

Patterned magnetic recording media

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Until some potentially superior technology such as heat assisted magnetic recording becomes practical, several solutions were proposed to extend the magnetic recording performance. Among them, the most promising in this stage of magnetic recording is the recording media comprising monodisperse high-anisotropy nanoparticles in a self-organized patterning. These media have higher thermal stability, delaying the superparamagnetic effect, low noise and higher signal resolution, which, in turn, led to higher areal density and a better signal-to-noise ratio. The self-organized patterned media permit a better control of the film surface, of the uniformity of the composition, of the geometry of constituent nanoparticles and their magnetic easy axis orientation, which led to the improvement of recording properties. Some considerations concerning the modeling of recording and readout processes on these media are also discussed. Understanding the magnetic properties of the patterned media ensures the desired control of the reversal and stability of these systems and is essential in determining their storage potential and in achieving their design.

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1. Introduction

The magnetic recording has known an accelerated progress, so that, for example, the recording areal density is increased now to double in less than a year. This progress is due to a huge accumulated know-how and to several findings in domains like material science, signal processing and recording technology [1–6]. One approaches the theoretical physical frontiers of the recording areal density, limits imposed by the energetically based assumptions concerning the thermal stability and the signal-to-noise ratio (SNR). Nevertheless, some research [7] proved that these limits can be overcome.

With the conventional longitudinal magnetic recording, the maximum attainable areal recording density has been assessed as physically limited to about 200 Gb/in². Further growth of this density is limited, firstly by the superparamagnetic effect, that is the thermal instability of the magnetization of the small magnetic grains of the magnetic recording medium, but, also by the limited possibilities to further improve writing heads design and pole materials in order to enhance the head writing field. Indeed, to achieve higher recording densities, the classical pathway was to reduce the volume V of grains. But smaller it becomes, the energy KV of grains (K – anisotropy constant) becomes of the same order as the fluctuations of thermal energy, $k_B T$ (k_B – Boltzmann's constant, T – temperature). Thus, to maintain thermal stability, that is acceptable values of the *factor of thermal stability*

$$\kappa = KV / k_B T, \quad (1)$$

the media anisotropy must be increased. An important difficulty faced with this approach is that as the anisotropy increases, the media coercivity draws nearer or even

exceeds the available field from the writing head. This makes it increasingly difficult to write the media.

For example, in the case of continuous polycrystalline media, in thin layer, SNR of the medium is directly related to the number of grains allotted to a bit, and the transition resolution between two successive bits depends on the grain size. Thus, with the currently used media, from CoCrPtX ($X = P, Ta, \dots$) alloys, at recording densities of around 80 Gb/in² the average size of the grains is of approximately 8 nm, the number of grains per bit is approximately 100, the bit size being around $250 \times 30 \text{ nm}^2$. The reduction below 100 of the number of grains per bit would lead to a dramatic decrease of the medium SNR. In order to decrease the bit cell size, but keeping SNR constant, the grain size must be reduced – operation impossible due to the superparamagnetic limit. (Note that with CoCrPt alloys, which have an uniaxial anisotropy constant K_u of around $2.2 \times 10^5 \text{ J/m}^3$, just imposing a thermal stability factor $\kappa > 40$ it results the minimum size of 8 nm, shown above.) Other materials can be also used, based on alloys such as FePt, SmCo, NdFeB etc., but these would imply more intense writing fields to reversal the grains magnetization, thus new soft magnetic materials for the poles of the writing head, with an extremely high saturation magnetization M_s , impossible to be obtained yet.

Perpendicular magnetic recording has also made significant progress in the past few years, recently resulting in high-density commercial disk drive products, with areal density of about 300 Gb/in². Nevertheless, there still remain some important factors limiting its performance, as, for instance, jitters that lower the SNR and, again, the superparamagnetic effect. The anisotropy of the granular media, the head-medium spacing, the saturation induction of existing materials, and the geometry of the magnetoresistive (MR) heads are the main

factors that determine the jitter configuration [8]. 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 and several solutions have been proposed. Among them very promising are the recording media comprising monodisperse high-anisotropy nanoparticles in a self-organized patterning. These media have higher thermal stability, low noise and higher signal resolution, which, in turn, led to higher recording density and a better SNR. Understanding the magnetic properties of these media leads to a better control of the reversal and stability of these systems and is essential in determining their storage potential and in achieving their design.

2. Principle of patterned media

A very important means of reducing the medium noise consists in eliminating the statistic fluctuations of the signal by using some magnetic grains very regular in point of size and layout, and magnetized in the same direction. This subject has been lately a topic of interest because the recording densities that can be thus achieved correspond to the minimum size of the thermally stable particles. Then the major noise source is no longer the media, but the method of locating and addressing individual particles.

The microtechnology industry, which has lately made huge progress in term of continuously scaling down the size of devices, faces now a fundamental barrier. The main application fields of this industry are microelectronics and data recording. In microelectronics, the diffraction limits require the search of new litho-graphic techniques. There are similar difficulties in data recording as well. Furthermore, the size of the recorded bits decreases faster than the limits accepted in micro-electronics. Or, one of the most important limitations concerns just the thermal stability of the written bits.

The long-time stability of the recorded data has thus become a major objective for hard disks. One of the solutions suggested lies in the development of the *patterned media* [9-21], which enable overcoming the superparamagnetic limit of the current thin-layer or granular media. Another main objective of this concept is to avoid write synchronization errors.

A patterned medium is a very regular plane arrangement of discrete dots (islands, elements) smaller than their critical monodomain size, and having a strong uniaxial magnetic anisotropy.

