Media for Magnetic Recording Beyond 100 Gbit/in.^{2}

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Abstract

The requirements for media for high-density magnetic recording are reviewed, particularly with respect to the emerging technology of perpendicular magnetic recording. It is discussed in general how suitable properties of the recording films can be achieved in practice. Several approaches to extend the thermal limit of magnetic recording technology are outlined.

Keywords: *film, magnetic properties, memory.*

Introduction

This article focuses on recording media as they are used in hard disk drives in personal or laptop computers and in other applications. Traditionally, the demand for ever-increasing recording density was achieved by scaling, but fundamental physical mechanisms no longer allow simple scaling. To date, most magnetic storage devices use longitudinal recording, where the magnetization of the bits lies in the plane of the magnetic film. In contrast to longitudinal recording, the magnetization in perpendicular recording is in a direction normal to the film plane. It is generally accepted that perpendicular magnetic recording is advantageous for a further increase in the areal density, and it is anticipated that the recording industry will transition to this technology.

Fundamentals of Magnetic Recording, Scaling Aspects

Figure 1 shows a sketch of the "heart" of a magnetic recording system for both longitudinal and perpendicular recording. For longitudinal recording, the write head consists of an electromagnet with a gap whose fringe field magnetizes the medium passing by it (see the article by McFadyen et al. in this issue). At readback, the magnetic field from the written magnetization pattern is sensed by a magnetoresistive transducer which changes its resistance in the presence of a magnetic field.

For perpendicular magnetic recording, the writing is accomplished by the main pole (shown on the right in Figure 1). The write flux is sent through the magnetic layer, then through a magnetically soft underlayer (SUL) beneath the storage layer; it finally reenters the head structure though the return pole. The field at the return pole is much smaller than that of the main pole. From field theory, it can be shown that the effect of the SUL on the write-field distribution can be viewed as if the head structure were imaged in the SUL, as indicated in the figure. The main pole and its image in the SUL can be considered as a ring head turned sideways,[1] and the media can be thought of as traveling through the deep gap field of the head rather than the fringe field; thus, higher-coercivity media can be written.[2,3] The read-head structure for perpendicular recording is identical to that used in longitudinal recording.

Granular recording media consisting of magnetically separated grains are used in magnetic recording. The grains are too small to support a domain structure (i.e., they are single domains). Figure 2 shows a plan-view electron microscope image of a medium. The individual grains can easily be identified as darker regions separated by lighter grain boundaries. In the magnetic recording process, the bits are written as magnetization patterns, with the magnetization pointing either "up" or "down" for perpendicular recording and "left" to "right" for longitudinal recording. The information is coded in the locations where the transition between opposing magnetizations occurs. As shown in Figure 2 (which illustrates longitudinal recording), the magnetization transition boundary needs to follow the given microstructure, as single-domain grains cannot be "cut" magnetically. The transition centers do not come to lie exactly where intended. These "misplacements" are unforeseeable and generally referred to as "transition jitter." Transition jitter is the most dominant factor for noise in the medium.

Figure 2 shows the idealized case of the grain size limit, in which the transition width is solely determined by the locations and distributions of the grains. Then, the transition width W is equal to the grain size D. For historical reasons, the transition width is described by a transition parameter, a, that is related to the transition width by $a = W/\pi$. It has been shown that the medium signal-to-noise ratio (SNR) scales with

$$\mathrm{SNR} \propto \frac{1}{a\sqrt{s}}. \quad (1)$$

The quantity s is called the cross-track correlation length and represents the statistical averaging effect that occurs across the track. For the grain size limit, one expects s to be close to the grain size D.

Typically, hcp Co alloys are used for the recording media. These materials exhibit uniaxial anisotropy—that is, the magnetization prefers to lie along an axis of easy magnetization (e.g., the c-axis). At zero applied field, the energy that keeps the magnetization on its easy axis is $K_U V$, where K_U is the anisotropy energy density and V is the volume of the grain. For materials relevant for recording media, K_U arises from the crystal properties of the material and is referred to as magnetocrystalline anisotropy. Stoner and Wohlfarth[4] have shown that the field required to switch the magnetization is related to $2K_U/(\mu_0 M_s)$, where μ_0 is the permeability in vacuum, $4\pi \times 10^{-7}$ V s (Am)$^{-1}$, and M_s is the saturation magnetization. The quantity $2K_U/(\mu_0 M_s)$ is also called the anisotropy field H_A and may be considered a fictitious field that holds the magnetization along the easy axis. The angle dependence of the switching field is important; the switching field is highest, 100% H_A, if the field is applied along the easy axis, and lowest, 50% H_A, if the field is applied at 45°.

