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Section 5b. MAGNETIC MATERIALS
Invited Paper

MAGNETIC MATERIALS FOR ADVANCED MAGNETIC RECORDING MEDIA

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The article presents the main properties of the media used for magnetic recording of information, analyses the sources of their performance limitations and proposes the solutions for passing over these limits. There are discussed the perspectives for the evolution of magnetic recording media, in order to increase the recording density, the medium thermal stability and to improve the signal to noise ratio.

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1. Introduction

The magnetic materials crystalline and amorphous found a large range of applications that are continuously expanded [1-6]. One of the leading applications is the magnetic recording of information.

The magnetic recording performances have known an accelerated progress, since the moment of the discovery of this method for the recording and reproduction of sound, image and information.

The progress was only 25-30% per year until the 80's, but it increased to 60% in the 90's due to the introduction of thin films media and magnetoresistive (MR) sensors. Today, this rate is greater than 100% per year, so the recording density and speed is doubled in less than a year. This progress is due to a huge know-how, accumulated during the years and on some important discoveries in domains like material science, signal processing and recording system technologies [7-10]. One thinks that one approach the theoretical physical frontiers of the recording density – limits imposed by the energetically based assumptions concerning the thermal stability and the signal to noise ratio (SNR). Nevertheless, some recent research [11] has shown that one can overpass these limits. Extended scientific studies are reported continuously on recording media [12,13].

The article presents the main properties of the media used for information magnetic recording, analyzing the sources of their performance limitation and proposing solutions for passing over these frontiers.

2. General considerations

According to the main features imposed to the magnetic recording media – a signal as high and a noise as low as possible – we firstly analyze the criteria imposed to these media: high magnetization; high coercivity, but correlated with the recording field; a particulate configuration, composed by monodomain particles or grains; narrow distributions of the particles or grains size, shapes and commutation fields; particles or grains as small as possible, but thermally stable and therefore a reduced thickness of the active magnetic film of the medium; a good alignment of the particle or grain easy axis.

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These criteria are outlined by the frequency analysis of the magnetic recording channel. Indeed, for the case of the longitudinal recording with an inductive head, the reading voltage is

$$e(k) \propto vw[kM(k)]\delta H_{\mathrm{g}}(k)e^{-kd}\,\frac{1-e^{-k\delta}}{k\delta} \tag{1}$$

where $k = 2\pi/\lambda$ is the wave number (λ - wave length); v - the relative speed of the medium before the head; w - the recording track width; δ - the medium thickness or the effective penetration depth of the field in the case of thicker media; d – the head-medium spacing, a – the transition parameter, giving the spacing of transitions and therefore defining the necessary space for information bits recording. The parameters $M(k)$ and $H_{\mathrm{g}}(k)$ will be defined below. This relationship allows us to identify the recording losses which can influence the quality of recording:

(i) *Losses due to the magnetization transition*, $\exp(-ka)$, given by the parameter

$$M(k) \propto M_{\mathrm{r}} \exp(-ka)/k \tag{2}$$

where M_{r} is the remanent magnetization of the medium. The adopted value for a is imposed by the condition of a convenient recording field or by the necessity to limit the head demagnetizing field. The signal is proportional to M_{r} for high wavelengths and it exponentially decreases for low wavelengths. Therefore, there is an optimal M_{r} corresponding to the highest signal amplitude.

A representative parameter for recording quality is the impulse width for half of its amplitude:

$$P_{50} = 2\left[g^2 + (d+a)(d+a+\delta)\right]^{1/2} \tag{3}$$

where $2g$ is the head gap.

(ii) *Gap losses*, $\exp(-kd)$, due to the factor

$$H_{\mathrm{g}}(k) = \sin\mathrm{c}(kg) = \frac{\sin(kg)}{kg} = \frac{\sin(2\pi g/\lambda)}{2\pi g/\lambda} \tag{4}$$

resulted from the *arctan* expression of the head field [14].

(iii) *Spacing losses*, $\exp(-kd)$, due to the head-medium spacing. For the most applications, these losses are the most important in the read out channel and are dominant for low wavelengths in the recording channel.

(iv) *Thickness losses*, given by the factor $[1-\exp(k\delta)]/k\delta$, are due to the thickness δ of the magnetic layer.

(v) *Losses due to the particles' length* - important if the particles' average length l is in the same range with the transition spacing - are represented by

$$\sin\mathrm{c}(\pi l/\lambda) = \frac{\sin(\pi l/\lambda)}{\pi l/\lambda}. \tag{5}$$

This short analysis shows a fine correlation between the magnetic properties and the recording performances for the heads and media. For example, using different head-medium interfaces, one established the following empirical relations [15]:

(i) the length of the magnetization transition is proportional with $(\delta M_{\mathrm{r}}/H_{\mathrm{c}})^{\mathrm{n}}$;

(ii) the signal width at its half amplitude is proportional with $(\delta/H_{\mathrm{c}})^{\mathrm{n}}$;

(iii) the reading signal amplitude is proportional with $(\delta M_{\mathrm{r}} H_{\mathrm{c}})^{\mathrm{n}}$.

The exponent n is about 0.5 for media with the squarness factor M_r/M_s close to the unit and is 1 for high values of the demagnetization ratio M_r/H_c (M_s is the saturation magnetization and H_c is the material coercivity). The energy product must be sufficiently high to assure a detectable magnetic field by the head near the medium.

The previous relations, apparently conflictual, are well satisfied by using a material with moderate coercivity H_c (semi-hard materials) for the medium magnetic layer. The remanent magnetization M_r must also be high, in order to have a good reading amplitude, without a significant influence on the recording resolution; it doesn't appear directly in the expression of the signal width, but influences the *n*-exponent value.