The magnetic material used for producing these media does not differ from the one used for continuous thin-layer media. It was proposed a recording scheme in which each bit is assigned to a dot of nanometric size, magnetized longitudinally or, preferably, perpendicular-ly. This system would be advantageous if these dots were monodomain [11-14, 22], because the constraints of the writing and readout processes are then considerably reduced. The bits shape is now determined not by the grain size, but only by the configuration process of dots. Due to the monodomain character of each element, its recording

is of the type “everything or nothing” (**1** or **0**), and the head need not be placed right above the bit. On the other hand, the transition noise, due to the magnetic coupling of the recorded bits, is eliminated, as a result of the non-magnetic barrier between dots [14]. The SNR of the readout signal is much better due to the absence of media noise and the excursion of transitions. Finally, the grain volume V can be much higher and thus the superparamagnetic limit is also much higher than for the current thin-film layers and areal recording densities of some Tb/in² can be reached [18].

When designing a patterned medium, the following requirements should be considered:

(i) The dots must be arranged in a 2D template very regular, with as little faults as possible.

(ii) The material must have strong uniaxial anisotropy so that the dots are monodomain and thermally stable.

(iii) A narrow distribution of the switching field ensured by the very regular shape and size of the dots, as well as by the weakness of the dipolar interactions.

(iv) The number of “faulty bits”, which are due to the absence of some dots or to the non homogeneity of the magnetic material, should be as small as possible.

In addition to the requirement that the dots should be monodomain it is better for their easy axes to be aligned. With the circular disks this requirement is much easier to be fulfilled using materials with perpendicular anisotropy than with in-plane anisotropy. Such an anisotropy is easier to be obtained as interfacial anisotropy rather than shape anisotropy, as in the latter case it should be used dots with higher aspect ratio, which limit the linear bit density.

Crystalline or interfacial anisotropy patterned dots could be obtained by the physical configuration of Co-Pt multilayers [23], by depositing on configured sub-strates [24, 25], by modifying the Co-Pt or FePt alloys under the action of ion beams [15, 26-28] or by configuration with electron beams or focused ion beams of some thin CoCrPt layers [29-33].

Thus, by the last method it could be obtained monodomain dots of square section with 67 nm period, which corresponds to a recording density of 140 Gb/in² [31, 34], in a frustrated chess-table arrangement, which is due to the magnetostatic coupling between dots, in general the exchange coupling being negligible. The measurements done on a Co₇₀Cr₁₈Pt₁₂ alloy have also proved that there is no thermal degradation of the perpendicular patterned medium, unlike a non-patterned medium of the same material [34], fact due to a significant decrease of the demagnetizing field. But, for the patterned medium it can be noticed a decrease of coercivity and, implicitly, of the magnetic anisotropy.

From a different point of view, the patterned media can be produced by an approach *top to bottom*, which implies producing the medium by sputtering and then patterning by lithography [35] or implant with ion beam [27], either an approach *bottom to top*, using selective (dimensional) precipitations of monodomain particles from the solution [36] or ordering them in very regular

arrangements by self-assembling methods [37]. As the thermal stability of a bit depends inversely on the number N of grains per bit, so that the patterned media could be successfully used, N must be decreased as much as possible. In the lithographic methods, a possible solution is enhancing the intergrain interactions by pre-venting the preferential segregation of Cr at their frontiers. In addition to the effects of intergranular segregation fundamental microstructural effects also occur, such as, the side effects on the reversal mechanisms of domain magnetization.

It can be said that up to nowadays none of the methods suggested for producing patterned media seems to combine a low cost price criterion at rapid patterning of a larger area (a few square centimeters) with dots bigger than 25 nm, with the possibility to design a special configuration by servosystems.

There are two main types of methods of producing patterned media: lithographic techniques and SOMA or a combination of the two approaches (for an extended review of manufacturing aspects of these media, see [38]). Another techniques proposed for fabricating patterned media are: phase separated AlSi films [39], the anodized alumina nanoholes [40, 41], and artificial aligned self-assembling [42].

3. Lithographic techniques of submicron configuration

The original conception consists in configuring a wide surface out of an exchange coupling material for the desired size of the bit. If it is required to improve the surface density of the recording, this area must be small [13, 43]. If the area is too large, there could appear a multidomain structure, and the presence of domain walls leads to a lower coercivity, whereas the noise increases since the net magnetic moment of each bit configuration may vary according to the walls fixing position. If we use groups of isolate particles, we risk having statistical fluctuations of the outgoing signal because the frontiers of the areas that have been lithographically defined become irregular.

The requirement to configure large areas, with regularly disposed nanometric dots, raises serious technological problems. Presently several lithographic techniques are used. In order to select the most suitable one, three criteria must be taken into consideration: (i) capacity of predetermining the material properties; (ii) the ability of the process to define the configuration; (iii) the influence of the configuration process on the magnetic properties of the dots.

Studies on Co- and CoNi-based multilayers have proved that, when correctly laid, these systems can have strong intergrain exchange coupling and an important perpendicular magnetic anisotropy. That is why it is convenient to use them for designing patterned media. Nevertheless, their relatively high Curie temperature is a major pitfall that has been overcome by replacing the Co by an alloy $\text{Co}_{1-x}\text{Ni}_x$; thus, the Curie temperature has been considerably lowered, but the magnetic properties have

also been affected. For $x = 0.5$, there were obtained configurations of dots under the form of a pyramid or a cone, whose diameters vary between 70 – 280 nm, high of about 15 nm, and having a period of 570 nm, or under the form of a disk with a diameter of about 200 nm [44]. Critical diameter of cylindrical dots, for which the monodomain character is assured, is given by:

$$d_{\text{cr}} \cong \frac{32}{\pi} \frac{Q\delta}{N_Z(h, d_{\text{cr}})}; \quad (2)$$

$N_Z(h, d_{\text{cr}})$ is the average demagnetizing factor of the cylinder, depending on its height h and diameter d , and

$$Q = 2K_u / (\mu_0 M_s^2) \quad (3)$$

is the quality factor of the material; $\delta = \sqrt{A/K_u}$ is the domain wall width [45]. Only the dots whose diameter is of about 70 nm are certainly monodomain and those with diameters above 180 nm are multidomain. Their shape influences their switching field, with values between 0.22 H_c and 0.5 H_c ($H_c = 1.5$ MA/m).