To ensure that the magnetization remains on its easy axis, the magnetic energy $K_U V$ needs to be high enough to withstand the effects of thermal agitation. The competition between the magnetic energy and the thermal energy is reflected in a transition probability, also referred to as a relaxation rate r:[5]

$$r = f_0 \exp\left(-\frac{K_U V}{k_B T}\right),$$
$$f_0 \approx 10^{10} \cdots 10^{11}\ \text{Hz}, \tag{2}$$

where f_0 is the relaxation frequency, and $k_B T$ represents the thermal energy (k_B is the Boltzmann constant and T is the temperature in kelvin). If $K_U V$ becomes too small, the magnetization is no longer stable. As rule of thumb, an energy barrier of 20 $k_B T$ (~0.5 eV) causes relaxation rates on the order of 1 per second, and no hysteresis is observed in an experiment for such a material ("superparamagnetism"[6]). For information storage applications, mean $K_U V$ values of 70–100 $k_B T$ are required to ensure sufficient thermal stability.[7,8]

Achieving a higher SNR in the medium requires smaller grains, which inevitably cause lower energy barriers ($K_U V$) that eventually lead to thermal instability. An obvious solution to this problem is to select materials with a higher K_U. Increasing K_U inevitably goes along with an increase in the anisotropy field H_A of the material, and higher fields are required to write to the media. Writing fields remain limited due to material constraints (FeCo has the maximum known saturation magnetization, with $\mu_0 M_s = 2.4$ T), and conventional magnetic recording must therefore find a reasonable compromise between writeability, thermal stability, and medium SNR. This constrained design space is also referred to as the "trilemma."[9] Current research in recording media is targeted to find ways to break the trilemma, or synonymously postpone the superparamagnetic limit. In this sense, perpendicular recording can be regarded as a trilemma breaker.

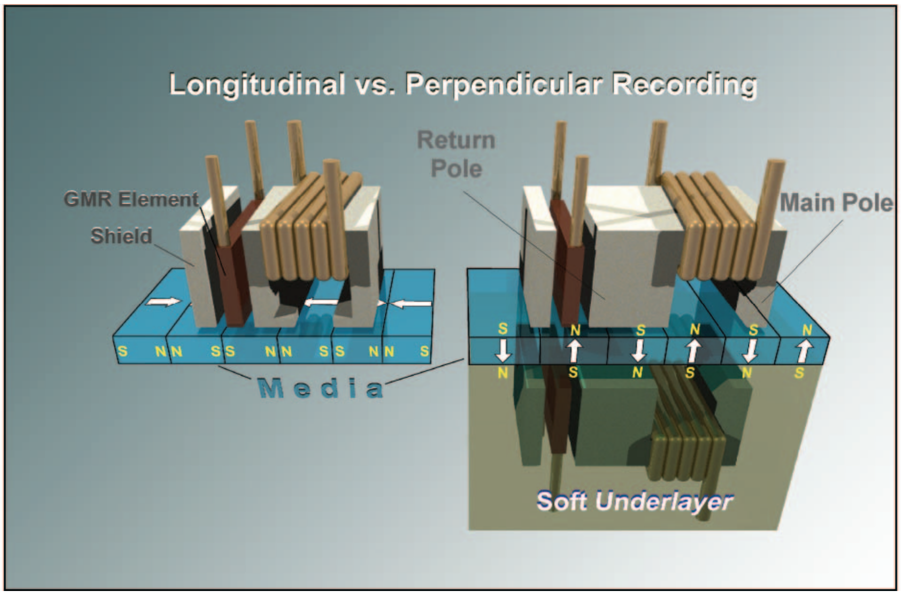

Figure 1. Schematic illustrations of the two modes of magnetic recording: (left) longitudinal recording and (right) perpendicular recording. In longitudinal recording, the medium is written using the fringe field of the gap. In perpendicular recording, the writing is achieved by the main pole (on the right). The write flux penetrates the media and is conducted via the magnetically soft underlayer (SUL) back into the return pole. The field configuration in the presence of the SUL can be viewed as if the head structure were imaged in the SUL. GMR is giant magnetoresistance.