Among the primary properties of the medium, the thickness δ is the parameter by which one optimizes usually its global performances. The digital recording is first limited by the recording density and then by the reading amplitude. This is the reason for producing ultra-thin media, with high H_c and M_r; however, a too strong remanence gives local demagnetizations (so, longer transitions) and a too big coercivity implies strong recording fields, which can saturate the head magnetic circuit.

In order to obtain a high-density recording, it is well to supervise: (i) the size and shape of the particles or grains; (ii) their magnetic anisotropy, magnetostatic coupling and the possible exchange coupling. In turn, these elements are determined by: (i) the mechanisms of the magnetization reversal of particles or grains; (ii) the medium noise; (iii) the long term stability in the presence of thermal perturbations; (iv) the internal demagnetizing fields; (v) their high speed commutation characteristics; (vi) the medium corrosion; (vii) the surface roughness, friction and wear.

3. Particulate media

The particulate media, which dominate the recording flexible media area (tapes and floppy disks) are obtained by deposing, on a rigid or flexible substrate, different kinds of magnetic particles incorporated in a non-magnetic binder.

For example, the γ-Fe_2O_3 particles are aciculate, with the length between 0.2 and 0.7 μm, and a thickness 7 times smaller. (For size lower than 0.2 μm, one touches the superparamagnetism limit and the particles' magnetization becomes unstable, due to their weak magnetocrystalline anisotropy; for particles greater than 1 μm, they have a multidomain structure, easy to modify even by weak fields). The particles have a strong shape anisotropy, with the easy axis oriented to the length direction. The coercivity of the medium is given by the magnetocrystalline and shape anisotropy of the particles and gives, in turn, the leakage field of the head, necessary to produce a magnetization transition. Due to their monodomain configuration, the magnetization mechanism of particles is the rotation of the magnetization vector. The particles are uniformly deposed on a polymer substrate and are aligned under the action of a magnetic field; for longitudinal recording, their long axes are parallel to the medium moving direction. The deposition is made mechanically and the alignment is operated when the binder is still humid and a little viscous, being followed by a rapid drying.

The very small thickness of the active magnetic layer is essential for obtaining a high density recording. Therefore, one supposed that the trend of media optimization would lead to the predominance of thin metallic films, with high remanence and coercivity, obtained by sputtering or evaporation. This prediction is not yet carried out, due to some technological and electronical reasons:

(i) the drawbacks of thin media, in comparison with the particulate ones – cost, wear, corrosion and noise – have not been considered;

(ii) the coming out of double-layer particulate media, which allow thin depositions, eliminating the advantage of more reduced thickness of continuous metallic media;

(iii) the development of high sensitivity magnetoresistance (MR) sensors (including those based on giant magnetoresistance effect – GMR and the spin-valve ones) reduces the importance of a high magnetization but increases the requirement of a low level of the medium.

This is why the particulate media are still predominant, despite that the thin layer tapes are more used in video applications. Among the tape media, the Ba ferrite has the highest potential to achieve very high recording densities, as well as for the perpendicular recording.

Magnetic properties. The intrinsic properties – saturation magnetization M_s, magneto-crystalline anisotropy constant K and Curie temperature T_C – depend on the material composition and morphology and on temperature. The extrinsic magnetic properties – coercivity H_c, remanence magnetization M_r and magnetic permeability μ - are influenced by the geometry of particles or grains and by their magnetostatic and exchange interactions.

To obtain a high remanence M_r, the saturation magnetization M_s must also be high and the rectangularity factor must be close to unit. But the medium demagnetizing field is proportional to M_r, so its optimum is finally a compromise between the two opposite tendencies. The amplitude of the reading flux, generated by the medium, is proportional with its density *n*. The noise due to the particles being proportional to $\sqrt{n}$, the signal to noise ratio (SNR) increases like $\sqrt{n}$. The medium must then contain a huge number of monodomain particles; the usual densities are 10^{20} - 10^{21}particles/m^3.

Another important parameter is the re-magnetizing field distribution (magnetization reversal) around the coercivity point, defined by the ratio $\Delta H/H_c$, where ΔH is the impulse width obtained through the derivation of the major hysteresis cycle around H_c, measured at the impulse half height. For reduced values of this ratio, $\Delta H/H_c = 0.2…0.3$, the most particles in the interesting zone commute for the same dispersion field, thus giving narrow magnetization transitions which favore the high-density recording.

An ideal recording media must contain the greatest possible number of fine particles, with a magnetic packing factor close to 100%, with high coercivity and remanence, low magnetostriction and a Curie temperature higher that the room one. The coercivity, which may be considered a measure of the necessary field for the particles' commutation, must be sufficiently high to assure the immunity for accidental commutation due to the thermal perturbations or the demagnetizing fields produced by the gradients of the magnetization. It must not depend on temperature, time or mechanical stresses; it must also be "accorded" to the head writing capability. The distribution of the re-magnetization field must be very narrow, to reduce the transition length and the print-through effect, and to optimize the overwriting of magnetic disks.

The magnetic anisotropy, essential for the coercivity of fine particles, may be magneto-crystalline or/and shape one, but always one prefers to be uniaxial. In the case of magnetocrystalline anisotropy, this condition imposes a hexagonal structure, with the senar axis *c* as easy axis, or a tetragonal structure. For shape anisotropy, the uniaxiality implies aciculate particles. When the two types of anisotropy are simultaneous, they are either added, if they are collinear like in the case of γ-Fe_2O_3 co-modified particles, or they are subtracted, if orthogonal, like in the Ba ferrite particles case.

