MAGNETIC STORAGE MEDIA

Magnetic recording of data relies on the controlled creation and reliable detection of regions of differing magnetization in a magnetic medium. Today's magnetic recording media are the result of impressively successful development since magnetic recording media were invented and first demonstrated 70 years ago. The development has been particularly fast in the last 15 to 20 years, during which many technical and commercial advances have been made. Media storage capacity has been dramatically raised from 5 to 10 Mbyte (megabytes) per disk platter in the early 1980s to 2 to 4 Gbyte (gigabytes) per disk platter in early 1998. (A decimal base is not used for numbers describing data stored. Arising from the computing usage of binary numbers, 1 Mbyte is the nearest power of 2 equivalent of 1 million, in other words, 1,048,576 bytes $\equiv 2^{20}$ bytes; and 1 Gbyte is the nearest binary equivalent of 10^9, that is, 2^{30}, bytes, in other words, 1,073,741,824 bytes.) In the same period, the price of a disk platter has also fallen by more than a factor of 100. Despite these successes, progress in raising the areal density (number of data bits per unit area) of recording media has not stopped or slowed down, and the total data storage capacity of disk drives is still increasing rapidly. It is predicted that an areal density of 20 Gbit/in.^{2} will be demonstrated, and that media above 10 Gbit/in.^{2} should be available commercially by the turn of the century. (With respect to disk diameter and area, the units used in the United States are still the inch and square inch, respectively.)

The purpose of this article is to give an overview of magnetic recording media, especially of the thin-film media developed recently on rigid disks, since this is the dominant, continuing area of magnetic recording media research and commercial progress. We begin with a short look at the history of recording media, followed by detailed discussion of current media and reference to the future of these media.

Historical Perspective

The earliest magnetic recording medium was a wire made of stainless steel, containing nickel and chromium. The wire was annealed so that single-domain particles of the ferrite phase precipitated in an austenitic, nonmagnetic matrix (1). The resulting coercivity of this wire recording medium, that is, the applied magnetic field required to reduce the magnetization to zero, was only a few hundred oersteds. This type of medium served to establish the concept of magnetic recording. However, the medium was never commercialized for two practical reasons: the recording head could not reliably read all the previously recorded information, since the wires were easily twisted, and the read–write process was interrupted whenever the thin wires broke and needed to be "repaired" by knotting the broken ends together. To improve upon this type of magnetic recording medium and to avoid its mechanical problems, a spliceable tape coated with synthetic particles, including γ-Fe_2O_3, was developed in the early 1940s (2). The particles were aciculate (needle-shaped) and were held with their long axes parallel to a polymer tape backing. The particles were believed to be single domain and to undergo magnetization reversal by coherent rotation. Extensive research and development work since that time has led to the successful commercial applications of a wide variety of magnetic tape media.

The particulate-coating approach was extended to rigid disk media in the 1950s with IBM's development of the first rigid magnetic recording medium—a 24 in. disk coated with γ-Fe_2O_3. As the technology evolved, in the late 1970s the sputtering form of vacuum deposition became well established as the method for applying the magnetic layer in the magnetic recording industry.

Sputtering is far superior to the earlier coating methods for making films because it can create a much higher packing density of the magnetic constituents, and this is a prerequisite for higher recording densities. The magnetic materials used in the vacuum deposition were mostly CoCr alloys (3,4), which easily provided media coercivities of about 300 Oe to 500 Oe—a large improvement from the 200 Oe to 300 Oe coercivities of γ-Fe_2O_3–coated particulate media. By the early 1980s, ternary CoCrX alloys (X being a metallic element), such as CoCrNi and CrCrTa, had evolved with substantially improved recording media characteristics (5). With the addition of Ni or Ta, the anisotropy of the alloys was greatly increased, resulting in higher coercivities and better recording performance. The ternary alloys CoCrTa have been so successful so that they have been widely used in the past 10 years, until they reached a coercivity limit at about 2500 Oe to 2700 Oe. Exceeding that limit has involved a large effort throughout academia and industry. By the early 1990s, Pt was found to be an excellent candidate for increasing the magnetocrystalline anisotropy by forming CoCrPt- and CoCrPtTa-based alloys (6,7,24) and so enhancing magnetic film coercivities. Since the crystalline anisotropy is a key intrinsic parameter for increasing the film coercivity, quaternary alloys have therefore emerged as the means to further development of high-recording-density media by breaking the ternary coercivity limit. Coercivities up to 4000 Oe have reliably been obtained for the CoCrTaPt alloy system (8). At the same time, other high-anisotropy alloys, such as CoSm- and FeSm-based alloys, have also been studied but their recording characteristics, both from academia and from industry, have been exceeded by the quaternary alloy CoCrPtTa. Development of underlayer and seed-layer technologies and optimization of the manufacturing process has also assisted in obtaining dramatic improvements in the performance of media, including the media signal-to-noise ratio (SNR), as we discuss later.

Fundamentals of Magnetic Recording

Magnetic recording is based on storing information in a magnetic medium by controlled writing (creation) of regions with differing magnetization. Requirements for high-density longitudinal recording media include desirable bulk magnetic properties, appropriate magnetic domain structure, and stability of the magnetizations and the read–write process. In this section we briefly review the writing and reading processes and analyze their performance, which is correlated with bulk magnetic properties and the spacing between the head and the medium. The section concludes with a short discussion of thermal stability, which is also correlated with the micromagnetic properties. The magnetic domain and medium microstructure will be discussed in the later sections.

The writing process is illustrated in Fig. 1(a). The coil current creates a writing field in the medium that establishes the local magnetization. Reversal of the current creates a magnetization transition. The longitudinal writing field H_x generated by the head coil current in the Karlqvist model (9) is

$$H_x(x, y) = \frac{H_g}{\pi}\left(\arctan\frac{x+g/2}{y} - \arctan\frac{x-g/2}{y}\right) \quad (1)$$

where g is the gap width of head, H_g is the magnetic field inside the head gap, and x and y are the coordinates at which H_x is to be calculated, as shown in Fig. 1(a). The peak value

