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Invited Paper

NEW SOLUTIONS FOR IMPROVING RECORDING PERFORMANCE OF MAGNETIC RECORDING MEDIA

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Until some potentially superior technology such as perpendicular recording becomes practical, several solutions were proposed to extend the longitudinal recording. Among them, the most promising in this stage of evolution of magnetic recording seems to be the magnetic recording media with thermal stabilization layers and the recording media comprising monodisperse high-anisotropy nanoparticles in a self-organized patterning. Both these types of media have been found to 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 media with thermal stabilization layers consist of two antiferromagnetically coupled ferro-magnetic layers. Their higher areal density and better thermal stability are due to the reduced value of the so-called magnetic thickness $M_r\delta$ (M_r – remanent magnetization, δ – layer thickness) and to the increased grain volume as compared to conventional (monolayer) media. On the other hand, the self-organized patterned media permit the 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. Understanding the magnetic properties of these media ensures the 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 performances have known an accelerated progress since the moment of the promotion of this method for the recording and reproduction of sound, image and information. The progress is today greater than 100% per year, so that the recording areal density has increased to double in less than a year. This progress is due to a huge accumulated know-how and to several important findings in domains like material science, signal processing and recording technology [1–19]. 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 recent research [20] seems to prove that these limits can be overpassed.

Until some potentially superior technology such as perpendicular recording becomes practical, several solutions have been proposed to extend the longitudinal recording. Among them, the most promising seems to be the recording media with thermal stabilization layers and the recording media comprising monodisperse high-anisotropy nanoparticles in a self-organized patterning. Both these kinds of media have been found to have higher thermal stability, low noise and higher signal resolution which, in turn, led to higher areal density and a better signal-to-noise ratio. Understanding the magnetic properties of these media ensures a better 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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2. Solutions for improving the energy barrier

Thermal degradation of written information, due to the superparamagnetic effect, has been recognized as the major limiting factor for high-density longitudinal recording. The best description of this phenomenon is done by the coefficient of thermal stabilization $\kappa = K_u V / k_B T$, where K_u is the constant of uniaxial anisotropy of the material, V is the grain volume, k_B – the Boltzmann's constant and T – the temperature. The minimum value of this coefficient that ensures the thermal stability of the medium is about 55.

In traditional scaling of longitudinal magnetic recording, both the volume V of magnetic grains and the so-called *magnetic thickness* $M_r\delta$ (M_r – remanent magnetization, δ – the physical thickness of the recording medium) are proportionally reduced. But such scaling leads just to the above mentioned limit of κ and facilitates the thermally activated reversal of the magnetization over its magnetic energy barrier $K_u V$ [7].

A possible solution to effectively increase the volume V of magnetic grains is a magnetic layer thicker than the grain diameter. The volume – and therefore the thermal stability – is then increased without increasing the density of grains and of the medium noise – concept similar to the argument the most often offered in favour of perpendicular recording. Nevertheless, unlike the perpendicular media, the magnetization configuration of longitudinal media is less favourable, because the demagnetising factor N increases considerably with the medium thickness, and the read out resolution is severely lost. A possible issue offers the technology of exchange polarization.

Indeed, let us consider an intermediate layer (2), uniaxial antiferromagnetic (AF), exchange coupled with the magnetic recording layer (1). The energy barrier is thus:

$$\Delta W \propto \left(K_{u,1} - w_{d,1}\right)V_1 + K_{u,2}V_2 ; \qquad (1)$$

the volumes V_1 and V_2 correspond in fact to the thickness of the layers, because the energy barrier is calculated for an isolated cylindrical grain. The density of demagnetising energy $w_{d,1}$ implies only the ferromagnetic layer, because in the AF part of this structure there is no magnetostatic interaction. The energy of exchange coupling is supposed to be much greater than all the other energy terms, so that the coupled volumes commute simultaneously, particularly by the excursion of a wall in the AF layer.