Medium noise. In a recording system there are a lot of noise sources – drive motors, head, implied electronics and medium – the last being the most important in a system correctly designed [15]. It is due to the statistic fluctuations of signals, produced by the variations of particles' shape and size, by their non-homogeneous dispersion, by the variation of the magnetic layer thickness and the surface roughness.

The noise is the strongest for DC erased media, when all the variations of individual particles are pointed out, and it becomes weaker for AC erased media, due to the local closure of the flux between the interacting particles, the flux "seen" by the head being reduced. On the contrary, in the case of thin metallic media the noise of DC erased media is the weakest because it is due to a small grain structure with a high packing factor, and the noise of AC erased media is stronger, its origin being the intergrain interactions (especially the exchange ones) which produce agglomerations of grains with the same commutation field.

Mechanical considerations. In the case of the magnetic tapes systems, which are the main users of particulate media, the mechanical constraints are more severe than the electromagnetic ones, in order to achieve high recording densities. The main mechanical considerations concern: the quality of the tape edges, the lateral positioning and the dimensional stability of the tape, the surface roughness, friction and wear. The substrate, the method of tape cutting, the binder and the lubricants also play an important role for the reliability and maintenance of these systems.

Among the substrate materials, the best is polybenzoxalum (PBO), very stable and the only one, which is characterized by small coefficients of thermal and hygroscope dilatations and an exceptional mechanical resistance. Unfortunately, it is not yet available in commercial quantities. The usual materials (PET, Kaplan, PEN etc.) have important thermal and hygroscope dilatations, dangerous for the quality of recording, especially in the tape systems, which use multitracks heads for improving the system efficiency. So, it is difficult to increase too much the track density – and, consequently, the recording surface density – for these systems, in opposition to the case of rigid disk systems. Therefore, the tape systems have a recording surface density lower with more than one order to those of rigid disk systems – and this difference is expected to increase in the future.

The characteristics of the main particle types, which are used for magnetic recording media, are presented in Table 1. The Figs. 1-4 reproduce some of these media micrographs.

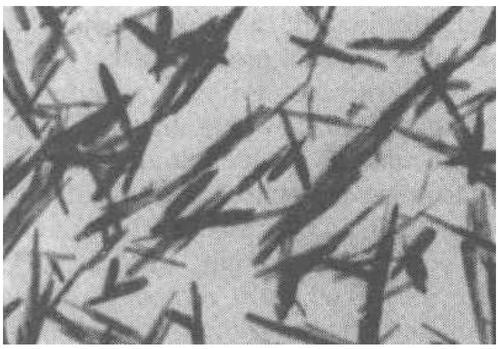
The γ-Fe_2O_3 media are spread in all the types of applications. The γ-Fe_2O_3 media Co-doped are used like tapes especially for digital and video recording. The same use is for metallic particulate media (Fe, pure or weak alloyed with Co), despite their stronger reactivity with resins and their easy oxidation in the presence of air. The CrO_2 media are also used for tapes; their reduced Curie temperature allows obtaining high-speed copies of the videotapes programs, by thermo-remanent transfer.

The Ba ferrite is unique among particulate media by the shape of its particles - hexagonal plaquettes - and its very strong magnetocrystalline anisotropy. It is the only material that can be used both for longitudinal recording and for perpendicular one, switching the easy axis orientation by adding of some metals (Co, Ni, Ti, Zn etc.). This material has the best potential of magnetic recording and is the only to be used to duplicate by contact at high speed digital tapes, by anhysteretic transfer.

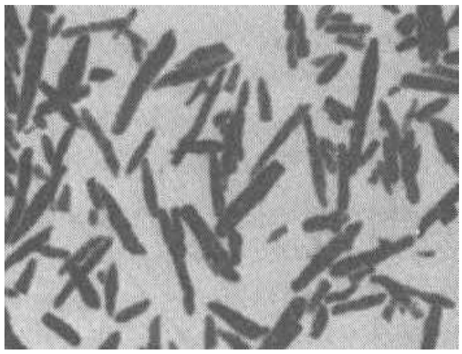
The particulate media don't allow ideal (abrupt) magnetization transitions due to: (i) the finite gradients for the longitudinal component of the leakage field and for the magnetization curve in the coercivity point; (ii) the demagnetizing phenomena in the medium; (iii) the finite thickness of the magnetic layer; (iv) the imperfect orientation of particles.

Table 1. Magnetic characteristics of several types of particles used for manufacturing the particulate media.

Material → Characteristic ↓	γ-Fe_2O_3	Co/ γ- Fe_2O_3	CrO_2	Fe	BaO · 6 Fe_2O_3
M_s [kA/m]	340	350	390	1000	380
M_r/M_s	0.5...0.8	0.5…0.8	0.5	0.3…0.5	0.6…0.7
T_C [°C]	600	600	125	768	320
K [kJ/m^3]	– 4.64	100	25	44	330
λ [$\times 10^6$]	–5	–5…–15	1	4	–
H_c [kA/m]	22...30	64	45...55	96	72
$\Delta H/H_c$	0.3…0.6	0.3…0.6	0.3…0.6	0.5…0.7	0.2…0.6
Density [kg/m^3]	4.6×10^3	4.8×10^3	4.9×10^3	5.8×10^3	5.3×10^3
Crystalline structure	cubic	cubic	tetragonal	CVC	hexagonal
Particle shape	needle-like	needle-like	needle-like	needle-like	platelet
Dimensions l/d [μm]	0.3/0.06	0.3/0.06	0.5/0.05	0.3/0.06	0.3/0.03
Type of magnetic order	ferri	ferri	ferro	ferro	ferri



(a)



(b)

Fig. 1. Electronic micrographs of γ–Fe_2O_3 particles, obtained from: a. α–FeOOH; b. α–Fe_2O_3 [7].