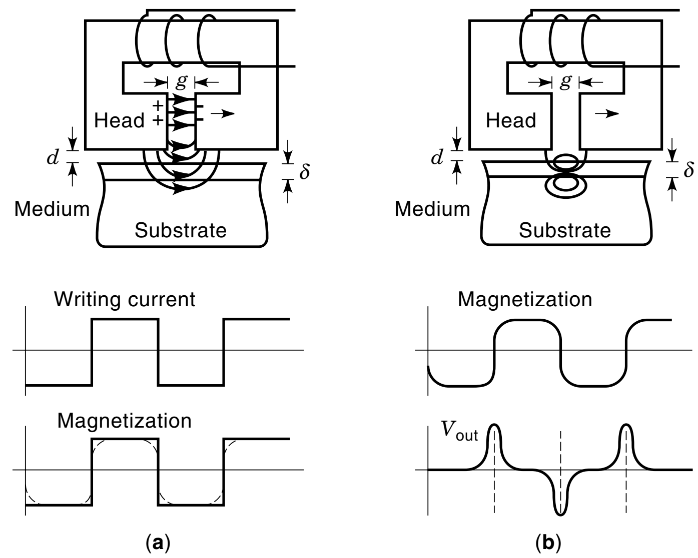


Figure 1. (a) Illustration of magnetic writing process. (b) Illustration of magnetic reading process.

of H_x is at $x = 0$ and can be expressed as

$$H_{x(\text{peak})} = H_x(0, y) = 2\frac{H_g}{\pi}\left(\arctan\frac{g/2}{y}\right) \quad (2)$$

A sufficient writing field must be applied to write magnetic transitions or to achieve a good overwrite of previously written data. It is commonly required that the writing field at the back of the medium is about 2.5 times the medium coercivity H_c. Taking $x = 0$, $y = d + \delta$ (where d is the spacing between head and medium and δ is the medium layer thickness) and $H_x(0, d + \delta) = 2.5H_c$, one can calculate the required H_g for a given H_c as

$$H_g = \frac{2.5\pi H_c}{2\arctan\left(\dfrac{g}{2(d+\delta)}\right)} \quad (3)$$

Assuming the following reasonable parameter values for calculating a magnitude for H_g, $H_c = 2000$ Oe, $d = 40$ nm, $\delta = 25$ nm, and $g = 260$ nm, and substituting these values into Eq. (3), one finds $H_g = 5900$ Oe. The parameters that are projected for a 10 Gbit/in.^{2} medium are (10) to be $H_c = 3000$ Oe, $d = 20$ nm, $\delta = 10$ nm, and $g = 200$ nm, from which one may find $H_g = 9200$ Oe. Hence, permalloy, which is a common head material, cannot be used to write such a high coercivity medium, and new head materials with higher saturation flux densities are required.

The magnetization transition obtained by writing data can be described fairly well with a simple arctangent function as shown in Fig. 2,

$$M_x = \frac{2}{\pi}M_r\left(\arctan\frac{x}{a}\right) \quad (4)$$

where M_r is the remanent magnetization of the medium and a is known as the transition parameter. It is notable that only one parameter a is needed to specify the transition characteristics: a small value of a corresponds to a rapid transition,

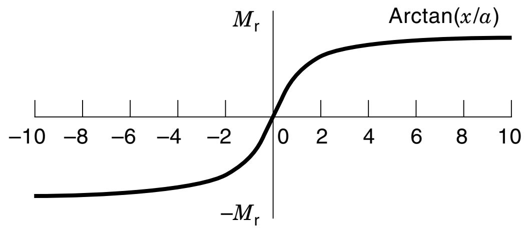


Figure 2. Arctangent form of magnetic transition.

and this favors high-density recording, as will be discussed in more detail in connection with the reading process.

The reading process is illustrated in Fig. 1(b). When a written magnetic transition in the medium passes under the head gap, the stray magnetic field from the medium will cause a change in magnetization in the head core and so will result in an induced output signal from the head coil. This signal is correlated with the head and medium parameters and the spacing between them. For an arctan magnetization transition, this output voltage can be expressed as follows (9,11,12):

$$V(x', d) = -2\mu_0\left(\frac{\eta n v w}{\pi g}\right)(M_r\delta) \times \left(\arctan\frac{x'+g/2}{a+d} - \arctan\frac{x'-g/2}{a+d}\right) \tag{5}$$

where η, n, v, w, and x' are the head efficiency, the number of coil turns in a head, the velocity of the medium relative to the head, and the recording track width in the medium, respectively. We note that Eq. (5) has the same form as Eq. (1) and the output voltage $V(x', d)$ is proportional to $M_r\delta$. Taking $x' = 0$ in Eq. (5), the peak voltage V_{p-p} is

$$V_{p-p} = 8\mu_0\left(\frac{\eta n v w}{\pi g}\right)(M_r\delta)\left(\arctan\frac{g/2}{a+d}\right) \tag{6}$$

The width of the output pulse, measured at one-half of the maximum amplitude level, is called PW_{50} and is given by

$$PW_{50} = [g^2 + 4(a+d)(a+d+\delta)]^{1/2} \tag{7}$$

where a is the transition parameter introduced in Eq. (4). The derivation of an expression for a has to take into account the details of the writing process. We shall not go into this process but simply give the result (89):

$$a = 2\sqrt{\frac{M_r\delta(d+\delta/2)}{H_c}} \tag{8}$$

The desirable bulk magnetic properties of media for high-density recording can be understood by considering the pulse width of an output signal. A narrow pulse, that is, a small PW_{50}, will allow an increase in the linear recording density. Equation (7) suggests that small g, d, δ, and a favor a decrease in the value of PW_{50} and therefore an increase in the linear density. However, the values of g, d, and δ are limited by other considerations: the gap width g has to be large enough to produce a sufficient field [see Eqs. (1) and (2)]; the head–medium spacing d has to be large enough to prevent mechanical wear of both the head and medium, and so has a minimum value that is limited by the surface roughness of the medium; and the medium thickness δ has to be great enough to provide sufficient signal [see Eqs. (5) and (6)]. To reduce δ and retain sufficient output signal, a large M_r of the medium is preferred. Therefore, an important approach to reducing PW_{50} is to shorten the transition parameter a, guided by Eq. (8), which indicates that this optimally requires decreasing $M_r\delta$ and increasing H_c.