The advantage of this construction relies in the fact that the entire area magnetically active is very close to the head, while the magnetic layer remains thin, which enables a high read out resolution. While recording, the magnetically active area, situated near the head, makes the magnetic interaction very efficient because it uses the most intense area head field.

However, there are certain elements which should be taken into consideration. Thus, in order to be efficient in terms of thermal stability, the term $K_{u,2}V_2$ must be high. One could think that the anisotropy constant $K_{u,2}$ should be at least comparable to that of the magnetic recording layer. But most of the AF materials have a cubic crystalline structure, and therefore a limited anisoptropy and those that are not cubical have complex crystalline structures, so that higher processing temperature is necessary. Or, due to the high chemical diffusion at these temperatures, it is difficult to achieve a correct chemical composition of the thin layers. Furthermore, the crystalline texture and the lattice constants must be correctly selected in order to maintain the coupling during the increasing of the recording layer of Co based *hcp* alloy. At the same time, even if we suppose that such a uniaxial material could be found and processed, its thickness should be chosen accordingly. Then, the thickness of the domain walls are in inverse relationship with the anisotropy energy of the material. Thus, if $K_{u,2}$ is high – as it must be – the thickness of the wall moving from the interface inside the AF layer in the writing process shall be small just before switching this layer. However, if the thickness of the AF layer is much bigger than the thickness of the wall, this layer may not commute, and then the coupling of the AF layer determines an increase in the thermal instability of the recorded information.

A different approach could borrow an element of the perpendicular recording using a soft magnetic layer to keep the magnetic flux as underlayer or as seed layer. The magnetostatic interactions between the the recording layer and this soft magnetic layer determines the closure through the soft layer of the magnetic flux associated to a written bit. The demagnetizing energy is thus reduced, which is useful especially when the head tranductor is not near the bit of interest. The magnetic transition is therefore more stable, and it will be narrower during the read out process.

However, there are two disadvantages of this solution. Firstly, the signal received by the head is weaker since a part of the magnetic flux passes through the keeper layer. Secondly, during the recording process, part of the head flux is keeped by the soft magnetic layer, which means that a stronger magnetic flux will be required.

Summing up, neither of these solutions seems to be more advantageaous than the simple increase in the anisotropy of the recording magnetic layer.

3. Antiferromagnetically coupled media

The concept of the antiferromagnetically coupled media has evolved as it follows. To start with, it has been found that if the thickness is properly controlled, one can obtain an exchange AF coupling by inserting a Cr layer between two ferromagnetic layers of Fe. Then, it has been noticed that if the Cr layer is inserted between two ferromagnetic layers of Co, the exchange coupling can be both feromagnetic and antiferromagnetic. Thus, if the configuration is correct, the magnetizations of the two ferromagnetic layers can be opposed. Or, if the magnetic moments of the two layers are equal, they compensate each other obtaining a synthetic AF structure. Recently, it has been found that by inserting a Ru *hcp* layer of approximately 0.8 nm thick between the Co *hcp* layers, the exchange coupling is considerably enhanced.

This concept can be used with an even or an odd number of layers of Co based alloy having different thicknesses and anisotropy constants. According to their choice and their disposal, the magnetostatic coupling between the layers can vary in order to effectively obtain a recording magnetic layer. Since the layer of Co alloy that is closest to the recording head has the strongest magnetization, and the magnetizations of the other layers compensate each other, the read out resolution is still good. However, the field of the writing head should be strong enough in order to simultaneously reverse the magnetization of all the Co layers. When annihilating the head field, the whole structure should relax until obtaing the AF position.

An increased recording density of conventional longitudinal media together with an improvement of their thermal stability and of the signal-to-noise ratio (SNR) can be obtained by reducing the magnetic thickness ($M_r\delta$) of the medium. Therefore, media structures with thermal stabilization layers have been recently suggested. These are known as:

- synthetic ferromagnetic media [21,22];
- antiferromagnetically coupled media [23,24];
- laminated antiferromagnetically coupled media [25–28].

They will be hereinafter labelled by means of the acronym AFC.

