possible signal-to-noise ratio (SNR). The perpendicular magnetic recording (PMR) with pole head and perpendicular media is the best alternative to the longitudinal one, especially to defer the superparamagnetic limit. PMR is also better situated to face the challenging design *trilemma* of magnetic recording: To increase the areal recording density, a possible solution can be the reduction of the flying height, but the today value, of 1 – 2 nm, is very close to the technological limits. The alternative solution is to lower down the grain volumes V, but to ensure the thermal stability of recorded information, the anisotropy constant K_u should be increased accordingly; the increased anisotropy asks for higher writing fields and such fields are unavailable with the saturation magnetization M_s of the magnetic materials of the current heads. This challenge results form the expression of the *thermal stability factor* $\kappa = K_{\mathrm{u}}V / k_{\mathrm{B}}T$ (k_B – the Boltzmann's constant; T – temperature), which is required to reach at least a value of 60…70 for a stable data storage. On the other hand a decrease of the grain size leads to a decrease of the thermal stability. PMR offers some important advantages: the use of probe heads, able to generate stronger fields, which, in turn, allow for the use of thicker media with high anisotropy; smaller grains; a higher SNR. However, PMR must still solve some technological problems, e.g. the problem of the distribution of the material properties, because small distributions of the orientation and anisotropy increase the transition parameter, while SNR varies opposite to the second power of this parameter – further limiting the recording density achieved in conventional perpendicular recording (CPR).

Obviously, an alternative technology is needed to overcome the physical limit of CPR. The most promising and viable successor of CPR is the *heat–assisted magnetic recording* (HAMR), which is a multi-disciplinary technology, a combination of magnetic and optical recording technology that proved experimentally areal densities of more than 1 Tb/in^2 [1-3]. HAMR allows the use of very small-grain media, required for recording at ultra-high densities, with a larger magnetic anisotropy at room temperature, thus assuring a good thermal stability, while the local heating above the Curie temperature of the medium leads to a temporary magnetic softening [4]. The realization of HAMR involved some challenges from both optical design and media properties [5]. In the optical design the use of near-field transducers (NFT) represents an important advance, because the laser beam is concentrated to nanosize, thus only locally heating the recording media above its Curie temperature during the writing process [6]. Regarding the media, a thermal design was used to produce the heating and cooling of the media within a very short time, about 1 ns, in order to achieve a much large effective writing field gradient (as compared with that in the current PMR technology) and generate a large thermal gradient for sharp bit edge definition.

Firstly, the principle of HAMR and the structure of a HAMR system are discussed. The writing methods are then reviewed, as well as the requirements for the materials needed for this type of recording. A last section summarizes the foreseeable challenges of the HAMR technology.

2. Principle of HAMR

The principle of HAMR is quite similar to that of the magneto-optical (MO) recording [7]. It is based on the drastic decrease of 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) when the temperature T of the media is increased. Thus, heating the medium locally to a temperature higher that the Curie point T_C decreases its coercive field below the available magnetic field generated by the writer and the magnetization of the grains situated in the heated area can be oriented along the writing head field. But then the locally heated region must be rapidly cooled to the room temperature, in order to ensure again a high coercive field that freezes this orientation of the media grains. A successful high-density recording requires a high resolution at both the recording and the read-back process.

For reading back the recorded information one uses MR heads, then ensuring higher SNRs and thus, higher recording densities. The true novelty of the HAMR technology consists in the extreme reduction of spatial and temporal scales.

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 is 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, mounted on the slider of the magnetic head.

3. Writing methods

If diode laser sources and conventional optics are used for the writing process of HAMR, there is an important problem to overcome: the diffraction limit. Or, utilizing a near-field transducer (NFT), excited by light from a laser diode and integrated on the writing head, this limit can be overcome to obtain an extremely narrow heating spot and small recorded bits [6]. For areal density beyond 1 Tb/in^2, sharp lines and thermal profiles are required. At this aim, HAMR imposes 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 [8]). The bits of corresponding size are heated usually by a system which comprises a waveguide and a NF generator that receives the light energy from the waveguide and produces optical NF light by excitation of plasmons, forming a nano-sized thermal spot on the media [6, 9].

The quality of the written-in signal is determined by both the writing magnetic field and the media thermal profile, the later being determined by the input laser power and NFT-to-media spacing [10-12]. The HAMR writing process suffers thermal mechanical impacts, generated by the laser-related sources, which produce nanosecond-scale transient in written-in signal. During this transient stage, the recorded signal is of bad quality and cannot be correctly read.