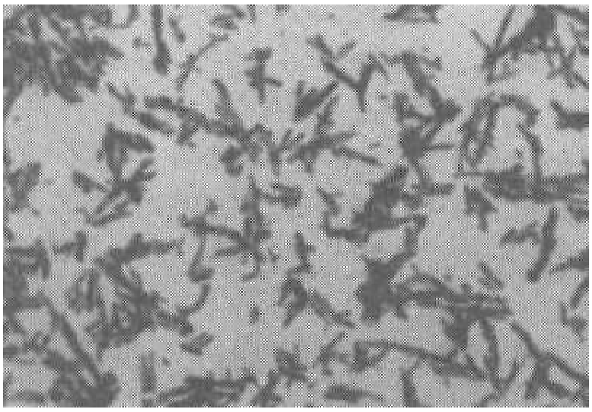


Fig. 2. Electronic micrographs of Fe particles [7].

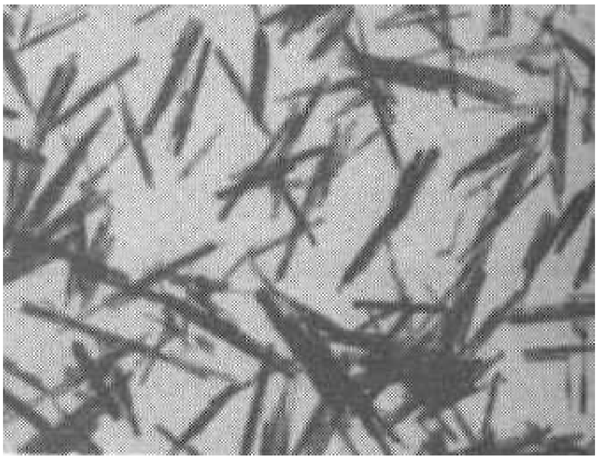


Fig. 3. Electronic micrographs of CrO_2 particles [7].

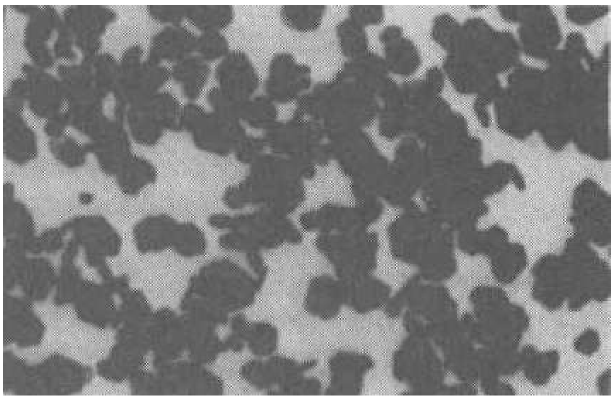


Fig. 4. Electronic micrographs of Ba ferrite plaquettes [7].

4. Thin film media

These media, which are obtained by electrochemical deposition, thermal evaporation and, especially, by sputtering certain metals or metallic oxides, are almost exclusively used for hard disks. Media are composed by small grains, in a non-magnetic phase, in order to reduce their exchange coupling – one of the most important causes of their noise. For the most cases, the material is a ferro-magnetic Co-based alloy. Thin film metallic media have two main advantages in comparison with the particulate media: (i) a magnetic package factor close to 100% and (ii) a very high saturation magnetization, due to the extensive use of cobalt. In their case, the previous mentioned drawbacks for particulate media are eliminated, excepting (i).

These media are realized by deposing on a flexible or rigid support (Al alloys for hard disks) of some ferromagnetic alloys based on Co (CoNiP, Co*R* etc.). One obtains extremely thin magnetic films (50-100 nm), as compared with the limit of 1 μm for the particulate media. The coercive field is about 50-100 kA/m.

The thin film tapes obtained by evaporation were promoted due to their reduced thickness of the magnetic layer and to their magnetization that is higher than for the metallic particulate tapes. Nevertheless, recent progress imposed to reconsider these arguments: (i) development of the double-layer particulate media allows very thin magnetic films (100 nm), and (ii) for high density recording one doesn't look for a too strong magnetization, due to the dispersion of the demagnetizing field in the transition regions. At the same time, the MR head use has eliminated the requirement of an important magnetization of the medium in order to obtain an optimized output signal.

On the other hand, the thin film tapes have several drawbacks [16]:

(i) the manufacturing process is much more expensive than for particulate media;

(ii) the necessity of substrates with improved thermal resistance and dimensional stability due to the higher deposition temperature;

(iii) the necessity of substrates with a very smooth surface, because any surface defect is reproduced by the surface of magnetic layer. Nevertheless, from the point of view of the head-medium interface, a too smooth surface of the substrate must be avoided, because it affects the wear and friction characteristics. In order to prevent these problems, the substrates for the media obtained by evaporation are first covered with a thin film containing small inorganic particles. In this way, on the deposited metallic layers, protuberances with 20-40 nm height, 200 nm diameter and a density of 10 protuberances/μm^3 result (Fig. 5);

(iv) the necessity of tape covering with a DCL (diamond-like-carbon) layer for protecting it against friction and corrosion, despite of the drawback of the increasing spacing losses;

(v) a lubrication supplementary layer must be applied on the DCL layer, in order to improve the friction properties of the head-medium interface;

(vi) a higher noise of the transitions, due to the strong intergrain coupling, which can be reduced by increasing the medium content in oxides.