Thermal stability is another important issue in high density recording as the crystalline grain size is reduced to attain increased areal recording density. The grain size should be as small as practical to satisfy the needs for a narrow transition, a high signal-to-noise ratio, and a smooth film surface. However, the grain size must be large enough to provide adequate thermal stability to guard against time-dependent magnetic effects (109,110). Using the thermal activation model, Sharrock pointed out that the measured coercivity H_c is time-dependent and can be expressed as

$$H_c(t) = H_o\left\{1 - \left[\frac{k_B T}{K_u V}\ln(At)\right]^n\right\} \tag{9}$$

where k_B, T, K_u, and V are the Boltzmann constant, absolute temperature, magnetic anisotropy, and grain volume, respectively, A is a time-independent constant, and n varies from 1/2 to 2/3 depending on the orientation distribution of grain moments with respect to the field. Therefore, the coercivity H_c that is relevant to long-term storage (large t) can be significantly less than that which is relevant to high frequency writing (small t). To satisfy the thermal stability requirement, the following condition should be obeyed:

$$\frac{K_u V}{k_B T} \geq 60 \text{ to } 80 \tag{10}$$

This formula indicates that a medium with high anisotropy K_u and large grain volume V will have enhanced thermal stability. However, a large grain volume V will degrade the signal-to-noise ratio and transition width, both of which are undesirable.

Further analysis indicates that if the condition

$$\frac{K_u V}{k_B T} \leq 25 \tag{11}$$

holds, the medium will lose coercivity and become superparamagnetic because the grains are too small to retain the orientation of their magnetic moments, owing to thermal agitation. This is the so-called superparamagnetic limit of recording media.

In summary, high-density recording requires a high medium coercivity H_c and a small $M_r\delta$. Since $M_r\delta$ must be large enough to give sufficient output signal, the most appropriate way to reduce the transition a is by increasing coercivity H_c. However, one should notice the correlation between H_c and H_g in Eq. (3) and should choose a high value of H_c that is within the saturation flux density limitation of the head material. The grain size has to be large enough to provide thermal stability, but as small as practical to increase the signal-to-noise ratio and reduce the transition width. It should also be pointed out that high anisotropy K_u favors the enhancement of both H_c and thermal stability.

Units Used for Magnetic Recording Media

The units used in describing magnetic recording media have not been unique, although most in the field have adopted mks units. Researchers and disk makers in the United States in this field still use cgs units, partly because the electromagnetism mathematics description and derivations were so much simplified by using cgs units and partly because of a reluctance to change. Most disk makers in the United States now use cgs units, but a few use mks units or a combination of both units. Table 1 contains those parameters that are often used for magnetic recording media and their unit conversions.

Types of Magnetic Recording Media

Magnetic recording media technology has rapidly evolved in the following categories: (1) particulate media, (2) rigid continuous thin media, and (3) patterned media.

Particulate media comprise magnetic particle dispersions coated onto tapes or flexible disks to form a polymer–particle composite structure akin to paint. The common early magnetic materials were iron oxide and cobalt-surface-treated iron oxide. More recently aciculate iron particles have been adopted. Particulate media are widely used in audiotapes and videotapes, in removable floppy disks, and in plastic credit, bank, or other cards.

Rigid continuous media are made of magnetic films deposited onto a rigid substrate. There are two types of film media: longitudinal and perpendicular, in which the magnetic moment axis is parallel or perpendicular to the film surface, respectively. In principle, perpendicular media can permit higher recording areal density than that of longitudinal media because of the demagnetization character resulting from recording data bits with opposite polarities in perpendicular media. However a number of factors, including head writing concerns, have limited the attainments of perpendicular recording. Perpendicular recording is still in the testing stage and today's typical rigid continuous thin film media rely on longitudinal films.

Therefore, in this article, we limit the discussion to rigid longitudinal thin films. Most commonly, the rigid substrates are made of aluminum–magnesium alloys, glass, or glass ceramics. The magnetic films have been deposited on to the substrates originally by plating, later by physical deposition of vapor from a thermal evaporation source, and currently are deposited by vacuum sputtering. Generally, the magnetic layers are Co alloys, most commonly on a CoCr-alloy base matrix.

Table 1. Parameters and Units Used in Magnetic Recording

Quantity	cgs	mks	Notes
Permeability of free space μ	1	$4\pi \times 10^{-7}$	
Intrinsic coercivity H_c	Oe	Oe	
Remanent coercivity H_{cr}	Oe	Oe	$H_{cr} \geq H_c$
Moment per volume M	emu/cm^3	A/m	
Remanent magnetization M_r	emu/cm^3	A/m	
Product of remanent moment and film thickness $M_r\delta$	emu/cm^2	A/m^2	
Product of remanent magnetic field flux and film thickness $B_r\delta$	G/cm^2		
Anisotropy constant K_u	ergs/cm^3	J/m^2	
Anisotropy field H_k	G	T	1 T = 10^4 G

Patterned media are considered to be the media for the future, although they are still in their infancy. Much effort is being devoted to patterned media, which have been demonstrated to have a much larger area density capacity than continuous media (13). Processes for making patterned media include photolithography etching and optical-interference-controlled etching (14). Many other techniques are in the development stage (15–18).

MAGNETIC RECORDING MEDIA ON RIGID DISKS

The development of magnetic rigid recording disks has progressed considerably, both in the fabrication methods and in the areal density. IBM built the first rigid disk in 1957. It was 24 in. in diameter, coated with Fe_2O_3, and held 5 Mbyte of data with an areal density of 10 Mbit/in.^{2} and a coercivity about a few hundred oersteds. Three years later, 14 in. disks were made using the same process but the disk was improved to hold more data, with the areal density increased to 100 Mbit/in.^{2} and the coercivity doubled over that of its predecessor.

In the early 1970s, thermal evaporation and electroplating technologies became available for magnetic recording media and showed substantial advantages over the particulate coating technique. New media could then be manufactured with higher media areal density. Meanwhile, the disk size was reduced further to 8 in. In the early 1980s, sputtering technology was adopted by virtue of its superiority to all the earlier media fabrication methods. Since the resultant magnetic thin films were much more homogeneous and had much better film integrity, sputtered media could attain much higher areal recording densities. Therefore, from the mid-1980s to the mid-1990s, rigid media have advanced rapidly from media areal densities of hundreds of Mbit/in.^{2} to the current production level of several Gbit/in.^{2} At the same time, the media size has shrunk further, through 6, 5.25, 3.5, 3.0, and 2.5 in., all the way to 1.8 in. in diameter for mobile computer applications.

Magnetic materials for the rigid media of the last 10 years have mostly been Co–Cr–X–Y–Z alloys, where X, Y, and Z refer to different transition metal elements. At present, 3.5 in. and 2.5 in. disks are the dominant, popular sizes and commonly employ CoCrPtTaX media alloys. The cost of the media has dropped dramatically to about $0.03 (US) per Mbyte from about $5.00 per MB a decade ago. Progress in this technology continues and is expected to result in 10 Gbit/in.^{2} disks being commercially available at the turn of the century.