Experimentally confirmed calculations have done for different materials the size of a cubic dot still thermally stable: Ba ferrite - 8 nm; Fe- or Co-based alloys - 4 nm; RE-TM alloys (TbFeCo, for example) - 12 nm; Co-based multilayers ($\text{Co}_{0.5}\text{Ni}_{0.5}/\text{Pt}$, for example) - 7 nm.

The materials have an intrinsic uniaxial anisotropy strong enough, which guarantees an important switching field and a long-term thermal stability. The dots can be configured so that to suppress the magnetostatic interactions. From this point of view, Co, Ni or Fe are less favored because in a 2D dense arrangement, they have strong magnetostatic interactions.

A new method has been also recently proposed [46], consisting of pre-configuration by nanoprinting of a non-magnetic layer on which it will be then deposited a magnetic material whose nanoconfiguration is thus ensured. Nanostructure of the silicon (non magnetic) layer can be made either by electron beam lithography [24, 25], capable of a resolution of 50 nm, followed by a edge cut with reactive ions or by nanoprinting with a special device. Thus, there were obtained nanoelements with diameter of about 30 nm and period of 60 nm [46, 47].

On the configured non-magnetic layer will then be deposited the desired magnetic material. This covers the upper part of the elements of the non-magnetic layer, thus creating the magnetic dots of the patterned medium.

From amongst the advantages of this technique we must underline: (i) configuration of the non-magnetic layer does not depend on the magnetic material choice; (ii) if the non magnetic layer is made of Si, any micro-electronic technology can be used to make small-size dots with a high aspect ratio; (iii) nanoprinting allows easy and low-cost duplication of the non-magnetic layer; (iv) the method can ensure the realization of large configurations, with arrangements of the dots which form circular tracks [46].

The lithographic techniques have an important potential. One of the main advantages of lithographically defined media is their capacity to predefine the information concerning the track and the training servo-

systems. However, producers have avoided it so far due to the high cost of these media, and to the difficulty to make a concentric disk configuration.

4. SOMA

The second way of configuring magnetic media consists in the use of the natural process of generating *self-ordered magnetic arrays* (SOMA). There are some chemical reactions generating them or biologic materials forming a structure of monodimensional particles. The recording media formed of high anisotropy mono-disperse nanoparticles (of exactly the same shape and size) have been proposed firstly for achieving very high recording densities of about 200 Gb/in². The chemically synthesized nanomagnets have size distributions extremely narrow, which favor the self-organized patterning, and enables potential densities of about 1 bit/particle, the equivalent of 10 – 50 Tb/in² (2 – 8 Tb/cm²) [36-49].

SOMA media can serve as: conventional media with reduced dispersion; bit-patterned media with bit-transitions defined by rows of particles; and single-particle-per-bit recording media.

Among the materials having very strong anisotropy, special attention is given to the phase L1₀ of the equiatomic CoPt alloy and of the FePt alloy, thermally stable until grain diameters of 3 – 4 nm, which corresponds to a uniaxial anisotropy constant $K_u = 5 \times 10^6$ J/m³ and, respectively, 6.6×10^6 J/m³ [50, 51]. In fact, the as-grown FePt and CoPt nanoparticles are mostly *fcc* and show superparamagnetic behavior. To obtain an ordered L1₀ structure, high temperature annealing is required. A self-assembled array of such particles shows well-aligned close-packed nanostructures on a substrate (fig.1); however, particles strongly coalesce during annealing [52-54], which results in undesirable increase in their size and distribution. This inconvenient can be prevented by adding a convenient stabilizer [55].

In order to synthesize arrays of monodisperse nanoparticles with a diameter of 4 nm from FePt alloy in phase L1₀, organic stabilizers in non-aqueous solutions were used [36]. It has been reported that the L1₀ FePt alloy with nearly equal atomic ratio can be made into chemically disordered A1 phase nanoparticles and form ordered pattern through chemical reduction followed by a self-assembling process [36]. But the unavoidable annealing process for magnetic as well as the crystallo-graphic phase transformation leads to some obstacles to apply these nanoparticles in magnetic recording [56]: (1) upon annealing, particles agglomerate and monodispersity is lost; (2) because the phase transformation involves new phase nucleation and growth, a single particle could develop multiple easy axes by forming twinned structures or antiphase boundaries. In order for the use of nanoparticles in recording media, their axes should be aligned during the self-assembling process, which cannot be achieved directly.

To solve these problems, different approaches have been proposed: the addition of a ternary element for reduction of the annealing temperature [57], usage of a

removable matrix for particle isolation, field annealing for the control of orientation [55], etc. Nevertheless, the phase transformation is from the isotropic state A1 to the anisotropic state L1₀ and thus is quite difficult to control it only by adjusting external parameters. It was pointed out that the ordering of FePt nanoparticles might be kinetically limited [58].