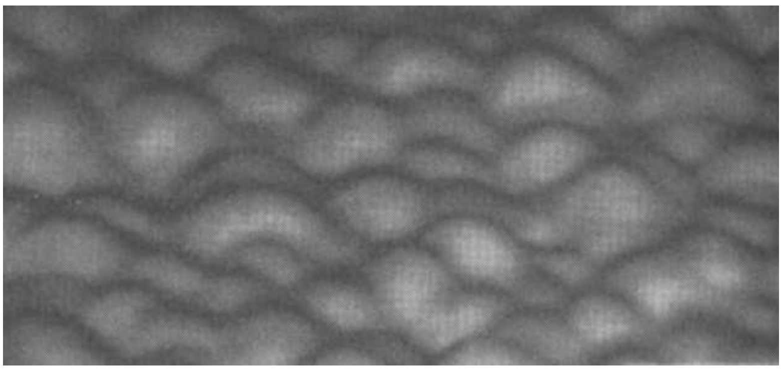


Fig. 5. AFM image of the surface topography for 60 nm Co-Cr-Pt layer, deposed on 10 nm Ga substrate [7].

Among the advantages of continuous metallic media, one must mention the good control of the microstructure that allows smaller dimensions of the grains, with a high degree of orientation their easy axis direction and a low dispersion of these dimensions. Even if they are insufficient to allow the replacement of particulate media by the continuous ones, these advantages have favored finding some promising niches on the recording media market. The situation might change if it will be possible to manufacture layers in oxides instead of metals, because these are capable of a strong perpendicular anisotropy, a good immunity at corrosion and an adequate interface from tribological point of view.

Magnetic properties. A special feature of the continuous metallic media is the facility to obtain different magnetic properties by varying only one geometric parameter. For example, in the case of Cr/Co multilayer media, the reducing of Co layer thickness from 160 nm to 40 nm determines a coercive field 10 times greater and a remanence 6 times more reduced.

Generally, the saturation magnetization – an intrinsic property – is more reduced for thin films than for the bulk samples. On the contrary, one can optimize the remanent magnetization – an extrinsic property – by modifying the layer microstructure and thickness, the deposition conditions or the substrate. Coercivity depends on the magnetocrystalline anisotropy and on the grain interaction, like in the case of particulate media.

The magnetization reversal is realized by coherent rotation of individual grains or grains group, or by moving the walls formed within long distance coupled grains. In the first case, the medium coercivity is given by the magnetocrystalline and shape anisotropies of grains, stresses and interactions between grains groups. In the second case, it depends on the wall energy, so on the magnetocrystalline anisotropy, the demagnetizing energy of walls, the non-homogeneities of film structure and the surface roughness.

The extremely reduced thickness of the continuous media allows very narrow magnetization transitions. The recording density increasing without a significant decreasing of the reading signal level is possible because the ferromagnetic materials have a saturation magnetization of about 10 times greater than the ferromagnetic oxides. For example, the remanent magnetization of a continuous medium having 72.6% Co-Ni-P exceeds 2 MA/m for a coercivity of 0.1 MA/m.

Two applications are possible for continuous metallic media: longitudinal recording and the perpendicular one. Indeed, the anisotropy of sputtered or evaporated Co-Cr thin films may be oriented in the layer plane or perpendicular to it, depending on the layer composition and preparing method. For an arbitrary orientation of the grain easy axis, the magnetization remains in plane but, when the thickness increases, some columns perpendicular on the plane are developed; their magnetocrystalline anisotropy leads to an anisotropy perpendicular on the plane. The modern double layers perpendicular media use a supplementary layer, which is magnetically soft, coupled with the head by the armature effect.

The only important drawback of these media is their weak resistance against the wear produced by the friction with the recording head. The vacuum deposed media are protected against oxidation by covering with a Cr thin film. In the case of electrochemical deposition, the medium surface is covered with a polymer having lubrication properties. Finally, in the case of media for hard disk systems, the contact wear is completely eliminated because the heads fly at small height over the disks.

Longitudinal media. The grains of a metallic layer are better placed than the particles of a conventional medium, which leads to magnetostatic and exchange couplings that are more intensive. This provides the necessary saturation magnetization, but leads to a magnetic domain structure that gives to the head leakage field a response different to those of an assembly of monodomain particles of conventional media. The thin film media are excited in the direction of their easy axis, induced during the deposition; the hysteresis cycles are very rectangular, with a remanence of 0.4-1 MA/m, versus only 0.3 MA/m for particulate media.

The magnetization transitions being sharper than for independent particles, the recording density is higher, if the transversal 180° walls have a regular shape, with fewer zigzags. These zigzags are due to the demagnetizing energy, which tends to broaden transitions and is more important for the layers with more defects, which block the walls moving.

Perpendicular media. The most known is of course the Co-Cr alloy, with 15-25% Cr. This medium has a very well expressed columnar structure, the easy axis being perpendicular on the layer. The nonmagnetic component (Cr) of the alloy tends to diffuse at grains boundaries, leading to a behavior similar to those of the semi-independent particles of conventional media. With these media one obtains a recording density which is superior to any other medium. In fact, the columns are very closed and the demagnetizing field, which produces transitions in longitudinal layers, is diminished by the existence of perpendicular domains with opposite magnetizations, because the demagnetizing energy is now distributed on the layer surface. The perpendicular mode promotes the formation of narrow domains, which explains the expected superior recording density.