Such media are made up of two thin ferromagnetic layers, labelled as S (above) and J (below), which are separated by a Ru layer whose thickness is selected so that it enables their antiferromagnetic (AF) exchange coupling (Fig. 1). (As with the conventional media, the AFC medium is made up of exchange uncoupled grains, but now each grain structure covers both layers due to the AF coupling.) For such a structure, the effective magnetic thickness is

$$(M_r\delta)_{eff} = (M_r\delta)_S - (M_r\delta)_J , \tag{2}$$

and the effective energy barrier is included in the range

$$K_S V_S < K_S V_{eff} < K_S V_S + K_S V_J , \tag{3}$$

where $K_S V_S$ and $K_S V_J$ are the magnetic energies of the grains belonging to the upper and to the lower layers. Thus, the AFC media enable scaling down the magnetic thickness without compromising the thermal stability.

Fig. 2 presents the typical hysteresis loop of a CAF structure made up of a S layer of CoPtCrB, with $(M_r\delta)_S$ = 3.8 mA and a J layer of CoPtCrTa, with $(M_r\delta)_J$ = 1.5 mA [29]. When applying a strong field, the AF coupling is surpassed, and the magnetizations of the two layers become parallel. Reducing the field below the effective exchange field H_{exc} determines the magnetization reversal of the J layer so that at remanence the magnetizations of the two layers are antiparallel. The magnetization of the stabilization layer J partly annihilates the magnetization of the recording layer S, reducing the magnetic thickness $(M_r\delta)$, but only when the magnetization of the J layer is reversed within the first quadrant of the hysteresis loop [30], that is if $J_{exc} > 2K_{u,J}\delta_J$. The decrease of the magnetic thickness is thus obtained as a result of the competition between the anisotropy energy and the exchange AF coupling energy.

Making a minor loop around H_{exc} prevents the magnetization reversal of the bottom layer. The width of the minor loop represents a measure of the coercitive field $H_{c,J}$ of this layer, while the centre of the loop is an adequate measure of the field H_{exc} (of the order 80 kA/m in this case). It is known that

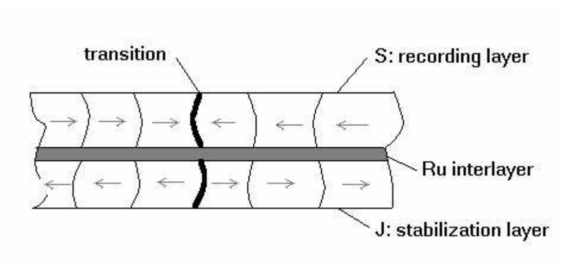

Fig. 1. Schematic representation of an AFC medium.

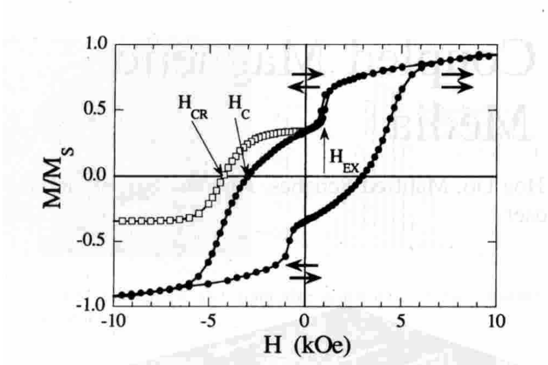

Fig. 2. Typical hysteresis loop of a AFC medium [29].