Studies of Magnetic Media on Rigid Disks

Magnetic recording media form one of the most successful research areas of transfer of research results into commercial application. Extensive studies of rigid media started in the early 1980s during the transition between electroplating and vacuum-sputtering technologies. Co, CoCr, CoCrNi alloys were the early materials studied in great detail (19–22). Fisher, Allan, and Pressesky proposed the CoCrTa magnetic alloy system (23), which lasted 10 years in commercial production until improvements in the performance of CoCrTa media became limited by coercivity limits of this alloy system. Lal and Eltoukhy (24) and other researchers (25) found that the addition of Pt to CoCr or CoCrTa systems could dramatically increase film coercivity. With the quaternary alloy system, coercivity ranges as high as 4000 Oe have been achieved at higher Pt concentration (8).

Magnetic recording media can be classified into three categories according to the principles and schemes employed in the recording process. The first category comprises the longitudinal recording media, on which large numbers of studies have been reported around the world. Longitudinal recording is one of the most successful examples of academic research and commercial applications stimulating each other and of science leading directly to products. The second category is of the perpendicular recording media. Studies of these media have shown the high potential of perpendicular recording for ultrahigh area recording density. For practical reasons, this type of recording scheme is still not in use and there is no commercial product available. However, a large number of studies have been done, mostly in Japan, where the work originated and where there is still the most research and continuing academic discussion. The last category is of the longitudinal type of media that have an added “keeper layer.” Keeper layer media have also attracted considerable attention, which has resulted in quite a number of studies. The rationale is that the resulting magnetic flux closure can increase the fundamental read-back signal. However, such media are less suited to high-areal-density recording because of the increased effective spacing between the head and the magnetic layers and higher media noise generated by the keeper layer. Such media are still in the experimental stage and are not used commercially.

Techniques of Fabricating Recording Media

Magnetic thin films can be fabricated by various techniques, but three major ones have been used commercially by the thin-film media industry.

Electroplating played an important early role and was the first technique to deposit thin films of magnetic material, such as Co or CoNi, onto disk substrates from solutions containing salts of Co and Ni and hypophosphite salts, along with buffers to maintain the solution pH. This technique is no longer considered suitable, however, for high-density media for reasons of film density, nonuniformity, and defects.

The second technique was thermal evaporation, which was first used in flexible media (29) and later used in rigid-disk media manufacturing. In this process, materials such as Co, FeCo, or FeCoCr alloys are inductively melted and evaporated on to a substrate that is constantly moving to ensure film uniformity. The evaporated material is deposited onto substrates at an angle away from normal incidence. This was reported to yield advantages such as higher in-plane anisotropy, and therefore higher coercivity and better hysteresis loop squareness, all of which are needed in longitudinal recording (30). This oblique deposition scheme was also helpful in that it allowed two sides of rigid disks to be deposited simultaneously. Figure 3 illustrates the oblique evaporation process of making a rigid media disk. The evaporation methods have been surpassed by sputtering.

Sputtering, the third technique, is now the most important and yields highly compact, dense film that is well suited to high-areal-density recording. Importantly, sputtered metal alloy deposits can closely copy the chemical composition of the sputtering target material and the film magnetic properties can largely be controlled by alloy stoichiometry and by process conditions. Of the range of available sputtering techniques—dc and RF forms of diode sputtering and dc, ac, and RF forms of magnetron sputtering—dc magnetron sputtering has proven to be the best manufacturing process.

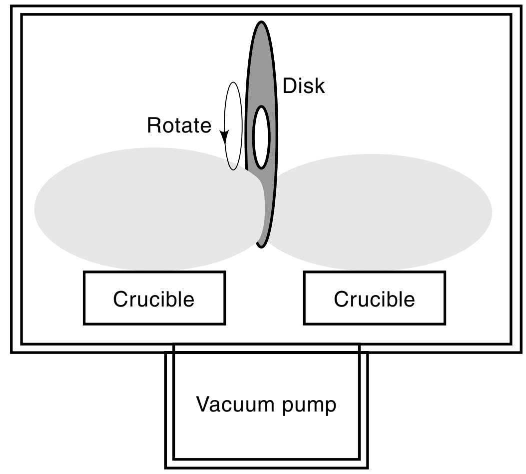


Figure 3. Illustration of the oblique evaporation process of making a rigid-disk media.

Given its importance in attaining the highest-density recording media, the sputtering process is described in detail in the following sections.

SPUTTERED THIN-FILM MEDIA

Sputtering Processes. Sputtering is an ion-bombardment process in which atoms are sputtered (removed) from a target (source of material) and deposited onto a substrate.

In a vacuum chamber at a low pressure of inert gas, a voltage difference is applied between a cathode and an anode to create a plasma, containing electrons and ions—Ar^+ in the case of argon, the most commonly used inert gas. The ions are accelerated towards the target (cathode) where they eject atoms of the target material, some of which, depending on the geometry of the system, can travel to be deposited on the substrate. This is a description of diode sputtering.

In magnetron sputtering, the plasma is additionally concentrated above the target by an enclosing magnetic field flux located at the sputtering sources. The magnetic field is imposed in such a way that the electrons are trapped in a region near the target surface, causing more intense ionization there. In standard sources, most of the sputtering occurs in an annular region around the center, as is shown in Fig. 4. The fierce ion bombardment does cause localized heating of the target, and this heating can cause some target materials to shatter if very large thermal gradients are allowed to develop and the target material cannot dissipate the heat fast enough. Sputtering targets and cathode systems are therefore cooled by flowing water to assist in dissipating the heat.

Electrical power can be supplied as RF, lower-frequency ac, or dc power, but dc power provides the highest sputtering rate, is more stable, and is best suited to manufacturing.

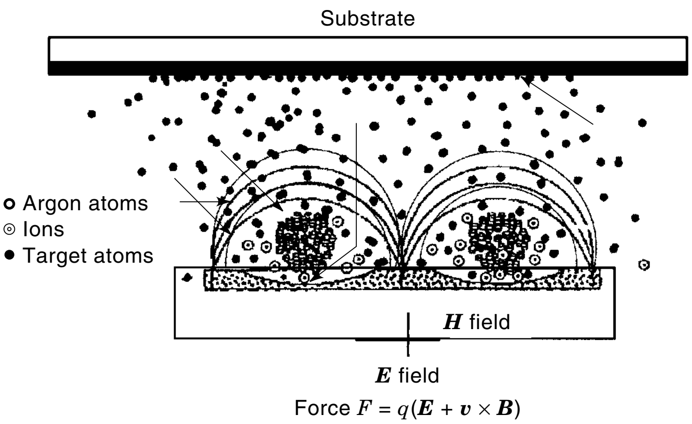


Figure 4. Schematic diagram of sputtering from a circular target.