Some of the methods used to realize HAMR are shown schematically in Fig. 1.

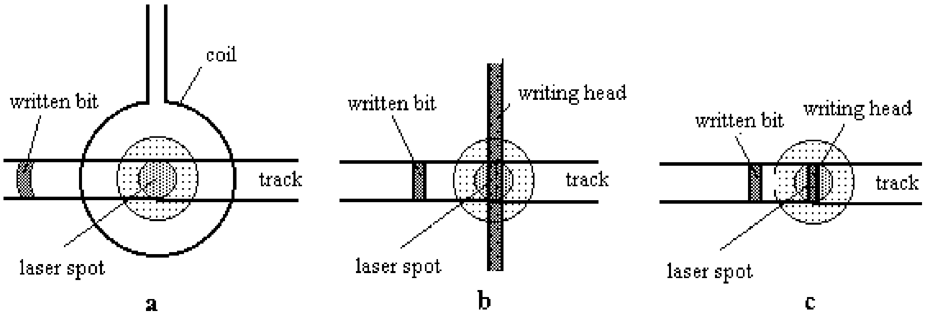

Fig. 1. Schematical representation of some methods to realize HAMR.

The first method uses a combination of a focused laser spot with a coil that supplies the writing field (Fig.1, a). The track width is then the same as the spot diameter. The readout uses the magnetic flux. The main disadvantage of this solution is that the recorded bits are crescent shape and less adequate for readout with MR heads. This disadvantage disappears when a conventional magnetic writing head is used (Fig.1,b). If the light spot is correctly focused, its width will determine the track width. The track width can also be magnetically determined (Fig.1,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 and a planar solid immersion mirror with a good numerical aperture does not assure a spot diameter below 120 nm. Fortunately, one can reduce the poles size below 100 nm using focused ion beam patterning.

Some requirements are needed for a good writing device [13]:

i. The head and the light source must be on the same side of the disk, to makes possible the NF optical recording and a permanent alignment of the head with the light spot.

ii. The writing field must cover only the track to be recorded and not extend over the adjacent tracks. 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 (and directly heated) track. Therefore, it is preferable that the diameter of the spot and the magnetic pole size be equal.

iii. 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. Thus it is obtained a reduction of the time between heating and writing and it becomes possible to use media with large thermal diffusivity, resulting in a short cooling time.

It is then 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 Fig.1,b and Fig.1,c), with a slight shift of the spot toward the trailing edge of the head.

A practical configuration of an integrated head is represented schematically in Figure 2.

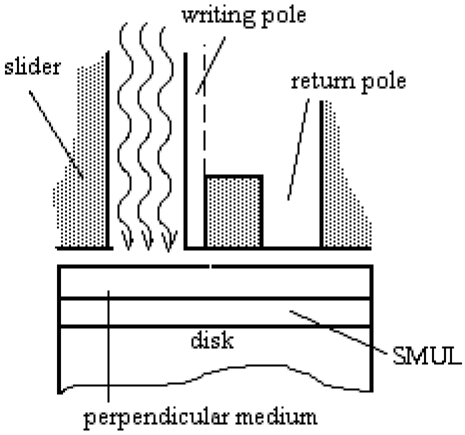

Fig. 2. A schematic configuration of a HAMR head.
The pole-type head is integrated with a light guide adjacent to the writing pole.

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 leads to a decrease of the transmission efficiency. The planar wave-guide is connected to a laser by an optical fiber. The pole acts as a metallic cladding layer and is partially transparent.

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 [14]. 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.

An important advantage of HAMR as compared with PMR is the ability to obtain much higher track densities, even if this gives an increase of cross-track profile and, therefore, an increase of the curvature effects [15].

4. Recording media for HAMR

The magnetic recording media for HAMR is usually granular, with more or less magnetically isolated grains. Materials used for recording media must have the highest uniaxial anisotropy possible and a large dependence on temperature of the switching field. Some materials, as $SmCo_5$, $Nd_2Fe_{12}B$ and FePt alloys, have been known for a long time as having large values of their anisotropy constant (for example, $7 \cdot 10^5$ 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 K_u [16]. To operationalize these high values of anisotropy, the grain size must be lowered below 50 nm.

The granular $L1_0$-ordered FePt:X alloy sputtered on glass disk is the most promising candidate as material for recording media; it permits the continued miniaturization of magnetic grains while delaying the superparamagnetic effects due to its very high magnetocrystalline anisotropy. Nevertheless, the lattice structure and the magnetic properties of the FePt-based alloys are affected by thermal agitation and, therefore, the heating and cooling issues are very important factors for HAMR media in both static and dynamic aspects [1].