$$H_{exc} \propto J_{exc} / (M_r\delta)_J ,$$

where J_{exc} (= 0.13×10^{-3} Js/m^2 for this system) is the exchange energy between the two layers, over the Ru layer [23]. The AF coupling of the layers is due to the RKKY interactions over the intermediate Ru layer, as well as to the dipolar coupling of the grains in the two layers. The dependence of these interactions on the thickness of the intermediate layer δ_{Ru} is done by the relation

$$H_{exc}(\delta_{Ru}) = \frac{H_0}{\delta_{Ru}^2} \frac{T\delta_{Ru}/\alpha}{\sinh(T\delta_{Ru}/\alpha)} \sin\left(\varphi + 2\pi\frac{\delta_{Ru}}{\lambda}\right) + H_d\, exp\left(-\frac{\delta_{Ru}}{\delta_d}\right), \tag{4}$$

where the first term of the right member is the standard RKKY term, which oscillates by the period λ and the phase φ, and it is damped by $1/\delta_{Ru}^2$, and the second term describes the dipolar interaction as an exponential decrease where the field H_d and the decrease length δ_d depend on the dimensions of the grains and on the thickness of the intergrain frontiers between the two layers.

The system has high signal resolution and low noise because of the reduction of the magnetic thickness $(M_r\delta)$, which is required in order to improve the transition parameter a. Indeed, in a conventional monolayer medium, the contribution of the medium to the value of the parameter a comes out of the formula

$$a \cong \sqrt{\frac{(M_r\delta)}{H_c}\left(d + \frac{\delta}{2}\right)C} , \tag{5}$$

where H_c represents the coercive field of the medium, d is the distance head-medium, and C is a constant determined by the other parameters of the recording [31].

One may question the applicability of this relation to AFC structures since the thickness δ of the medium can increase even when the magnetic thickness ($M_r\delta$) decreases. Nevertheless, a surprising result is in the fact that, for AFC media, the pulse width PW_{50} can scale by the average value of the magnetic thickness of the medium just as with the monolayer media [21,23]. But PW_{50} depends both on the $(M_r\delta)_{eff}$ of the medium and on the magnetic thickness of each of the two layers. For a monolayer medium, PW_{50} depends on the transition parameter a according to the relation:

$$PW_{50} \cong 2\sqrt{g^2 + (d + a)^2} \tag{6}$$

($2g$ – the head gap), the previous observation suggesting similar values for the parameter a. This behaviour can be better understood by taking into account the responses of the recording layer S and of the stabilization layer J in terms of superpositioning two opposed signals [24]. Reducing ($M_r\delta$) determines a reduced value of the transition parameter, whereas the increase in the total thickness of the layer improves thermal stability due to a larger grain volume as compared to the conventional medium [21,23,24,32-35]. This structure enables an independent optimization of the magnetic thickness and of the thermal stability by adjusting the thickness and the magnetic properties of each layer. Thus, it has been observed that thermal stability improves if the bottom layer has a stronger magnetic anisotropy [33], and if the AF exchange coupling J between the two layers is stronger [33,36,37] – observations that have often been experimentally confirmed [22,35,38,39].

At the same time, it has been observed that in a correctly obtained AFC medium the writing field is smaller than in a monolayer stable medium, and it also has a high SNR [32].

During the writing process, the recording head first defines the transition in the S layer, while the head field saturates the stabilizing layer J. The transition in the J layer is then determined by the exchange interactions with the recording layer S. The fact that the system can have the magnetizations of the two layers oriented antiparallelly in the remanent state sets a superior limit to the thickness and coercivity of the stabilizing layer J. In other words, the system must satisfy the condition $H_{exc} > H_{c,J}$, where $H_{c,J}$ is the coercitive field of the layer J.

Experience has proved that in the beginning, the magnetic thickness ($M_r\delta$) decreases when the thickness of the stabilization layer increases due to the AF coupling. The maximum thickness of δ_J, beyond which this decrease no longer appears, depends both on $K_{u,J}$ and on $M_{r,J}$. When the anisotropy constant $K_{u,J}$ increases, the maximum thickness decreases, which proves that for a given value of the exchange integral J, the decrease in the magnetic thickness of the media can be controlled by adjusting the parameters of the stabilization layer.

The magnetic thickness ($M_r\delta$) can also be reduced by increasing the exchange parameter J, which can be done by inserting thin interface layers of Co under and above the intermediate layer of Ru (Fig. 3,b) [27]. The increase in the thickness of these supplementary layers also determines the increase of J. This effect may have several explanations:

(1) In the presence of thermal energy, the bigger grains in the stabilization layer have greater coercivity than H_{exc}, for lower values of J. However, when J is increased, in most grains $H_{exc} > H_c$, so that the magnetic thickness ($M_r\delta$) decreases.