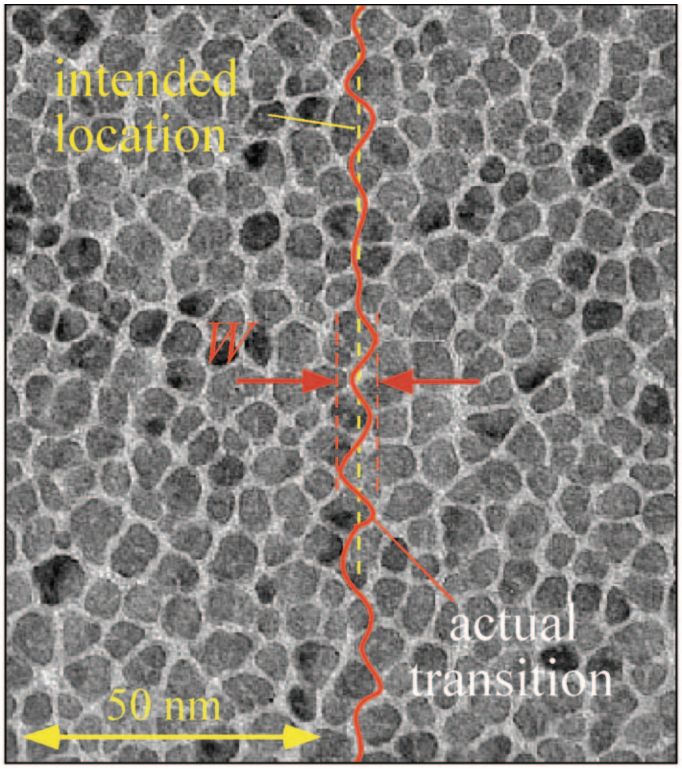

Figure 2. Demonstration of a written transition in a granular magnetic recording medium. The transition boundary has to follow the microstructure of the medium. The figure depicts the most optimistic case in which the recording is within the grain size limit.

Requirements for Magnetic Recording Media

Figure 3 shows a schematic view of a hysteresis loop in the perpendicular direction of a perpendicular recording medium. The field required to switch 50% of the magnetization is called the coercivity, and the field at which magnetization reversal starts is called the nucleation field. Due to demagnetization effects, the hysteresis loop of a perpendicular medium is shallower than that of a longitudinal medium. To ensure saturation recording, the head needs to produce sufficient field to overcome the switching field augmented by the demagnetizing field. A hysteresis loop with a steep slope is desired because it reduces the transition width and increases the SNR.

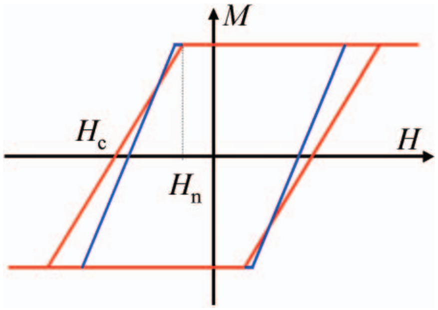

Figure 3. Hysteresis loop in a perpendicular recording medium. The field at which the magnetization M *is zero is the coercivity* H_c*, and the field at which the magnetization starts to reverse is called the nucleation field* H_n*. Red curve: hysteresis loop along the perpendicular direction without exchange between the grains. Blue curve: steeper loop caused by the presence of intergranular exchange.*

Demagnetizing effects can be reduced by using materials with a low M_s, but this also reduces the anisotropy constant K. Most practical perpendicular media have M_s between 400 kA/m and 800 kA/m and an anisotropy field in the range of 1000–1200 kA/m (12.5–15 kOe).

Historically, and continuing through the present, cobalt alloys have been employed as the primary recording layer material. The inherently high magnetocrystalline anisotropy of such alloys—K_U ranges from 10^5 J/m^3 to 10^6 J/m^3 (10^6–10^7 erg/cm^3)—is largely attributable to the natural symmetry of the hcp crystal structure. The anisotropy may be increased by expanding the c/a ratio toward the ideal of 1.633, with an increasing risk of inducing stacking-fault formation. Cobalt in the absence of strain effects has a c/a ratio of ~1.62. Doping cobalt with platinum is highly effective in increasing the anisotropy field, as the large atomic radius (1.387 Å) engenders an expansion of the c-axis relative to the a-axis, leading to high K_U while not diluting the magnetization mechanically. The shallow decline in M_s occurs because Pt is polarized when incorporated in a magnetic microstructure.[10] To control the magnetization, Cr is the mainstay dopant. Cr is nearly identical in size to the host cobalt matrix and therefore does not distort the lattice. The magnetization is diluted in direct proportion to the reduction of Bohr magnetons per unit volume. In addition, Cr improves the corrosion-resistance of the material. Therefore, through addition of Cr and Pt in proper proportions to a cobalt matrix, the magnetic properties can generally be tailored according to the requirements of the recording system.[11]