The metallic tapes have some specific applications, but the domain where the thin film media remain sovereign is those of hard disk systems.

Lu and Charap [17,18] showed that, if the scaling of the recording parameters continue, the thermal instability (the superparamagnetism limit) of the recording data might appear at 40 Gbits/in^2. Even if this limit value can be discussed, the reasons advanced for determine it are very significant for the future of the recording media industry. The reasoning is based on two principles. The first postulates that the writing head field is limited at a certain percent of the saturation magnetization of the head material; for the current available materials, the medium coercivity cannot surpass 0.4 MA/m. The second principle imposes a certain minimal medium SNR, at about 20 dB, which is necessary to the sure reading of the recorded data.

In the case of particulate tapes it is reasonable to use the particles number n by volume unit, but in the hard disk systems, in order to maintain a reduced head-medium spacing, the media might be formed of a single grain layer, so it is more convenient to use the concept of the surface density N of these "particles" (in fact grains). In these conditions, the usual estimation of 20 dB for a convenient SNR leads to a minimum of about 100 grains for each bit cell. The average dimensions of the grains give the recording surface density. A high recording density imposes grains with as small as possible size, but their excessive reducing might lead to the superparamagnetism limit when the magnetization configuration became thermally unstable. This instability is described by Neel's relation that links the commutation probability with the energy barrier capable to block it:

$$\tau = \tau_0 \exp(\Delta W / k_B T), \tag{6}$$

where $1/\tau$ is the probability of magnetization reversal in time unit and the frequency $1/\tau_0$ is 10^{-9} s^{-1} for the most of magnetic materials; k_B is Boltzmann constant. For uniaxial magnetic materials, one obtains for a stability of 25 years

$$\Delta W \propto (K_u - w_d)V \tag{7}$$

where w_d is the demagnetizing energy density, K_u is the uniaxial anisotropy constant and V is the particle volume. One estimates that $K_u V / k_B T \geq 60$ for a long-time stability.

For hard disks, it’s ideal that the easy axis of grains be randomly oriented in the disk plane, in order to avoid an irregular level of the signal when the disk turns. Assuming that the grains do not interact, then, if a grain is magnetically perpendicular on the recording direction, it doesn't contribute to the signal reproduction and one might consider it like a medium void. According to the Stoner-Wohlfarth model, the grains oriented in the recording direction have a more reduced coercivity and they are less thermally stable. The effect of this dispersion of grain orientations is a less rectangular hysteresis cycle.

A simple model of the isotropic media allows establishing the imposed conditions for manufacturing high performance media [19]. One supposes the grains to be randomly distributed in the disk plane and non-interacting by exchange; there is no intergrain interaction, except of the neighbor grains in a bit cell, where the demagnetizing fields acts. Regarding the equation (7), a higher anisotropy leads to a potentially higher demagnetizing energy, but its maximum is imposed by the writing transducer field H_t and by the medium properties. The condition to realize the overwriting of the previous recording data is that the energy product $\mu_0 H_t M_s$ surpass the medium anisotropy K_u. When the grains interact, a higher field is necessary. Before using different heads (inductive for writing and MR for reading), one used single heads (Permalloy alloy) characterized by a negligible magneto-striction. The saturation magnetization of Permalloy is only 2/3 from the value of the materials used today (Co-Fe, FeN_x). The two heads can also be optimized by decoupling the writing and reading functions of the head transducers. In this manner, the available recording fields are higher than 0.4 MA/m. The improvement of the media tribological characteristics will also allow more reduced head flying heights. These factors lead to recording fields of 0.8 MA/m, which also allow the increasing of the medium anisotropy. In practical systems, the demagnetizing fields must not reduce too much the constant K_u.

In these conditions, it is convenient to use a thinner magnetic layer, with a low magnetization but detectable by the read out head. The tendency of M_s diminishing is opposite to the necessity of a high value of this magnitude, imposed by the recording of the high anisotropy media. So, one doesn't expect the using of the materials with a too higher anisotropy in comparison with the current materials. These are Co alloyed with Pt and Cr; Pt is added to increase the Co anisotropy, and Cr reduces the exchange coupling of magnetic grains. For example, the saturation magnetization of the 68%Co–20%Cr–12%Pt alloy is close to 0.5 MA/m, and its anisotropy constant K_u may be 3.3 10^5 J/m^3. One can obtain in this manner an *effective* anisotropy constant of the isotropic media that is 50% higher that the value used in the current calculation of the instability limit.

The situation is more complicated, because the grains' shape and size, their anisotropies and interactions are not the same. The nucleation and the growth of grains during the deposition leads to a logarithmic distribution of their size. The smallest grains are under the thermal stability limit, and the biggest ones contribute to the noise increasing. A small increasing of the exchange coupling of grains may improve the thermal stability of the small grains, because their commutation processes are associated with those produced by the bigger grains.

Fig. 6 presents the structure of thin film media that are used for the modern hard disks [19].

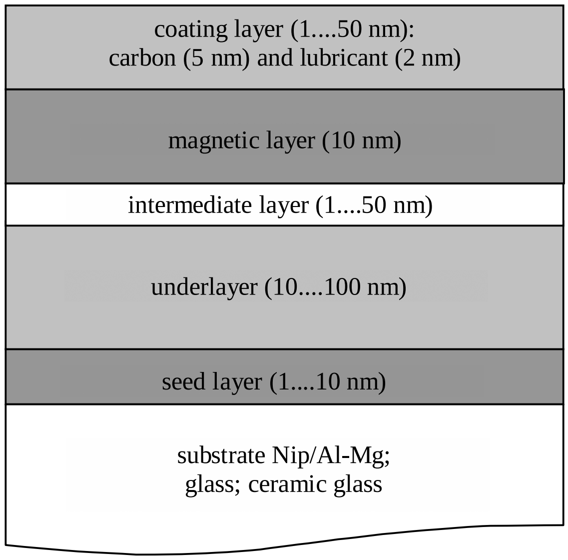


Fig. 6. Structure of modern hard disks.