(2) For a particle of the AFC structure, made up of a single grain of the two layers AF coupled, the energy minimum is attained when the magnetic moments of the grains in the recording and stabilization layers (of the AFC particle) are either parallel or antiparallel. But for a group of particles, the alignment of the moments in the two layers is determined by the competition between the magnetostatic, anisotropy, and AF exchange energies. The minimum energy is no longer attained when orienting the group of AFC particles at 0° or at 180°. However, if the energy of the AF coupling increases, the minimum energy is still attained at such an alignment (0° or 180°) of the magnetic moments of the two layers. Thus, the magnetic thickness ($M_r\delta$) decreases when J increases [40].

The above arguments concerning the decrease in ($M_r\delta$), based on energy considerations, are only qualitative, especially with regard to estimating J. Or, the numerical simulations and theoretical estimates show a value of the J constant above 10^{-3} J/m^2, [40-42], which is a lot more than the values resulting from the examination of the minor hysteresis loops, of about 0.08×10^{-3} J/m^2 [43], in order to lead to a decrease in the magnetic thickness ($M_r\delta$). This incongruity is due mainly to thermal energy, systematically left out in simulations and theoretical approaches [25,26,28,43,44]. It is true that in order to reduce the magnetic thickness ($M_r\delta$), it is necessary that

$$H_{exc} > H_c(T=0) = 2\frac{K_{u,J}}{\mu_0 M_J} = 0.52 \text{ MA/m}.$$

At room temperature, the coercive field of a system of particles depends on the time in accordance with Sharrock's equation:

$$H_c(t) = H_0\left[1-\left(\frac{k_B T}{K_u V}\ln\frac{f_0 t}{\ln 2}\right)^n\right], \quad (7)$$

with $f_0 = 10^{-9}$ s, according to which, if the coefficient κ is lower (as it is the case of the grains in the stabilization layer), the coercive field decreases in time. Therefore, after a few seconds (that is the time for measuring by using a VSM), the coercitive field will be a lot smaller than $H_c(T=0)$. Thus, due to the thermal energy $k_B T$, the condition $H_{exc} > H_c$ necessary in order to reduce ($M_r\delta$) can be achieved even for lower values of the exchange constant J (or of the exchange field $H_{exc} = J/(M_J\delta_J)$) [26].

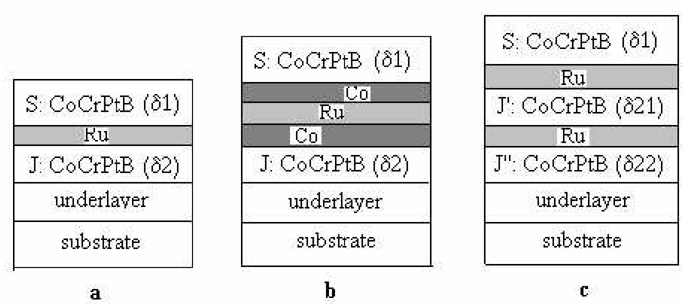

Fig. 3. Different types of media in structure AFC [28]: *a* – normal structure; *b* – structure with improved *J*; *c* – multilayer structure.

Although the remanent state is thermally stable, thermal activation plays a major role from the point of view of the reversal properties in the AFC media [26,35,39,44], which is different from conventional media. Indeed, H_{exc} is low as compared to the anisotropy field of most Co based alloys used for recording media. However, it is thermal energy the one to determine, a little late, the decrease in the field $H_{c,J}$ below the value H_{exc}, thus enabling the antiparallel orientation of the magnetizations of the two layers. Therefore, there is a certain time gap between the moment of removing the head field and the moment of reversing the magnetization of the J layer. The duration of this relaxation process greatly influences the characteristics of the recording. If the relaxation time is too short (of about 1 ns), the magnetization reversal of the stabilization layer affects the recording of the following transition, leading to a non-linear excursion of the transition. On the contrary, if this time span is too long (about 1 s), the layer J may not have enough time to switch during a complete rotation of the disk, which will affect the read out signal. The thermal equilibrium reached by the layer J after the recording also influences a lot other characteristics of the recording process. Thus, a fundamental shortcoming of the AFC configuration lies in the non-linear transition, always much greater for these media because during the writing process, both the recording and the stabilization layers are saturated in the same direction, generating a demagnetaizing field much stronger at the moment of inscribing the transition.