Place of Sputtering in the Disk-Manufacturing Process. Figure 5(a) shows a flow chart of the process for making disks and Fig. 5(b) shows a configuration of a pass-by-type sputtering machine for manufacturing rigid-disk media. Blank substrates are polished to a smoothness that will permit the head to fly at the required height without any impact with the disk during disk rotation. Disks are then washed and sputter-coated in a system of the type shown schematically in Fig. 6. The sputtering process itself is discussed in more detail in the following sections. After sputtering, disks are given post-sputtering treatments, including tape burnishing of the disk surfaces and dip lubrication. The disks are then subjected to head glide (flying) and certification tests.

Types of Sputtering. The main sputtering categories are diode sputtering, dc (constant-field) magnetron sputtering, rf (radio frequency) magnetron sputtering, and ac (alternating-field) magnetron sputtering.

Diode-sputtering systems are undemanding in design and construction and were the first to be used because the cathode can be quite simple and operation only requires application of an electric field between the cathode and anode. During diode sputtering, a plasma of positive inert-gas ions and electrons is generated, but the plasma is not closely confined. Many electrons therefore can bombard the substrate, which increases the substrate temperature in an uncontrolled manner and so affects film growth. It was found that the sputtering efficiency for this technique was low and that the film mechanical properties could not be kept within a narrow range. The diode technique was therefore quickly abandoned and was replaced for magnetic media by magnetron sputtering.

In magnetron sputtering, the cathode target design accommodates a magnet behind the target whose external field encloses the surface of the sputtering target. Under the influence of both the applied electric and magnetic fields, plasma electrons are strongly confined and so both the electron heating of the substrate and the consequent interference in film growth are minimal. The confinement of the electrons through the action of the Lorentz force is illustrated in Fig. 4. The nature of the applied electric field generates three important variants of magnetron sputtering.

Most popular in the media industry is dc magnetron sputtering, in which a constant voltage is applied between cathode and anode. This form of magnetron sputtering is easy and efficient, but demands that every part of the target surface must have good electrical conductivity to avoid both micro-arcing and the associated ejection of particles that can otherwise form detrimental defects in the disk. This "target spit" problem is commonly observed in dc sputtering of carbon targets but can easily be overcome by using RF magnetron sputtering. By preventing the accumulation of charge on the target, a radio-frequency oscillating electric field eliminates micro-arcs and so minimizes the introduction of defects in the disk surface. However, RF magnetron sputtering is not as straightforward as dc sputtering in its operation, because it is less stable and because it demands careful matching of the power source to the dynamic load that the sputtering system

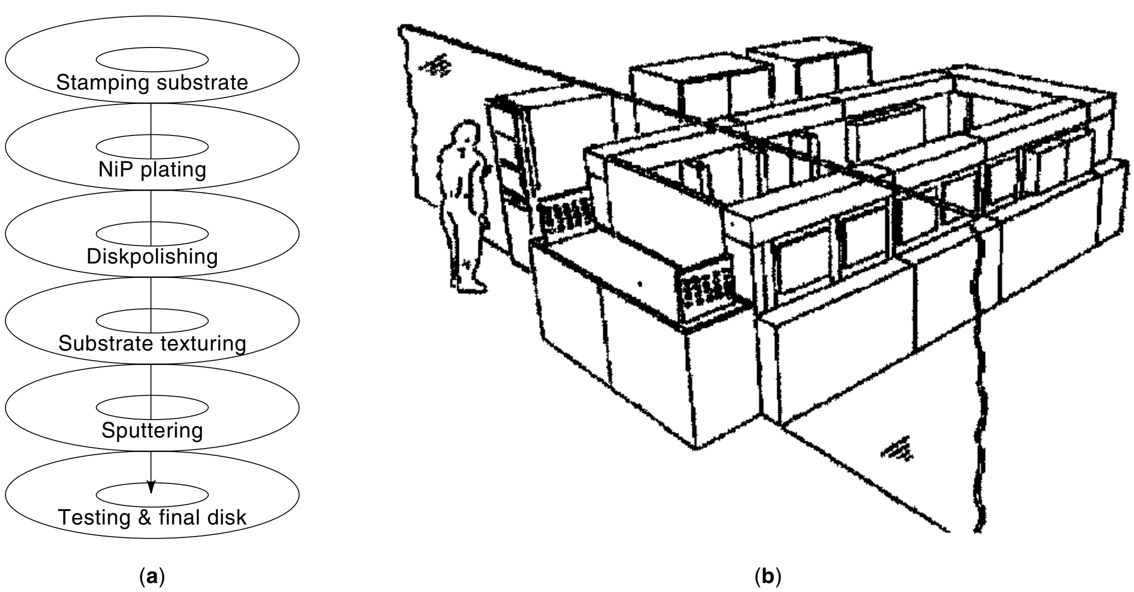


Figure 5. (a) The disk-manufacturing sequence. (b) A configuration of a pass-by type of sputter system (ULVAC sputtering system). [Fig. 5(b) courtesy of ULVAC.]

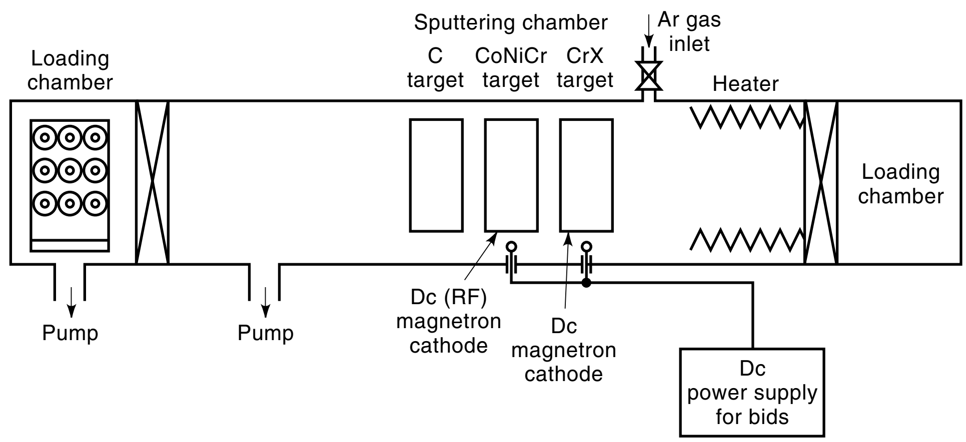


Figure 6. Schematic arrangement of a magnetron sputtering system.

presents. Few disk makers have therefore used this technique. To minimize instability problems and to permit use of less conductive targets without micro-arcing, the lower-frequency (<1 kHz) ac magnetron sputtering can be used with improved results. However, most disk makers currently use dc magnetron sputtering because it is simple and reliable.