Tailoring Intergranular Exchange

In magnetic materials, the quantum mechanical exchange forces strive to create a uniform magnetization. For medium design, it is a reasonable approximation to assume that the exchange forces inside each magnetic grain are so strong that the magnetization remains uniform at all times. As shown in Figure 2, the grains are physically separated from one another, and, hence, the exchange coupling between grains is weakened. It is well known that exchange coupling between grains causes "clustering," that is, it facilitates collective magnetization reversal. This increases transition jitter; therefore, the conventional wisdom has been to suppress intergranular exchange in longitudinal recording at all cost.

Although intergranular exchange also causes clustering effects for perpendicular media, the optimum design for perpendicular recording media is not zero intergranular exchange. As illustrated by the blue curve in Figure 3, the introduction of intergranular exchange makes the magnetization loop steeper and results in narrower transitions. There is an optimum intergranular exchange which balances the transition narrowing effect and the increase of the cluster size.[9] An additional advantage of intergranular exchange is an increased margin against thermally induced magnetization reversal. In perpendicular recording, the demagnetizing fields are strongest in the center of the bit, and consequently, they reduce the available energy barrier that resists the thermal forces.[12] The intergranular exchange counters the demagnetizing effect and stabilizes the most critical magnetization patterns.

The traditional method of controlling intergranular exchange has been a process configuration promoting the metallurgical segregation of Cr in the Co alloy matrix. Although the process is not completely understood, Cr segregates at substrate temperatures above 200°C, leading to Co concentrated predominantly inside the grain core and sufficient amounts of Cr at the grain boundary to render them nonmagnetic. As in the case for longitudinal medium processing, boron can be added to enhance the segregation. For Co(0001)-oriented growth, however, there is an increased risk of stacking-fault formation with increasing boron concentration.[13]

One issue central to metallurgical segregation processes for both longitudinal and perpendicular orientations is the natural compositional variation occurring from grain to grain. The amount of Cr segregated to the grain boundary varies proportionally with the grain diameter, resulting in an anisotropy distribution that leads to wider transitions and hence poorer SNR. The industrywide solution to this dilemma is to employ that portion of the Thornton diagram[14] wherein the growth of thin films favors columnar grains with a notable excess of space between grains emanating from shadow void processes. In this way, it is possible to physically separate the grains with vacuum. The dynamics involved in creating such structures can be summarized as "hit-and-stick"; that is, the deposition conditions are manipulated so that the arriving adsorbate is not capable of more than a few atomic jumps along the crystal surface. However, there is more than sufficient energy to enable the homoepitaxial advancement of the crystal surface. Typical conditions for this type of growth are high gas pressure (typically Ar, in the range of 30–50 mTorr), low deposition rate, and low substrate temperature. In limiting the lateral migration of alloy species, the compositional variation becomes insensitive to the width of the grain size distribution.

Although the grain-boundary regions are decidedly porous, significant contact remains between neighboring cobalt grains, thus resulting in intergranular exchange. A further refinement of the process, then, is to introduce the codeposited presence of a nonmagnetic oxide.[15] During the growth process, the oxide does not incorporate within the growing crystal. This two-phase microstructure enables a uniform (with respect to film thickness) magnetic decoupling of the grains.

A powerful way to reintroduce weak and uniform exchange coupling is to employ a dual-layer structure, wherein the first magnetic layer has highly exchange-decoupled grains and the thickness of the second, more continuous layer controls the intergranular exchange (coupled continuous granular media[16]).

Grain Size, Grain Size Distributions, Grain Volumes, and c-Axis Orientation

A small grain size is desirable for high SNR, but it brings with it a smaller magnetic energy K_UV to withstand the effect of thermal agitation. Since it is the grain volume and not the grain area that enters in the magnetic energy, it is attractive to increase the film thickness—that is, to make media with "tall and slim" grains. Film thicknesses of up to 15–20 nm are indeed common for perpendicular recording media. For longitudinal media, thick layers with high saturation magnetization are unfavorable because the transitions become wide due to the increased demagnetizing fields.