To obtain the $L1_0$ structure the FePt alloy must be subjected to high *in situ* or post-annealing temperature (at least 700ºC) or it must be epitaxially grown on different intermediate layers (usually of MgO). In this last case the mismatch of FePt alloy and intermediate layer gets to lattice strain, thus permitting a reduction of the necessary ordering temperature. A MgO underlayer offers a good performance, because it induces the ordering of (001) textured FePt alloy and serves as a diffusion barrier between FePt and its intermediate layer. The small thickness of the MgO layer serves to control the crystal orientation of the recording layer. To get a good structure of MgO intermediate layer it is deposited on a NiTa seed layer. The MgO is also added – as well as other additives: SiO_2, Al_2O_3, C, etc. – in high volume fraction to achieve the grain isolation of the very small magnetic grains for ultrahigh density media applications, even if the increasing volume fraction of the additives produces the reduction of media packing density and the deterioration of FePt film texture, limiting the desired increase of the recording density. However, the use of MgO presents some drawbacks: the use of low temperatures (below 100ºC) too different from the high deposition temperature of FePt and other intermediate layers; long fabrication time and, especially, its nonconductive nature requiring RF sputtering (to avoid in mass production). Indeed, the MgO layer acts as a thermal barrier; increasing its thickness blocks more thermal energy to flow into the heat sink layer, which produces the increasing of the recording layer temperature and of the thermal spot size. An alternative to MgO is the conductive TiN and TiC layer deposited on CrRu [17, 18].

To improve the medium's thermal performance and the thermal diffusion, the introduction of a heat sink layer, typically Au, but also Cr, Al or Cu [19], between the seed layer and the glass substrate is recommended.

FePt-C and FePtC-Ag granular films were been extensively investigated. Granular films with well isolated grains can be obtained only with small film thickness (around 6 nm), when the grains are mostly spherically shaped. If the thickness increases, a secondary nucleation, due to an accumulation of C atoms on the film surface, gives to a two-layer structure. The doping with Ag improves the chemical ordering of FePtC-Ag film. Nevertheless, by introducing Ag into FePt-based granular film may produce some problems by the aggregation of the Ag resulted in a rough surface morphology and seriously affect the fly stability of the HAMR media. Therefore, there is a tradeoff between the chemical ordering improvement and the surface morphology control of FePt-based granular film with additional Ag doping [20].

The uniformity of the microstructure was obtained in the case of FePt-C-based granular film, when the microstructure development depends on the crystal growth rate of the FePt grains and the grain growth was not suppressed at its initial stage [20]. To obtain the desired microstructure of well-isolated columnar grains, with a size less than 7 nm, a high C content is needed to form continuous grain boundaries at the initial film growth stage. Thus, the grain size can be preserved due to the presence of the rigid grain boundaries, and the epitaxial growth of grains is ensured.

A bit-patterned (BP) media is also a possible and promising solution for HAMR to obtain high recording densities, over 5 Tb/in^2. In this case, data bits are written on litographically patterned magnetic dots that behave as single-domains. The recording density can be pushed up because the volume of the dots is greater that the volume of magnetic domains in a continuous granular media; the size of one bit is less than 10 nm. Nevertheless, the technology based on lithography and nanoprinting involves the process of etching to form the magnetic bit, which damages the bit, thus affecting the magnetic anisotropy and increasing the switching field distribution.

5. Challenges in harm development

The paper reviews the most important recent 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 highlights some significant technical challenges addressed by this very promising technology that need to be resolved before its widespread adoption. They can be summarized as follows:

i. Obtaining a very low grain size for different types of media used in current products (below 5 nm). For example, to obtain a recording density of about 4 Tb/in^2, each recording bit must occupy an area of 160 nm^2; or, with an average grain size in recording layer of 4.5 nm, an average grain pitch of 5.4 nm and at least two grains in the track direction, it results a track pitch of maximum 15 nm [21]. To write such narrow tracks, the width of the write head or of the laser spot must be of the same order – that arise important technological difficulties. A convenient design of the single pole write head was proposed at this aim (Fig.3) [21]. With a laser spot much narrower that the head, the written track width and sharpness of written transitions are dominated by the thermal gradient in media. Higher values of SNR may be obtained with wider written tracks and/or by increasing the head width. This objective is important in the case of composite media, proposed to obtain a strong reduction of the required switching field at temperatures much below T_C.