Effects of Sputtering Process Control on Media Properties. The sputtering process has a great impact on thin-film mechanical properties, magnetic properties, and recording performance. For magnetic recording media, the sputtering process is as important as correct selection of the magnetic alloy composition and of the underlayer materials. Many parameters and factors affect the sputtering process. For example, changes in the sputtering power, the sputtering working pressure, the substrate temperature, and the substrate bias voltage all act to change the mobility of deposited adatoms.

Although the sputtering process is complex, it is the energy of adatoms that finally controls the film growth and film properties. It has been demonstrated that altering the mobility of the adatoms causes large changes in the mechanical and magnetic properties and in the morphology of the magnetic film. Figure 7 is the classic diagram that illustrates how the sputtering process affects film growth, which therefore alters the film properties (31,32). Films sputtered onto a substrate at high temperature, high substrate bias voltage, low argon pressure, and high sputtering power tend to be fully dense and to have few grain boundaries. The grain size of the films sputter deposited under these conditions therefore tends to be relatively large and the films have a well-defined grain morphology. On the other hand, films sputter deposited under conditions of lower substrate temperature, no bias, higher working pressure, or lower sputtering power tend to be porous, with a smaller grain size and wavy film surface morphology. Gao, Malmhall, and Chen studied and reported on the correlation between sputtering process conditions with film mechanical properties (32,91).

To make media that have good magnetic properties and good recording performance, the preferred sputtering parameters are high substrate temperature T_{sub} (for NiP/A1 substrate media, this means above T_{sub} = 250°C), about a 250 V substrate bias, low pressure, and relatively high sputtering power. Of course, making a medium with specified magnetic properties requires a combination of these sputter-deposition parameters. How to select a suitable combination depends on the actual sputtering system, alloy selection, and media configuration that is going to be used. There is no absolute recipe for making a universally good magnetic recording medium; in industrial production, certain process parameters cannot be adjusted for optimal media performance because of constraints on production throughput and practicality. For example, low-mobility sputtering can usually result in a medium with a better signal-to-noise ratio (SNR), but the process has not been adopted commercially because of its limited throughput.

Sputtering System Configurations. An additional aspect of sputtering systems that is important to making good recording media is the configuration of the sputtering systems as *static* or *pass-by*. In pass-by systems, the substrates are conveyed past the sputtering targets; in static systems the substrates are stationary in front of target during film deposition. The static types of systems are usually smaller and have targets that can readily be exchanged. In these systems, it is

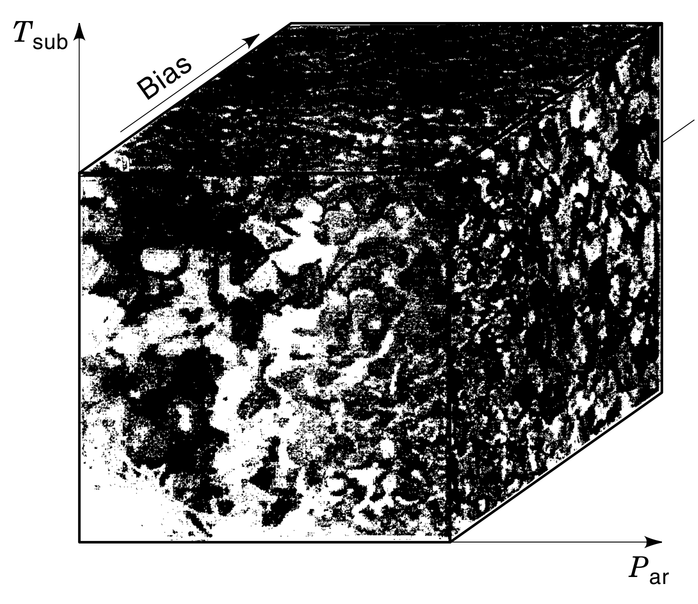


Figure 7. Schematic illustration of the effects of bias voltage, sputter chamber pressure, and substrate temperature on thin film morphology and grain structure.

also easier to develop and to control the sputtering process. Pass-by sputtering systems usually have the advantage in mass production if the sputtering yields can be properly maintained.

Disks sputtered in static sputter systems usually have good magnetic property uniformity around the circumferential direction but less so in the radial direction. Radial variations can, however, be minimized by optimizing both the magnetic flux distribution in front of the target surface and also the combination of sputtering power and duration. On the other hand, pass-by sputter systems usually yield disks with better magnetic property profiles in the radial direction. Studies have shown that pass-by sputtering systems tend to provide disks with poorer modulation in the circumferential direction (33,34) but that this problem can be minimized by depositing an appropriate seed layer underneath the underlayer and the magnetic layer (35–37).

Pass-by sputtering systems usually tend to have larger chambers than those of static sputtering systems; sufficiently good vacuum is therefore harder to attain and maintain. Studies have shown that vacuum integrity is also important to making high-density recording media disks of high quality and that improved vacuum correlates strongly with higher coercivity in the disk (38,39). Therefore it is common that magnetic alloys with higher anisotropy have to be used in pass-by systems to achieve the same media coercivity as is obtained in static sputtering systems with alloys of lower anisotropy. Constantly improving and optimizing the vacuum performance of sputtering system is an important and essential task for system makers.

Thin-Film Media Magnetics

Magnetic Properties of Thin Films. Magnetic properties that characterize media are most importantly the intrinsic anisotropy, the coercivity H_c, the saturation magnetization, the squareness S, and the coercivity squareness S^* [or the switching field distribution (SFD)]. Since the film coercivity encountered by a recording head is actually the remanent coercivity H_{rc}, this is the parameter more freqeuntly used by disk makers. The relation between the intrinsic and remanent coercivity can be seen in Fig. 8.