The grain size distribution is typically lognormal, as expected for a nucleation-and-growth–type manufacturing process. Advanced media have grain size distributions σ_D/D as low as ~0.2 (where σ_D is the standard deviation). The historical evolution of the grain size and distribution is shown in Figure 4. Fortunately, the intergranular exchange acts to stabilize the smaller grains and the energy-barrier distribution is considerably narrower than that expected from the grain size distribution itself.

The grain size in perpendicularly oriented (0001) Co alloys is to the first order dominated by the template grain size of the sublayer structure. The sublayer structure is therefore constructed to all at once provide the appropriate crystal orientation, a fine grain size, and a granular roughness capable of initiating the physical separation processes in the magnetic layer above. It is a generally accepted practice to mate the magnetic layer with a Ru alloy comprising a similar hcp structure and lattice parameter engineered to enable parallel alignment with the Co alloy. Ruthenium alloys make suitable interlayer selections as their high melting point and high surface energy lead to a finely dispersed nucleation density with a narrow distribution in critical nuclei size. The high surface energy also ensures that as the layer thickens the grain surface, it will form a dome shape, thus engendering the ability to entrain oxide material at the onset of the magnetic layer growth process. Figure 5 shows a cross-sectional transmission electron micrograph of a typical perpendicularly oriented medium sample. While not perfect, substantial amorphous oxide is present in the crevices on the side of the magnetic layer–interlayer interface, as can be seen from the difference in diffraction contrast. There is generally more than one magnetic grain co-nucleated atop each template interlayer grain. In principle, this can be a way to realize a reduced grain size, but it remains challenging to properly devise a process that minimizes the lateral exchange incursion inherent to coalesced grains. It happens, however, that as the co-nuclei grow, they too develop a physical separation void arising from the hit-and-stick process. This fact is properly exploited by infusing a dose of reactive oxygen at the beginning of the magnetic process to provide excess oxide available to establish the nonmagnetic boundary more quickly.

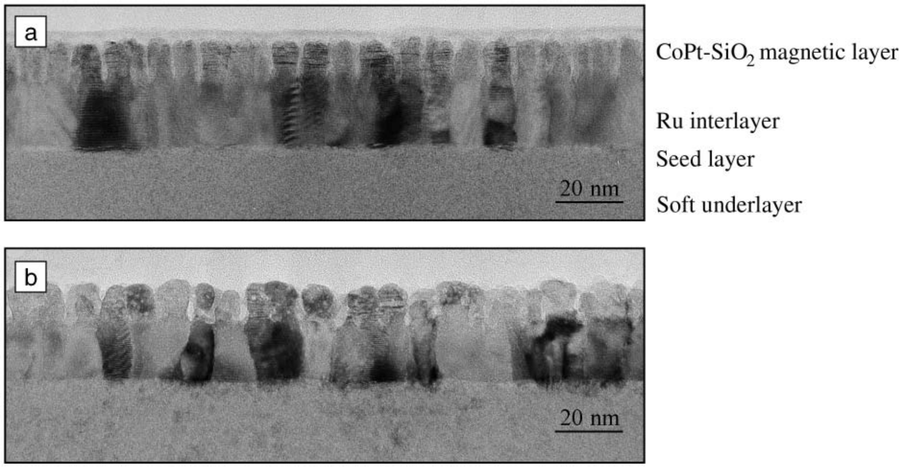

Figure 5. (a) Cross-sectional transmission electron micrograph of a typical perpendicular recording medium design. (b) Cross-sectional image of a medium design lacking an appropriate seed layer.

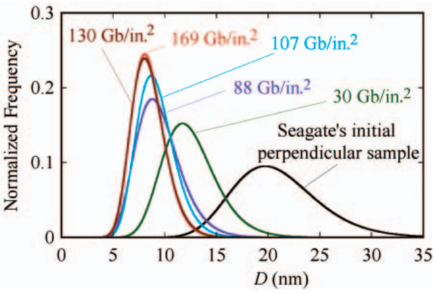

Figure 4. Grain size distributions for various generations of recording media. The grain size typically follows a lognormal distribution.