In order to be able to control such effects, the energy and time scales relevant for the two layers and for the interaction between them must be characterized as well as possible. This is achieved by measuring the dependences on thickness and temperature of the minor and major hysteresis loops.

A small value of the coercive field H_c and a greater value of H_{exc}, can also be obtained by reducing the thickness of the stabilization layer, although the decrease of ($M_r\delta$) thus achieved is not enough in general. This can be also achieved by increasing the exchange constant J [33,45,46], although this solution generally leads to intensifying the medium noise [33,45]. In order to overcome this shortcoming, the multilayer structure presented in Fig. 3,*c* has been suggested: the decrease in the magnetic thickness is due to the two stabilization layers, which could be both thinner than in the bilayer AFC configuration. This determines a decrease in H_c and an increase of H_{exc}, and it also reduces the media noise. This shortcoming is not inherent to the AFC configuration, so that one shall always find alloys capable of an increased AF exchange without affecting the SNR [47].

There still remains the controversial problem of the origin of thermal stability provided by AFC structures at low values of magnetic thickness ($M_r\delta$). There are three possible explanations [28]:

i. The antiparallel allignment of the moments determines a decrease in the magnetic thickness even if the recording layer is thicker than in a conventional monolayer medium. The stabilization layer only reduces magnetic thickness, and thermal stability is consolidated by increasing the thickness of the recording layer.

ii. The existence of a volume effect, which lies in increasing the energy barrier, due to the increase of the anisotropy energy (K_uV). Regarding the AFC media, the grains of the two layers grow epitaxially, and they can be assimilated into one grain, larger in volume:

$$(K_u V)_{eff} = K_u V_S + \eta K_u V_J \,, \tag{8}$$

where η is an efficiency factor.

iii. The existence of a surface effect since J is a constant of surface energy, and its presence at the two interfaces leads to the appearance of an excess energy, so that the actual increase of a grain energy can be written

$$(K_u V)_{eff} = K_u V_S + JA \,, \tag{9}$$

where A is the area of the corresponding grains in the layers S and J, exchange coupled.

Each of these alternatives has been supported by experimental results, but not simultaneously.

One should also notice that, although the information recorded on the AFC structure media is more stable than it is on conventional monolayer media, the thermal activation of the layer J plays a major role in the writing process because the two layers have different thermal activation barriers.

In general, it is considered that the AFC bilayer configuration can improve the stabilization coefficient κ by about 20% [47]. In laboratory conditions and for AFC media, there have been recently obtained recording densities a little above 100 Gb/in^2, for values of 3.5 mA … 3.7 mA [48] and even 2.5 mA [38] of the magnetic thickness of the medium, and for commercial use in the mobile systems (laptop) values above 35 Gb/in^2 [49].

4. 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 dimensions and lay-out, and which are oriented in the same direction. This subject has been lately a topic of interest for researchers because the recording densities that can be thus achieved correspond to the minimum size of the particles thermally stable. The major noise source is no longer represented by the media, but by the method of locating and addressing individual particles. Supposing that we could find a way of addressing them, even the pure Co particles have a storage capacity of several Tb/in^2, which means that the particles of materials with higher anisotropy can be even smaller.