The product $M_r\delta$ of remanent magnetization M_r and medium physical thickness δ is often used because of its direct relationship with the recording readback amplitude. As the media density is increased, the magnetic transition length parameter a must become shorter. According to the Williams–Comstock model [Eq. (8)], to reduce a and so shorten the transition, either H_c should be increased or $M_r\delta$ should be reduced, or both should occur.

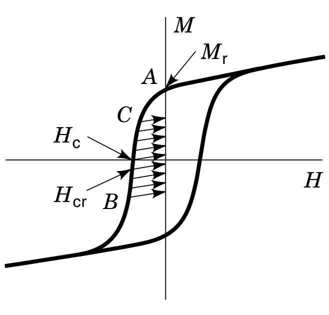


Figure 8. Hysteresis loop of a thin-film disk.

Coercivity in thin-film media is predominantly controlled by the magnetocrystalline anisotropy of the target materials, by processing that affects the film microstructure and the magnetic interaction between grains, and by the extrinsic aspects of the microstructure of the magnetic media that influence the difficulty of domain-wall motion and of nucleating reverse domains. Both intrinsic anisotropy and media processing must be optimized to create media with high loop squareness and high coercivity.

Anisotropy and Its Origin. A magnetic recording medium exhibits a high coercivity and a high hysteresis loop squareness because of the anisotropy and the interactions among the grains in the film. The total, or effective, anisotropy of a medium is the sum, principally, of three parts: crystalline anisotropy, shape anisotropy, and elastic anisotropy, the latter being due to the film stress created during the sputtering process. This total anisotropy is therefore

$$K_{\text{total}} = K_u + K_{\text{shape}} + K_{\text{elastic}} \tag{12}$$

Here, K_u is the magnetic anisotropy constant, which is an intrinsic parameter and is determined for each crystalline phase by its composition and structure. K_{shape} and $K_{elastic}$ are extrinsic parameters and so their values are process dependent. K_{shape} includes the effect of the geometry of the thin film and the shape of the grains and depends on the sputtering process and on the surface morphology of the substrate. $K_{elastic}$ includes strain and stress effects but contributes significantly if the medium possesses a nonzero magnetostriction (magnetostriction constant $\lambda \neq 0$). In the CoCrTa alloy system, $K_{elastic} = \frac{3}{2}\lambda\sigma$, where σ is the mechanical film stress, and can contribute up to one-quarter of the total medium coercivity (38).

There is still ambiguity about the role of the mechanical surface texture of the disk substrate in improving H_c and loop squareness. Results are scattered, but there are four main hypotheses: (1) the mechanical substrate texture induces grain shape anisotropy (39,40); (2) the mechanical texture induces crystalline easy-axis alignment along the texture line (41); (3) the substrate texture line induces anisotropic stress between the radial and circumferential directions (38,42), and (4) texture line geometry effects induce anisotropy (43).

This last hypothesis assumes that crystal c axes of all grains in the magnetic layer are epitaxially well aligned on the underlayer—parallel to the (002) plane of the underlayer in the case of a body-centered-cubic underlayer structure. In this case, therefore, the grain c axes lying along the texture groove lines do not tilt out of the film plane, whereas c axes perpendicular to the texture groove lines may be tilted out of the film plane.

Statistically, a predominant effect of c-axis alignment along texture grooves is observed. This last hypothesis is convincing and is confirmed by experiments with and without substrate heating (39). On the other hand, $K_{elastic}$ may not depend only on one mechanism; two or three mechanisms may actually combine to change the total anisotropy K_{total}.

Magnetostatic and Exchange Interactions and the Loop Squareness. The origins of hysteresis squareness behavior were explored theoretically and experimentally by Hughes, Bertram, and Chen. Hughes (44) considered magnetostatic energy and anisotropic energy and Zhu and Bertram (45) principally explored exchange energy aspects. The total energy density E_t describing the magnetization therefore is

$$E_t = E_a + E_m + E_e \tag{13}$$

where E_a, E_m, and E_e are the anisotropic, magnetostatic, and exchange energy densities, respectively. The hysteresis squareness depends on their magnitudes and on their relative contributions to E_t.

For a medium that has high magnetostatic grain interactions among grains, the hysteresis loop is square but has lower H_c. When the exchange interaction is taken into account, the hysteresis loop of the medium obtained by computer modeling also showed higher loop squareness and smaller coercivity. Chen and Yamashita obtained experimental confirmation of this result. Figure 9 shows the media morphology and the hysteresis loops of three film media whose grains have different magnetostatic and exchange interactions (46).

Magnetization Reversal. Magnetic reversal in thin-film media can be classed into three different models: In the first, the grains are completely separate and reverse their magnetization independently; in the second, the grains are strongly exchange coupled and are grouped closely together as grain clusters, which reverse their magnetization cluster by cluster; and in the third, the grains are not strongly exchange coupled but are coupled magnetostatically, over a longer range, in magnetic domains in which magnetic reversal occurs by movement of domain walls.

Understanding the mechanism of magnetization reversal is of great importance in making high-performance media, because the mechanism of the magnetization reversal directly relates to the media noise and the media signal-to-noise ratio. For example, the first reversal mode results in very low media noise but the second mode usually leads to high media noise. Media noise is a key limiting factor that we discuss in the later sections.

Magnetic Alloy Selection. Magnetic alloy selection predominantly depends on the bulk magnetic properties, specifically the film coercivity H_c required to satisfy hard drive specifications based on recording models such as that of Williams and Comstock. The next most important is the media signal-to-noise ratio performance attainable with alloys of suitable H_c. This selection criterion has become significantly more important as the media areal density has increased.