The optimal approach is to prepare L1₀ FePt nanoparticles without post deposition annealing. Indeed, by increasing the temperature during the growth of particles in colloidal method, partially ordered FePt nanoparticles could be made. However, particle uniformity became a problem since overheating usually leads to particle agglomeration. Or intermatrix synthesis is able to make isolated L1₀ FePt nanoparticles [59].

Another technique to directly prepare the mono-disperse L1₀ FePt nanoparticles is a gas phase aggregation technique that relies on the subtle control over the nucleation and growth of particles at the atomic level [56]. Using these highly ordered FePt nanoparticles (of unique octahedron shape) monolayer patterns have been achieved through self-assembly in aqueous solution. Different other chemical syntheses were also used [60].

Theoretically, areal recording densities of about 10 Tb/in² become possible.

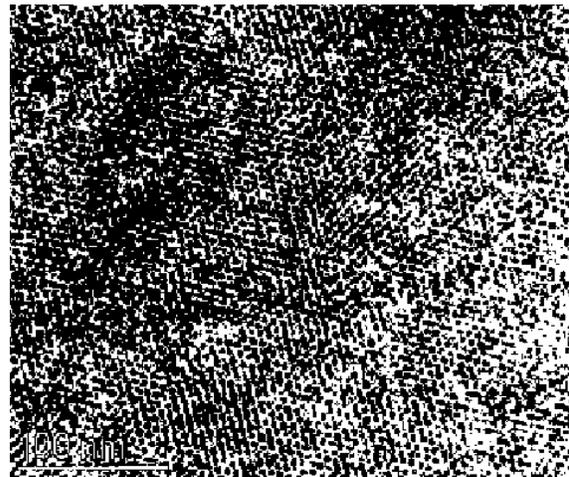


Fig. 1. TEM image of a self-organized *hcp* monolayer of protein-encapsulated nanoparticles [63].

Synthesis methods were also used in order to obtain nanoparticles of Co [61], but for nanoparticles of high anisotropy CoPt alloy, the control of the process was no longer satisfactory. In this latter case, a better size control was obtained by aqueous synthesis, but the monodisperse precursors for the phase L1₀ of the equiatomic CoPt alloy were only produced by means of the biological template of ferritine [62]. Indeed, some proteins naturally arrange on a surface in an *hcp* regular square form. Since their growth is determined by a DNA code, their size is extremely uniform. Some of them have cavities that can be filled in with magnetic material. The metallic particles can then be produced with very regular dimensions, by precipitation from surfactants, which also limits the sizes of the

particles [36, 37]. When depositing on the substrate, these particles are disposed in extremely ordered arrangements.

Such a miraculous protein is the *ferritine*, which enables the strict control of the size of metallic grains synthesized in its spherical cavity. Due to the uniformity of its outer dimensions, this protein leads to the forming of some thin, self-patterned, and extremely regular layers, independently from any possible distribution of dimensions (which is also very unlikely) of the grains made of synthesized material. Moreover, the covering shell of the protein, about 2 nm thick, prevents the grains from synthesizing at the high temperatures necessary to change the CoPt alloy into the $L1_0$ phase.

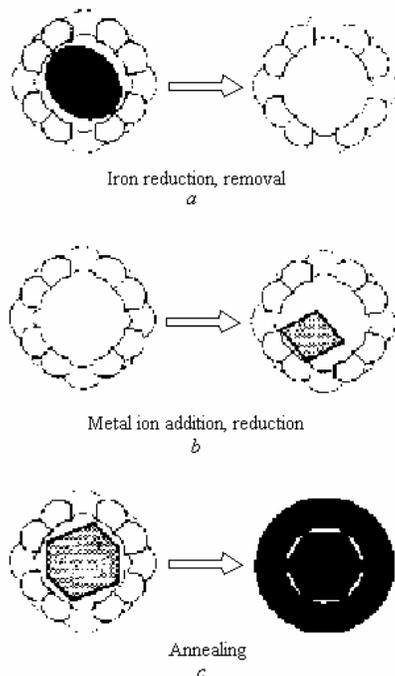


Fig. 2. Scheme for the production of biologically nanomagnets: *a* – amorphous ferrihydrite is reduced and removed from proteins to form apoferritin, *b* – then reconstituted with Co and Pt ions, and chemically reduced to form a full metal alloy core, *c* – that is annealed to form the phase $L1_0$ encased in a carbonized template [63].

Ferritine is made up of 24 almost identical sub-unities forming a sphere whose exterior diameter is of 12 nm; inside there is a spherical cavity whose diameter is of 7.5 – 8 nm (Fig. 2). It is in this cavity that Fe is biologically deposited as ferrihydrite. This protein resists at temperatures relatively high from the viewpoint of biological systems (65°C). The protein missing the original iron oxide yoke is called apoferritin; it is used to encapsulate nanocrystals by strictly controlling their size.

The superparamagnetic Co-Pt precursor grains are prepared in apoferritin out of aqueous reactive under synthesis conditions that allow for the control of the grain size, as well as their structure and composition. In order to obtain the $L1_0$ phase of magnetic nanoparticles, the

material is heated at 500 – 650 °C for 60 minutes; then the protein cover is also carbonized (Fig. 2,c). The recording densities thus obtained are higher than those obtained with Fe-Pt alloy, namely 2.2 Gb/in².

However, in order to attain the forecast recording densities of some Tb/in², a strict control of the layer surface, of the uniformity of the composition, of thermal stability, of nanoparticles sizes, as well as of the orientation of their easy axes is required. If this control is not enough for refining of nanoparticles, one could use combined systems, for example the track patterning, by applying some grooves to strictly delimitate the tracks.