The microtechnology industry, which has lately made huge progress in term of continuously scaling down the size of devices, is now faced with a fundamental barrier. The main fields where this industry is applied are microelectronics and data recording. In microelectronics, the diffraction limits require the search of new lithographic technics. There are similar difficulties in data recording as well. Furthermore, the size of the recorded bits decreases faster than the limits accepted in microelectronics. One of the most important limitations concerns the thermal stability of the written bits. The smaller they become, their energy becomes of the same order as the fluctuations of thermal energy.

The stability in time of the recorded data has thus become a major objective for hard disks. One of the solutions suggested in order to go beyond the current limitations lies in the development of the *patterned media* [50–53], which enable overcoming the superparamagnetic limit of the current thin-layer media. Although the density of the data recorded on disk systems has practically doubled yearly during the last ten years, the access time has decreased only by 7 % yearly, which diminishes the performance of the desktop computers.

The main cause of this shortcoming is the architecture of the hard disk systems itself. Access time is mainly determined by the time that is required for the disk to rotate until it reaches the desired position. Or, in the current construction there is only one head for each side of the disk, so that the ratio between the number of heads and the bits on the disk quickly decreases at the same time as its capacity increases. In a correctly scalable architecture, it would be ideal if this ratio did not depend on the capacity. The solution lies in a radical change of the disk architecture so that it becomes scalable. From a mechanical point of view, the only solution is represented by the increase in the number of heads; however, since the number of necessary heads is of thousands, the future systems will have to be designed micromechanically. In such a system, called *scanning probe array*, a configuration of 32×32 writing/reading microheads is scanned on the recording media. The system can be based on optical, mechanical, thermal or magnetic detection principles. By using a discrete magnetic recording scheme, a recording density of the order Tb/in^2 can be theoretically obtained.

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

The principle of patterned media was introduced in the 60's to overcome the difficulties related to positioning the heads. The magnetic material that was 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. This system would be advantageous if these elements were mono-domain [39,54]. 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. The SNR of the read out signal is much better due to the absence of media noise and the excursion of transitions. Finally, the superparamagnetic limit is much superior to the one of the current thin-film layers.

When designing a patterned medium, the following requirements should 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 switch 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.

Different methods of producing these have been suggested. There are two types of methods: lithographic techniques and SOMA.

The lithographic techniques of submicronic 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 [54]. 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 problems to the configuration technology, which has not yet been developed even in the research laboratories. 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 final magnetic properties of the dots.

The research on Co- and CoNi-based multilayers has proved that, when correctly laid, these systems can have strong intergrain exchange coupling and important 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. This pitfall has been overcome by replacing the Co by an alloy $Co_{1-x}Ni_x$. 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 [55]. Only the dots whose diameter is of about 70 nm are certainly monodomain and those with diameters above 180 nm are only multi-domain. There is no a clear relationship between the diameter of the dots and their coercivity. Their shape influences their switch field, with values between 0.22 H_c and 0.5 H_c (H_c = 1.5 MA/m).

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

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

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.

The second way of configurating magnetic media consists in the use of the natural process of generating *self-ordered magnetic arrays* (SOMA). There are chemical reactions generating them or biologic materials forming a structure of monodimensional particles. The recording media formed of high anisotropy monodisperse nanoparticles (of exactly the same shape and size) have been proposed for achieving very high recording densities of about 200 Gb/in. The chemically synthesised nano-magnets have size distributions extremely narrow, which favour the self-organised patterning, and enables potential densities of about 1 bit/particle, the equivalent of 10 – 50 Tb/in^2 (2 – 8 Tb/cm^2) [56].

Among the materials having very strong anisotropy, special attention is given to the phase $L1_0$ of the equiatomic CoPt alloy and of the Fe-Pt alloy, thermally stable until grain diameters of 3 – 4 nm, which corresponds to a uniaxial anisotropy constant $K_u = 5 \times 10^6$ J/m^3 and, respectively, 6.6×10^6 J/m^3 [57,58]. In order to synthesize arrays of monodisperse nanoparticles with a diameter of 4 nm from Fe-Pt alloy in phase $L1_0$, organic stabilizers in non-aqueous solutions were used [59]. In thin layers of about 120 nm thick, made up of assemblies of nanoparticles of $Fe_{48}Pt_{52,}$ there were magnetization transitions corresponding to a recording density of 1.3 Gb/in^2 (0.2 Gb/cm^2).