The mobile computation applications impose a glass or ceramic glass substrate of 65μm, while most desktop computer systems utilize a substrate composed by a 95 μm NiP/AlMg alloy, electrolitically polished. For the two cases, the substrates are very smooth, with average roughness of less than 1 nm. The manufacturing technology is somewhat different for the two cases, leading to a different evolution of the initializing layer texture.

In fact, many layers compose a "recording medium". Firstly one deposes on substrate a Cr-base *bcc* underlayer, which controls the grain size of the following layers and the crystalline texture for epitaxial growth. Recently, between substrate and underlayer an initial (seed) layer was interposed in order to initialize the desired underlayer texture, to isolate the Cr from the substrate and to assure a small grain size and a narrow grain size distribution. The role of the intermediate layer placed between the underlayer and the magnetic layer is to transfer the underlayer epitaxial growth to the active magnetic layer, to improve the underlayer crystalline texture and to introduce a chemical diffusion source for isolating the intergrain boundaries of the magnetic layer and for weakening or eliminating their interface stress.

Finally, the assembly is covered with a ceramic like coating for protection against corrosion, especially carbon (CH_x or CN_x), and with a lubricant.

Co essentially composes the magnetic layer. But the Co grains remain coupled by exchange and their coercivity is reduced, even if the grains are growth on a substrate, in order to induce the pure uniaxial *hcp* phase. One can suppose that this is the effect of the internal defects, which reduces the local anisotropy and allows the domain walls nucleation. Adding Ni and Cr, one can improve the coercivity, but the intergrain exchange coupling remains. In a CoCrTa alloy, a Cr content of 10-16%at reduces the saturation magnetization, the anisotropy and the intergrain exchange coupling. The effect is due to the Cr diffusion at the grains boundaries. The weak Ta content, 2-8%at, which dissolves into Co, is necessary to expend the lattice and to favore the Cr concentration at the grains boundaries. This isolation of the Co-based alloy grains allows the obtaining of media with a very low noise and with a coercivity of 0.16 MA/m, but which have an anisotropy constant that represents only a third of the single crystal bulk Co value.

In order to increase the coercivity, which is always under 0.4 MA/m, the modern alloys almost include Pt, but with a limited content (6-14%at), not only for its price, but also especially because the exchange coupling between the grains might be favored again. To counteract this last effect, one can add Cr and a little B and Nb, the last having the same effect like Ta, to promote the Cr segregation at the grain boundaries. One must also mention that the alloy becomes nonmagnetic if the Cr content is higher than 25%, but its distribution is very non-uniform; for example, if the average content is 22%, inside the grains this is only 6-7%. On the other hand, B also segregates on the grains boundaries and it is interstitially localized in the *hcp* lattice. However, too much content in B produce its diffusion on the interface between the intermediate layer and the magnetic one, disrupting the epitaxial growth.

If the substrate is made of NiP/AlMg alloy, the most efficient for the intermediate layer is Cr. Adding Pt to the Co alloy of the magnetic layer, the *hcp* lattice constants are changing. The Pt addition has imposed the Cr-alloys introduction both in the underlayer and in the intermediate one, because Pt increases the Cr lattice constant, obtaining small grains and maintaining the *bcc* crystal structure. The Cr-based alloys used today contain V, Ti, Mo, W or Ru. A lattice constant, which corresponds to the *hcp* lattice, can be selected by adjusting the composition. The "according" of the underlayer lattice with the magnetic layer containing Pt is realized by using the *hcp* transition structures of the intermediate layer. For this, one frequently uses an alloy $Co_{1-x}Cr_x$, $x \in [35\%; 45\%]$at, with lattice constants comparable with the Co one, even if the alloy is non-magnetic.

Various elements with a diffusive role (Mn, Zn, Cu) can be added to the underlayer and to the intermediate one. The method is efficient for interposing a thin *hcp* intermediate layer, between the diffusion source and the magnetic layer. The intermediate layer helps the diffusant to localize exactly at the Co grains frontiers of the magnetic layer. Mn and Cr have the same atomic size and form a solid *bcc* solution; one can alloy an important quantity of Mn to Cr, even if, at the beginning, one adds only Mn, in order to increase the Néel temperature well above the room temperature. Because their antiferromagnetic coupling (AF), the thermal stability of Co grains can be improved and the transition length of the recording bits can be shortened. The analysis of the AF exchange coupling is difficult because Cr and CrMn alloy are incommensurable antiferromagnets. Furthermore, their magneto-crystalline anisotropy is smaller than the Co-alloys one, so one has a very limited increasing of the effective anisotropy constant.

To improve the system performances, one must obtain an effective increase of the magnetic grain volume, that of the energy barrier ΔW. A possible solution may be to realize a magnetic layer thicker than the grain diameter, because one obtains in this way a good thermal stability, without increasing too much the grains density and the noise.