Among the materials used for preparing the SOMA media, only the system using ferritine or a similar template have proved that they do not depend on the distribution of the dimensions of nanoparticles synthetically obtained, and they have allowed for wide *hcp* configurations. Under the current technological conditions, a self-organized monolayer of Co-Pt nanoparticles obtained from apoferritin allows for obtaining recording densities of 4.5 Tb/in² (0.7 Tb/cm²) [63].

The SOMA technique has the advantage that the media obtaining process has a low cost, but there are still a lot of unknown things concerning the ordering parameters and the way of disposing these arrangements. However, there is still the great advantage of the possibility to obtain particles identical in size. Irrespective of the production method used for monosized magnetic particles, it is very important for them to be oriented in the same direction. Indeed, if some particles are oriented at 90° on the recording direction, they appear as voids. If they are randomly oriented, there are many such voids, and many other particles will generate a low signal. The signal processing technology should then compensate for this disadvantage that significantly reduces the potential areal recording density. A way of eliminating this disadvantage consists in configuring some monocrystalline thin-film layers. Thus, thin-film layers of Co alloys have been epitaxially deposited on monocrystalline substrates of MgO or Si having different orientations [64]. A metal that does not chemically interact with Si, but whose lattice constant is compatible with that of Si is then deposited; Ag is the most convenient.

Thus, the way to obtaining patterned media is definitively open.

5. Writing patterned media with a probe head

Recording on configured materials is possible both in longitudinal mode and in perpendicular one, the latter being favoured. A recent theory [65] establishes the major factors which limit the arrangement density of the monodomain nanoparticles.

One considers an ideal cylindrical probe head, whose magnetisation \mathbf{M} is directed lengthwise towards the medium and whose section is of a very small area A (fig.3). If the magnetic poles are concentrated only on the air-bearing surface (ABS) of the head, and under the recording magnetic layer there is no soft underlayer

(SUL), the in-plane (radial) component and the perpendicular one of the head field have the expressions [66]:

$$H_r(r, y) = AM \frac{r}{(r^2 + y^2)^{3/2}} = H_h \frac{ry^2}{(r^2 + y^2)^{3/2}}, \quad (4)$$

$$H_y(r, y) = AM \frac{y}{(r^2 + y^2)^{3/2}} = H_h \frac{y^3}{(r^2 + y^2)^{3/2}}, \quad (5)$$

where (Fig. 3,a):

$$H_h = \frac{AM}{y^2} = H_y(0, y). \quad (6)$$

The field generated by the head upon applying a short current pulse must be powerful enough to change the magnetization of the dot under the head, but at the same time not enough to reverse the magnetization of any other element of the configuration (whose geometry is represented in Fig. 3,b).

In fact, different kinds of imperfections of the dots pattern deteriorate system performance; these imperfections result in a SNR that is quite analog to a traditional medium SNR and is termed as *read-back medium SNR* [67, 68]. Different noise sources were identified to contribute to this SNR: fluctuations of the dot spacing r ; fluctuations of the dot width; fluctuations of the magnetization saturation; fluctuations of the dot thickness t ; fluctuations of the dot shape; and bit edge roughness. They can be correlated or not correlated.

Neglecting the interactions between dots, the required field must be:

$$H_y(0, y) = H_h = C_c H_K, \quad (7)$$

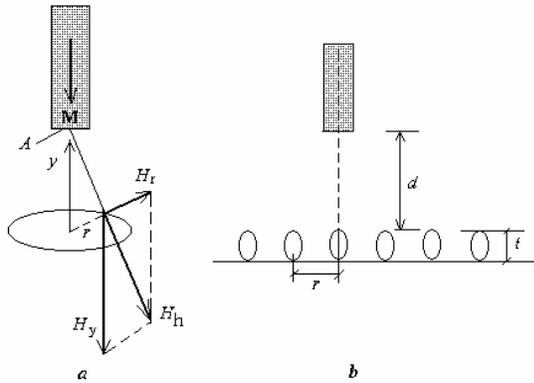


Fig. 3. Explains the writing process with an ideal probe head on a patterned medium: a – head field; b – position of the head before a dot of the medium.

where H_K is the anisotropy field of the dot, $y = d + t/2$ is the distance from the head to the midheight of particle, and C_c is a numeric constant which reports the head field $H_y(0, y)$ at its minimum value H_K . The dots from distances $r > 0$ must not be under the action of a field capable of reversing their magnetisation, which can be written:

$$H_r^{2/3} + H_y^{2/3} < H_K^{2/3}. \quad (8)$$

From the previous equations it follows:

$$C_c^{2/3} \left[\left(\frac{r}{y} \right)^{2/3} + 1 \right] < \left(\frac{r}{y} \right)^2 + 1. \quad (9)$$

The maximum value of the head field, H_K , corresponds to $C_c = 1$ and, according to (9), leads to $r > y$. If the dots are arranged regularly, in a square network, the maximum arrangement density is $1/(d + t/2)^2$; for $(d + t/2) = 20$ nm, it results a density of 2.5×10^{15} dots/m² (or 1.6×10^{12} dots/in²). At such a density, there is no maximum limit for the head field or for the position of the head or other elements.

If, for instance, the dots density were decreased by 50%, the result would be, according to (9), a maximum of the parameter C_c of about 1.5; the head can then be located during recording accordingly with $C_c = 1.25 \pm 0.25$, so with a tolerance of $\pm 20\%$.

The fluctuations of the dot spacing represent jitter and lead to time shifts of the individual responses of each dot [68].