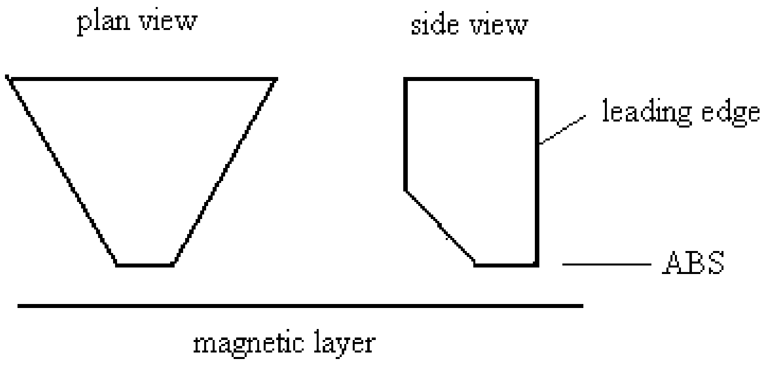

Fig. 3. Proposed design of a main write head for HAMR [15].

ii. The thermal design of HAMR media must assure a reduced (even negligible) 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 layers separating the recording layer from the substrate (interlayer, seed layer and heat sink layer) is crucial from the viewpoint of the thermal design of HARM media so more as this design must take into consideration the magnetic, structural and even mechanical properties of the media configuration. A thorough study of the correlation between the dynamic structural/magnetic/thermal properties of the media during and after laser heating – the so-called analysis in four dimensions, with the time as fourth dimension – is needed [5].

iii. To obtain ultrahigh recording densities, well above 1 Tb/in^2, spot sizes of less than 25 nm and an efficient coupling to lossy metallic media are needed. Such small spots can be produced by NFTs with various design, using surface plasmon resonance. A significant challenge with these transducers is their lifetime. The NFTs are realized of metallic elements that focalize the optical field via plasmonic electromagnetic modes that produce significant Joule heating within metals. Different optically resonant structures (disks or cavities) [6] are used to collect the far-field light from lasers and focus it to spots on the order of 10s of nanometers. Many improvements can still be done in the proposal of new geometries and materials to fabricate the NFTs [22, 23]. With the best transducers, NF power coupling efficiencies of (10…14)% become possible, under the restriction that the transducers fly at less than 5 nm above the medium. An important problem is also the fact that the NFT lifetime decreases with increased thermal load, which necessitates properly weighing potential tradeoffs between recording performance and laser power, therefore the introduction of a maximum allowed laser – power, experimentally (empirically) defined [24].

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 [8]. 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. Heat dissipation for the light source must be then a mandatory part of this integrated slider design.

v. Understanding and reducing the medium noise in the recording process is critical in making HAMR viable [25, 26]. The micromagnetic simulation of HAMR waveforms [26] proves that the variation of the Curie point T_C affects the recording process more than the anisotropy of the medium, due to its stronger impact on the switching time window that produces a significant transition jitter noise. The distribution of switching coupling enhances also transition jitter noise. Experiment confirmed some aspects of this prevision [27, 28], but the studies must be extended.

vi. A critical challenge for the HAMR technology is the reliability issue resulting from the deterioration of the NFTs under high temperature. The main reasons are the low energy-coupling between NFT and the recording media and the absorption of the optical frequencies by the NFT itself [29]. A solution can be the introduction of a thermal barrier layer into the HAMR media stick between the sink layer and the underlayer. The material of this function layer must have a thermal conductivity strongly increasing with temperature; the heat flow at the first heating stage will be thus reduced and a smaller laser power could be used to heat up the media to the operating temperature. The most convenient material for this better thermal control seems to be Cu_2O [29].

vii. In HAMR, the thermal profile inside the recording media often has a circular or elliptical temperature contours within the medium plane, that always create transitions with significant curvature [21, 30, 31]. Such transitions are non-compatible with read heads, which have straight gaps, and yield edge erasure at high linear densities, because the width of a written track becomes narrower with decreasing transition spacing. They are three main underlying mechanisms responsible for this phenomenon: (i) from the track center toward track edges the peak temperature decreases well below Curie point; (ii) the thermal gradient degrades all the way to zero at track edges; and (iii) erase-after-write enhances. Due to these mechanisms, the SNR degrades much faster near track edges that in track center [32]. Different solutions can be proposed to obtain a straight transition without changing the circular thermal profile, for example by varying the head field amplitude across the track width [32]. These proposals must be deeply studied and technologically implemented to confirm the previsions [15].

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