Returning to Figure 5, the initial crystalline layer shown is the seed layer. Seed layers are important in establishing the crystallographic texture for the interlayer grown above them. It is therefore common practice to employ low-surface-energy fcc materials that tend to wet the amorphous SUL surface and orient such that the close-packed planes (111) are plane-parallel. Of course, the fcc (111) planes make suitable templates for hcp (0001) growth, assuming appropriate matching of lattice parameters. Figure 5b shows the result of making no attempt to control the interlayer nucleation orientation. A higher dispersion in the basal plane normal [Co(0002)] results in competitive growth and grain fanning (i.e., dilation).

Since the switching field depends on the field angle, a poor *c*-axis orientation leads to broader transitions, even for identical grains. Modern perpendicular media are so well oriented that the media can be considered perfectly aligned as far as the recording process is concerned. This is not true for longitudinal media, for which the industry has not succeeded in achieving good *c*-axis orientation along the circumference. These microstructural effects are key factors that favor perpendicular recording for achieving higher density storage.

Extensions of Perpendicular Recording and Alternative Approaches

A very promising extension to perpendicular recording is composite media.[17,18] A composite medium has a two-layer structure with materials of different magnetic properties. Material 1 has such a high anisotropy field that it cannot be written with available head fields, and Material 2 serves as a switching assist. Using a properly tuned exchange coupling between the two layers, a composite grain can have a smaller switching field than a corresponding particle switching according to the mechanism described by Stoner and Wohlfarth for the same K_UV. Composite media can thus break the trilemma. The result is the most effective when the contrast between the materials is the most pronounced: $M_{s2}/M_{s1} \gg 1$ and $H_{A2}/H_{A1} \ll 1$.

Table I gives an overview of the magnetic properties of available materials (see also Reference 19). All current recording media are based on hcp CoPt, which has maximum anisotropy fields of approximately 2000–2400 kA/m (25–30 kOe). A realization of the full benefit of composite media therefore requires other material systems, such as FePt in the $L1_0$ phase.

For almost all magnetic materials, increasing the temperature causes the anisotropy to decrease, and the field required to switch the material is correspondingly decreased. The basic idea of heat-assisted magnetic recording is to heat the media during the writing process to temporarily lower the switching field.[20] The full anisotropy remains available during storage.

On the other hand, bit-patterned media address the trilemma in a completely dif-

Table I: Magnetic Properties of Various Materials Considered for High-Density Magnetic Recording.

Material	Structure	K (kJ/m^3)	M_s (kA/m)	H_A (kA/m)	T_c (K)	d_w (nm)	D_p (nm)
Co	hcp	540	1440	597	1404	19	6.7
Co_3Pt	…	2000	1100	2890	1200	9.9	4.4
CoCrPt	hcp	100–500	200–700	500–1600	~500	14–30	8–14
CoX/Pt	multilayers	1000	360	4420	500	9.9	5.5
CoX/Pd	multilayers	600	360	2650	500	13	6.5
FePt	$L1_0$	7000	1140	9770	750	3.8	2.9
CoPt	$L1_0$	4900	800	9750	840	6.3	3.2
$SmCo_5$	hcp	14,000	910	24,000	1000	3.8	2.3

Notes: K = anisotropy energy density; M_s = saturation magnetization; H_A = anisotropy field; T_c = Curie temperature; d_w = domain wall width; and D_p = dimensions of a cube of the respective material, which has a magnetic energy KV of 40 k_BT. Conversions to CGS units: 1000 kJ/m^3 = 10^7 erg/cm^3, 1 kA/m = 1 emu/cm^3, and 1000 kA/m = 12.5 kOe.

ferent way: rather than recording one bit on a large number of grains (50–100), one grain or magnetic island represents one bit. The entire volume of the bit contributes to the magnetic energy, and stable media can be achieved with much lower anisotropies. However, bit-patterned media manufacturing brings along a completely new set of challenges.[21]

Summary

We have reviewed comprehensively the state of affairs as they pertain to current magnetic recording media paradigms. Structure–property relationships have been elucidated in terms of cobalt alloy microstructural effects on key magnetic properties, including magnetocrystalline anisotropy, intergranular exchange energy, and grain size. These observations have been made in view of their resulting effect on the physics governing recording performance. Finally, prospects for future ultrahigh recording designs were discussed; assisted writing schemes and bit-patterned media are two current contenders for next-generation recording paradigms.

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