If the medium is not uniform, being characterized by a certain dispersion of the anisotropy constants of the dots, $H_K \pm \Delta H_K$, in order to be able to write the head field must overcome the highest anisotropy field $H_h = C_c(H_K + \Delta H_K)$, $C_c \geq 1$, but also meet the condition of non-recording the neighbouring elements:

$$H_r^{2/3} + H_y^{2/3} < (H_K - \Delta H_K)^{2/3}. \quad (10)$$

Then it results:

$$C_c^{2/3} \left[\left(\frac{r}{y} \right)^{2/3} + 1 \right] < \left(\frac{H_K - \Delta H_K}{H_K + \Delta H_K} \right)^{2/3} \left[\left(\frac{r}{y} \right)^2 + 1 \right] \quad (11)$$

and by comparing this result with (9) it results a new upper limit of the reference constant:

$$C_K = C_c \frac{H_K + \Delta H_K}{H_K - \Delta H_K}, \quad (12)$$

which must replace the limit C_c prior identified for the head field. The new limit C_K reunites both the limitation of the head field and the dispersion of the anisotropy field and requires revision of the allowed density. Thus, if $\Delta H_K / H_K = 0.2$, it results $C_K = 1.5 C_c$ and the recording density deduced in the previous example is decreased to 30% of the maximum possible value.

The possible taken into account of the variation of head and/or elements position leads to, in its turn, the increase of the distance r between dots in comparison with

the values determined in the precedent conditions – and implicitly, to a supplementary decrease of the arrangement density.

A further analysis takes into account interactions between particles, neglected so far, in rapport with the writing head field and of the anisotropy one. Or, especially in the case of high recording densities, this supposition is impracticable [69]. For the recorded bit the most unfavourable case is when all interaction fields are opposed to the writing field and for the neighbouring bits when all interaction fields would contribute to the undesirable process of their magnetisation reversal.

The interaction field acting on any element is directly proportional to magnetization, gM , the proportionality factor g being determined by the magnetization position and direction of all the dots of the assembly.

During the recording process, the head field must exceed the value corresponding to the least favourable case:

$$H_h = C_c (H_K + \Delta H_K + g_{\max} M), \quad C_c \geq 1, \quad (13)$$

on condition to neglect any in-plan field component, very low, anyway; g_{\max} is the maximum value which the geometric factor g can have.

The restriction not to record by the head field of a neighbouring element now must take into account the supposition that the demagnetizing field acts as to facilitate the switching of the dot and to effectively reduce the anisotropy field to the value $(H_K - \Delta H_K - g_{\max} M)$. Condition (9) takes the form

$$C_c^{2/3} \left[\left(\frac{r}{y} \right)^{2/3} + 1 \right] < \left(\frac{H_K - \Delta H_K - g_{\max} M}{H_K + \Delta H_K + g_{\max} M} \right)^{2/3} \left[\left(\frac{r}{y} \right)^2 + 1 \right] \quad (14)$$

leading to a new expression of the upper limit

$$C_{K,M} = C_c \frac{H_K + \Delta H_K + g_{\max} M}{H_K - \Delta H_K - g_{\max} M}, \quad (15)$$

expression which includes all factors controlling the process.

In order to minimise the effect of the interactions, the ratio $g_{\max} M / H_K$ should be as low as possible. In a regular shape homogeneously magnetized element it can be considered, for simplicity, $g_{\max} = 1$, value that can be adopted in an overestimated way, if the real value is not known.

We must note that a recent analysis [70] proved that to achieve optimum write efficiency, a small degree of head/bit misregistration (about 20% - 30% of the bit size) is required. The patterning of SUL helps boost the write efficiency by more than 20%. The reduction of the bit size

at a given areal bit density leads to the decrease of the write efficiency. At the same time, a small degree of bit edge roughness (< 10% of the bit size) has only a weak influence on magnetization reversal process.

6. Modeling the readout process

A special problem is the replay process from patterned media. The few approaches were focused mainly on longitudinal media [30, 71] or they used conventional 2D modeling [72, 73]. However, to analyze the readout process in ultrahigh-density recording system, more accurate models must be utilized, because otherwise all the subsequent analyses may become inaccurate. In particular, it is important to evaluate the influence of the characteristics of the medium on the off-track performance of the data recovery channel.

In the conventional modeling of the readout process, it is assumed that media magnetization and head field are uniform across the track, and, consequently, the reciprocity integral may be written as a function of the track direction only. But in the case of patterned media the shape of the recorded bit is determined only by the geometry of the dot and not by the configuration of the recording head. The assumption of the uniform medium magnetization under the readout head is therefore inaccurate, because the width of the recorded dot may be comparable or less than the track width of current GMR sensors. To accurately predict the form of the readout signal analysis must be of the 3D level. Such an analysis was performed in [74] for the readout process from perpendicular patterned media using conventional GMR replay heads.

The system geometry is represented on the Fig. 4.

The GMR element (of unit reciprocity potential), of length $2L$, width $2W$ and semi-infinite height, lies at a distance d above the patterned medium (of thickness δ) and at equal distances G from the side shields. It is at a distance $t = d + \delta$ from the SUL of the medium, which is assumed to be ideal ($\mu \rightarrow \infty$). The coordinate origin is at the midpoint of the ABS of the GMR element.

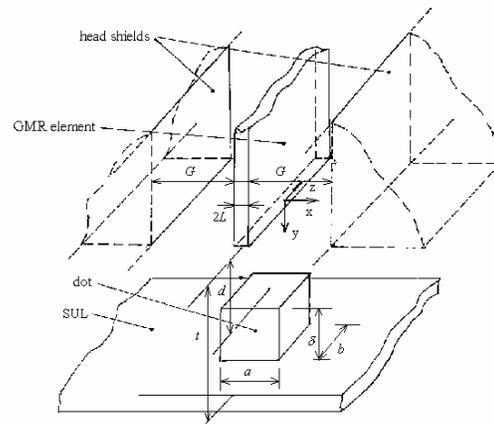


Fig. 4. The geometry of the readout system with GMR head on a perpendicular patterned medium [74].