Another solution assumes the use of an intermediate layer, which is composed by a uniaxial AF material, exchange coupled to the magnetic layer. Indeed, the energy barrier from (6) becomes in this case:

$$\Delta W \propto \left(K_{u,1} - w_{d,1}\right)V_1 + K_{u,2}V_2\,, \tag{8}$$

where the subscripts 1 and 2 denote the magnetic layer, respectively the AF intermediate layer. The volumes V_1 and V_2 signify the thickness of the two layers, because ΔW is computed for a single cylindrical shaped isolated grain. The demagnetizing energy density $w_{d,1}$ involves only the magnetic layer volume, because there are no magnetostatic interactions originating from the AF part of this structure. One assumes that the exchange coupling of the two layers is as strong as they commute simultaneously, especially by the propagation of a domain wall in the AF layer. The advantage of this structure is that, the magnetic layer remaining very thin, the entire active magnetic region is in the close proximity of the head that assures a high-resolution playback. During the writing process, the magnetic layer being close to the head, where the writing field is the strongest, the magnetic interaction is very efficient. It is very important that the AF layer has a significant $K_{u,2}V_2$ contribution; this is enough difficult to be realized because the most AF materials have a cubic crystalline structure, so a limited anisotropy.

Another approach is the use of a soft magnetic keeper layer as underlayer or seed layer. This layer has the role to assure the flux closure path of a recorded bit pattern inside the magnetic layer. One eliminates in this way an important part of the demagnetizing energy, which is useful especially if the head transducer is not too close to the bit of interest. The transition is more stable and will be sharper during read out. However, this solution has two drawbacks: (i) for read out, for a given quantity of the recording layer material, the signal received by the head is weaker, because an important part of the magnetic flux passes through the keeper layer and (ii) during the record process, a part of the head flux is shorted away from the hard magnetic layer into the keeper layer, so a stronger flux is needed.

None of these solutions is more advantageous than the simple increasing of the recording layer anisotropy.

Another way to improve the longitudinal recording is the SNR improving without reducing the grain size. There are two solutions.

The orientation of the easy axis of each magnetic grain along the recording direction, which is difficult if taking into account the disk rotation, even if the recording perpendicular mode is used, or the reduction of the bit cell aspect ratio. In fact if the medium remanent squarness is close to 1, the dispersion of the number of grains sampled in a bit cell is reduced and the noise statistic is considerably changed.

The simplest case is the perpendicular recording, even if one can adapt the concept to any anisotropy orientation. If the noise is to remain low, the ideal orientation ratio of the remanent magnetization must be sufficiently high for not having any grain, which don't produce a strong signal.

One has proved that the SNR improvement can be obtained by adopting a convenient value of the bit cell aspect (shape) ratio, close to 1 [19]. When this ratio increases, the demagnetizing factor increases for longitudinal recording media, but is improved for the perpendicular media. This recording density improvement, due to a better SNR, may be a real advantage of the strongly oriented perpendicular media. Nowadays, a longitudinal medium strongly oriented along the circular direction of the disk tracks has not yet been realized.

A second way – more important – to reduce the medium noise, is the diminishing of the statistical fluctuations of signals, using magnetic grains that are very regular in size and location. Ideally, all the grains must be oriented in the same direction. The recording densities that can be realized in this way correspond to the smallest size of the grains, which are stable from the thermal point of view. Then, the major noise source is no longer the medium, but the method of finding and addressing the individual magnetic grains. Assuming that there is a way to address them, even the pure Co grains have the potential to store many Tbits/in^2, so the grains of higher anisotropy materials can be smaller.

Some methods for obtaining these *patterned media* were proposed. The first uses lithographic techniques to configurate the magnetic material. A real advantage of these media is the capacity to predefine the information relative to the track and to the driving servosystems, even if until now this procedure has been avoided, due to its supplementary cost and the difficulty to realize concentric disk configurations.

The second method for patterning magnetic media is to use the natural process of generating the "self ordered magnetic arrays" (SOMA). There are chemical reactions capable to form a mono-dimension particle or grain structure. Some proteins are self-arranged in an *hcp* structure or in a square regular array when coated on a surface. Their growth is governed by a DNA code and so, their size is extremely uniform. Some of them present cavities that can be filled with magnetic material. The procedure has the advantage of a low cost and of the possibility to realize particles with practically identical dimensions, but there are too many unknowns related to the parameters of these arrangements and the way to orient them correctly.

5. Conclusions

The spectacular progress of the magnetic recording performances, especially in the hard disk systems, correlated with the constant and substantial reduction of the recorded bit cost, is due to the following two important technological progresses:

(i) The scaling reduction of the recording system parameters that depend on the signal wavelength: the head-medium spacing, the magnetization transition length, the thickness of the active magnetic layer of the medium and the dimensions of heads.

(ii) The MR transducers introduction into the head manufacturing and their evolution to GMR sensors and spin valve type ones, which have sensitivities that completely compensate the signal diminishing due to the recording density increasing.

However, the obstacles for continuing the increase of the recording density, due both to the fundamental (physical) limits, generated by the atomic structure of the mater, and to the technological and economic restrictions, become more and more important.

Therefore, in order to assure a reasonable lifetime of the recording media, duration which is limited both by their thermal stability (by the particles superparamagnetism limit) and by a correct time dependence of their coercivity and a convenient SNR, materials with improved magnetic characteristics must be chosen (or invented). Moreover, a better SNR imposes the improvement of the signal treatment methods; from this point of view, bigger data blocks, similar to those used today in magnetooptical recording, might be more advantageous. One can also increase the energy barrier of the commutation process, but, in order to make it without the increase of media noise, it must search new heads, with a very sophisticated configuration.

Without a fundamental changing of the recording mode, the recording surface density can not be increased more than two times the current level. The improvement of the medium SNR without reducing the grains or particles size imposes new media structures and new manufacturing technologies.

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