Similar synthesis methods were used in order to obtain nanoparticles of Co [60], but for nano-particles 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 $L1_0$ of the equiatomic CoPt alloy were only produced by means of the biological template of ferritine [59].

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 [59,62]. 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 synthesised material. Moreover, the covering shell of the protein, about 2 nm thick, prevents the grains from synthesising at the high temperatures necessary to change the CoPt alloy into the $L1_0$ phase.

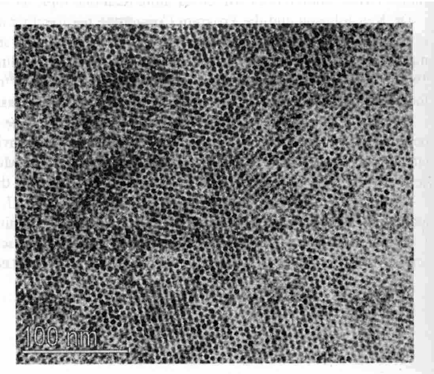

Fig. 4. TEM image of a self-organized *hcp* monolayer of protein-encapsulated nanoparticles.

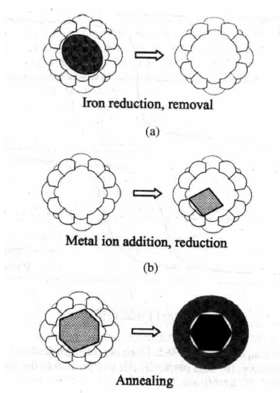

Fig. 5. Scheme for the production of biologically nanomagnets: *a* – amorphous ferrihydrite is reduced and removed from proteins to form apoferritin, *b* – then reconstituted with Co and Pt ions, and chemically reduced to form a full metal alloy core, *c* – that is annealed to form the phase $L1_0$ encased in a carbonized template [63].

Ferritine is made up of 24 almost identical subunities 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. 5). 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), and also at large variations of the pH for a limited period of time. The protein missing the original iron oxyde 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 reactives 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. 5,*c*). The recording densities thus obtained are higher than those obtained with Fe-Pt alloy, namely 2.2 Gb/in^2.

However, we are still far behind from the forecast recording densities of about 200 Gb/in^2, which, in order to be attained, require 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. If this control is not enough for refining of nanoparticles, one could use combined systems using, for example, 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 nano-particles 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/in^2 (0.7 Tb/cm^2) [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 monosize magnetic particles, it is very important for them to be oriented in the same direction.

Indeed, let us consider the limit case of a single particle corresponding to each recorded bit. 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 configurating 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 from this point of view.

Thus, the way for getting patterned media is definitively open.

5. Conclusions

With regard to the AFC structure media, it is still necessary to experiment a lot until reaching optimum performance. On the other hand, the structure should be optimised again after replacement of the writing or reading heads or when modifying their flying height. One should also take into consideration the fact that we supposed that the size and the distribution of the grains, and intergrain exchange coupling remain small enough to be able to control the media noise. It was supposed also that the Ru layer is perfectly homogeneous throughout the entire medium because otherwise there would be parts of the surface ferromagnetically exchange coupled whose effect would be “to see” very thick ferromagnetic layers. Others remain AF coupled. Undoubtedly, there is still a lot to be cleared up concerning the effect of thermal energy in the behaviour of these recording media.

The effect of the superparamagnetic behaviour of particles will soon force the industry to find alternatives for the current hard disk technology. The discrete magnetic recording using patterned media is regarded today as the next possible step ahead in magnetic recording. 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.

On the other hand, 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 [65,66]. 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.

There are of course alternatives to discrete magnetic recording. Such an alternative would be avoiding the superparamagnetic behaviour of the very small written bits by means of using very strong 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, it seems that 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 temporarly reduce its coercivity.

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