The readout tension due to an arbitrary change in medium magnetization is calculated using the reciprocity integral [6]. In the case of a GMR head, it is directly proportional to the flux signal received by the sensor through its ABS. In this 2D case, when the medium is at $\bar{x} = vt$ position, the flux $\Phi_{\text{signal}}(\bar{x})$ is given by the scalar correlation integral [3, 6]:

$$\Phi_{\text{signal}}(\bar{x}) = \mu_0 W_t \int_{-\infty}^{\infty} dx \int_d^{d+\delta} H_y(x, y) M_y(x - \bar{x}) dy, \quad (16)$$

where H_y is the sensitivity function of the head, W_t is the effective width and M_y is the perpendicular component of the magnetization. The sensitivity function of the head is related to the derivative of the scalar magnetic potential φ , and then we can write equation (16) in the form:

$$\Phi_{\text{signal}}(\bar{x}) = \mu_0 W_t \int_{-\infty}^{\infty} \left[- \int_d^{d+\delta} \frac{\partial \varphi(x, y)}{\partial y} dy \right] M_y(x - \bar{x}) dx \quad (17)$$

which contains some correlation integrals \otimes :

$$\Phi_{\text{signal}}(\bar{x}) = \mu_0 W_t \times \left\{ \left[M_y(x) \otimes \varphi(x, d) \right] - \left[M_y(x) \otimes \varphi(x, d + \delta) \right] \right\}. \quad (18)$$

Therefore, the reciprocity formula for the GMR head may be written in the form [54]:

$$\Phi_{\text{signal}}(\bar{x}) = \mu_0 W_t F^{-1} \left[\hat{M}_y^*(k_x) \cdot \hat{\varphi}(k_x, d) \right] - \mu_0 W_t F^{-1} \left[\hat{M}_y^*(k_x) \cdot \hat{\varphi}(k_x, d + \delta) \right]; \quad (19)$$

\hat{M}_y^* is the complex conjugate Fourier transform of M_y , $\hat{\varphi}$ is the Fourier transform of φ , k_x is the Fourier transform wave-number in x , and F^{-1} is the inverse Fourier transform operator.

To obtain the magnetic flux in the GMR sensor due to a magnetization change in the medium, the magnetic (scalar) potential distributions on the both (top, $y = d$, and bottom, $y = d + \delta$) faces of the medium must be determined. In the absence of SUL, one can use the method proposed by Potter [75], considering the GMR head as a double inductive Karlqvist head. The potential at ABS can be expressed with a satisfactory accuracy as a linear variation across the gap between the GMR sensor and a side shield

$$\varphi(x, 0) = \begin{cases} 1, & 0 \leq |x| \leq L, \\ (L + G - |x|)/G, & L < |x| < L + G, \\ 0, & |x| \geq L + G. \end{cases} \quad (20)$$

Some other approximations were been also proposed.

It results now the expression of the potential anywhere below the ABS, using the spacing loss expression [6, 76]:

$$\hat{\varphi}(k_x, y) = \hat{\varphi}(k_x, 0) e^{-k_x y}. \quad (21)$$

On the contrary, in the presence of SUL, the approach becomes more complex. As a first approximation, one can take the SUL into consideration by introducing the sensitivity function of the head and of its image in SUL [77]. Another approach involves the calculation of the potential φ distribution below ABS, for example as a weighted sum of the potential variation between the pole corner and the SUL (rather than the pole corner and the shield) [78]. The results were satisfactory, but they are not appropriate in 3D, when track edge effects are important, because this technique provides no variation of the potential across the track.

In the case of patterned media, the shape and the size of recorded domains depend on the geometry of the magnetic dots and, therefore, a more accurate model of the readout process is needed, taking into account the magnetization variations in both in-plane directions, x and z . This observation imposes the extension in 3D of the reciprocity integral:

$$\begin{aligned} \Phi_{\text{signal}}(\bar{x}) &= \mu_0 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left[- \int_d^{d+\delta} \frac{\partial \varphi(x, y, z)}{\partial y} dy \right] \times \\ &\quad \times M_y(x - \bar{x}) dx dz = \\ &= \mu_0 F^{-1} \left[\hat{M}_y^*(k_x, k_z) \cdot \hat{\varphi}(k_x, d, k_z) \right] - \\ &\quad - \mu_0 F^{-1} \left[\hat{M}_y^*(k_x, k_z) \cdot \hat{\varphi}(k_x, d + \delta, k_z) \right] \end{aligned} \quad (22)$$

Fourier techniques are then employed to obtain the Fourier transform of the potential at ABS ($y = 0$) and at any other plane below ABS, at $y = t$ (the SUL plane) for example [79]. These functions are related by [76]:

$$F^{-1}[\varphi(k_x, y, k_z)] = \frac{\text{sh}(\kappa(t - y))}{\text{sh}(\kappa t)} F^{-1}[\varphi(k_x, 0, k_z)] \quad (23)$$

with $\kappa = (k_x^2 + k_z^2)^{1/2}$, k_x and k_z being the wave-numbers along (x) and across (z) the track direction. This last equation leads to better approximate expressions for the potential under the GMR head and under shields.

Applying this technique [74] proves that in the case of a patterned medium with SUL the shape of the readout pulse is practically independent of the dot width, but in the absence of SUL the pulse response depends largely on the shape of the magnetic dot, in particular on its width. For a constant length of the bit, its width becomes very large as compared to the width of the GMR sensor and, therefore, the response is similar to that resulting in a 2D approach [75, 80]. A similar conclusion results if the sensor width is increased, keeping the bit width constant. When the widths of the head sensor and of the dot are comparable, the amount of overshoot in an isolated pulse is overestimated using conventional 2D approaches [74]. They are even minimum when these widths are equal, but in this case the pulsewidth is also at its maximum. Therefore, a compromise must be obtained between the pulsewidth required and the amount of overshoot tolerated by the electronics of the channel.

A later analysis of the same authors [81] concerns the off-track performance of patterned media storage systems,

taking into account the finite track width and using again a 3D replay model that predicts accurately the replay signal for the shape constrained media. They have shown that the shape of dots, the film thickness and the presence of SUL have little effect on the off-track signal. Nevertheless, the distribution of dots can have an important impact on the channel performance, particularly in the presence of the track misregistration. Dots can be arranged on a regular square grid (Fig. 5,a) or packed in a hexagonal lattice (Fig. 5,b), depending upon the lithographic approach employed [82]. When the dots are distributed over a hexagonal lattice, the channel bit-error-rate performance is better; in particular, the read channel is more tolerant to track misregistration than in the case of the square array distribution of the dots. To obtain a satisfactory bit-error-rate ($< 10^{-5}$) SNR must be improved by about 3 dB for the case of a hexagonal lattice, whereas for the square array this performance is constrained by the inter-track-interference introduced by the track misregistration and is largely independent on SNR. This better performance of the *hcp* medium is due especially to the reduced inter-track-interference in the timing window, since the dots belonging to the neighboring tracks are not directly adjacent to the dots situated on the main track, but displaced by half a period along the track.

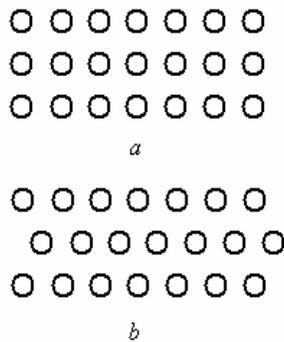


Fig. 5. Possible arrangements of magnetic dots: a – regular square lattice; b – hexagonal lattice.

7. Conclusions

The future extremely high-density recording media ($> 1 \text{ Tb/in}^2$) require further reduction of magnetic grain size and thus materials with ultrahigh magnetocrystalline anisotropy are needed to overcome the superparamagnetic limit. The directly prepared highly oriented nanoparticles with the same shape and their self-assembling into ordered superstructures in mono- or multilayers are appropriate for fabricating patterned recording media targeting for areal densities above 1 Tb/in^2 (one talk about more than 10 Tb/in^2 ...). Although some issues such as long-range-ordered patterning, control of the disk surface roughness, signal readback, etc., still remain critical engineering problems to solve [56], the successful preparation of these systems forms one solid basis for the continuous areal density increase for future.

The recording on patterned media is very sensitive to the distributions of the magnetic properties and the dot spacing [68].

A thorough analysis proves that patterned media with conventional magnetic work well at 1 Tb/in^2 with either a pole head/SUL or with a ring head. In the absence of distributions (fluctuations), the performance is limited by the write ability and the timing errors caused by the distributions of the demagnetizing fields. Such a system works therefore best if the interactions are as small as possible. So flat dots are favourable because they have smaller interaction fields and allow higher average head fields. On the other hand, the best ring head performance corresponds to relatively large gaps. Another observation is that the constraint $\kappa > 20$ for the neighbour track means that the grain volume V cannot be scaled at higher densities. If the bit aspect ratio is 1 (circular dots), the achievable areal density is seriously reduced, because the head field is generally insufficient. Using a ring head for the low – bit aspect ratio seems to be mitigated by opening the gap. The best performance requires composite media [68], in association with a pole head/SUL, although the use of ring heads also gives some advantages. The effects of distributions can be mitigated in all cases, by using convenient head designs with higher field gradients.

The effect of the superparamagnetic behaviour of particles will soon force the industry to find alternatives for the current hard disk technology. The magnetic recording using patterned media is regarded today as the next possible step ahead in magnetic recording, as well as the hybrid recording [6]. However, the discrete magnetic media will have to adapt to the rotating disk systems, so that circular arrangements of the dots must be envisaged. The lithographic technology with electrons beam is considered to be the most adequate for such arrangements.

The recording capacity of the system and the data transfer speed are more or less proportional, so that both of them will have to be accordingly increased. This will certainly cause a revolution in the hard disks technology: high rotation speed of the disk, and data transfer rate of about Tbyte/s with only one reading/writing head will force again the recording industry to search for new alternatives. The scanning probe array system could be such a solution [83, 84]. Rectangular arrangements are very convenient for the multiheads of these recording systems on condition that a periodicity of the structures under 50 nm could be ensured.

One possible route to higher recording densities is to use multilevel recording, where more than two states are stored per dot. An example of this approach is to use two decoupled layers with different coercive fields deposited onto the same dot. Data can be thus stored on each layer and addressed independently [54], leading to a significant gain in recording density.

There are of course alternatives to discrete magnetic recording. Such an alternative would be avoiding the superparamagnetic behavior of the very small written bits by means of using very high anisotropy media. But the writing fields that can be generated with the conventional heads used in hard disk systems would be not enough then,

and for the time being, there are no materials for heads whose saturation magnetization be much higher. One solution would be the local heating of the media in order to temporarily reduce its coercivity, as in the case of hybrid recording.

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