Early magnetic inductive media required only low coercivity (less than 2000 Oe) to deliver a high signal, and so the bulk magnetic properties were of greatest concern. Most of the alloys used were then CoCrTa, CoNiCr, CoCr*X* (where *X* represents a different element) or something close to these ternary systems. As the required coercivity is increased, however, alloys with higher magnetocrystalline anisotropy must be considered. For this purpose, Pt-containing alloys have

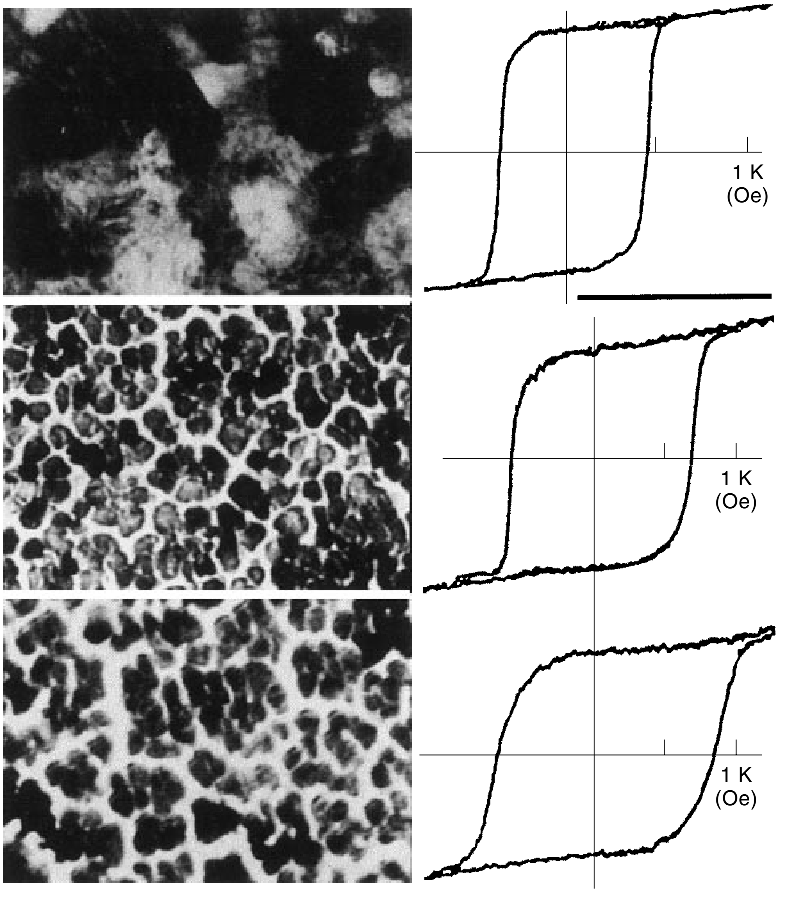


Figure 9. Morphology and hysteresis loops of films with different intergranular interactions.

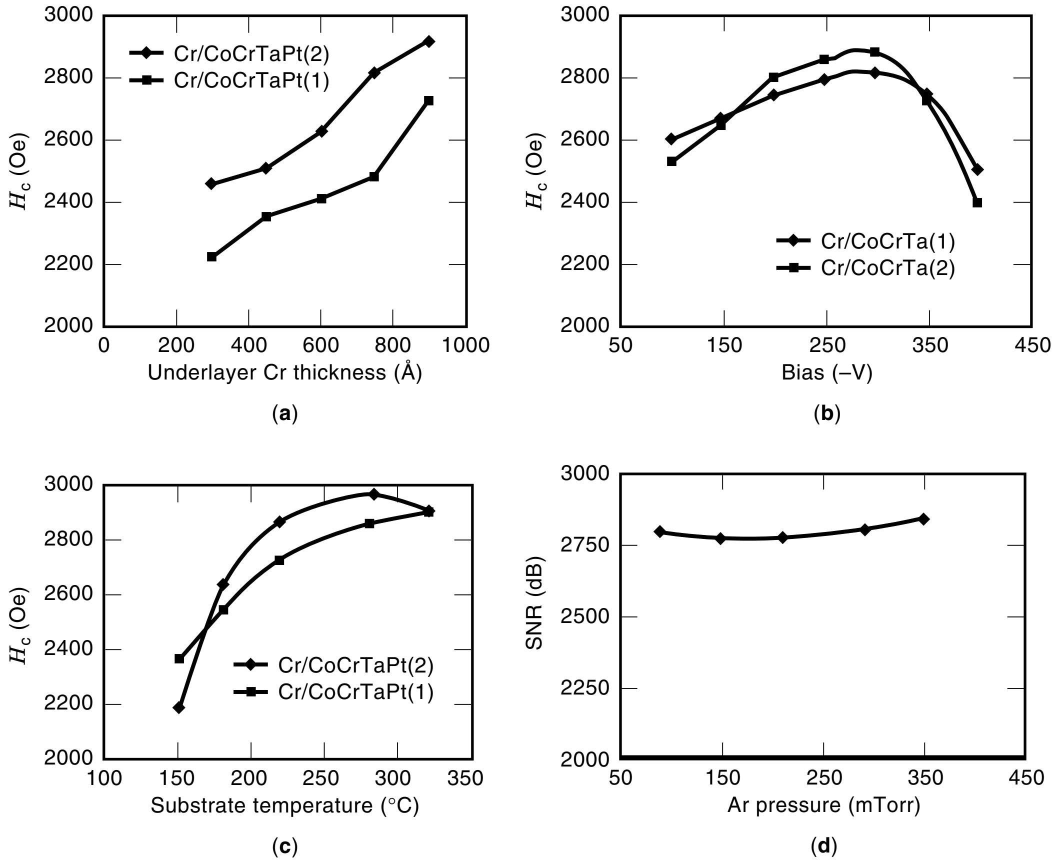


Figure 10. Process effects on H_c and the media signal-to-noise ratio for CoCrPtTa and CoCrTa media on Cr underlayers: (a) underlayer thickness, (b) bias effect, (c) substrate temperature, and (d) chamber pressure. Curves 1 and 2 refer to differing media compositions within the labeled alloy system.

been the most popular choice, although other alloy systems have been demonstrated to give higher film coercivity (47). Currently popular alloys with high crystalline anisotropy are CoCrPtTa, CoCrPt, CoCrPtB, or CoCrPtTa*X* where *X* can be Ni, B, Si, Zr, or Hf. Many studies have shown advantages in recording performance resulting from the addition of a fifth element *X* to CoCrPtTa. The performance enhancement includes improvements in media signal-to-noise ratio, and/or overwrite and PW_{50} improvements (48,49). However, the physics behind these gains is still under active discussion.

Correlation of Magnetic Properties with Sputtering Process and Process Control. The magnetic properties of the media films closely depend on the film-making process. When the media configuration is defined—that is, when the underlayer, seed layer (which is sometimes used) and magnetic alloys are defined—variations in the process of fabricating the media still exhibit pronounced effects on the magnetic properties of the film medium. The coercivity depends strongly on the substrate temperature, the underlayer thickness, and the substrate bias, and sometimes also on the sputtering working pressure. However, sputtering under higher power density minimizes the pressure effect on film coercivity. Figure 10 shows the effects of these process parameters on the film coercivity of a CoCrPtTa medium.

Process control is an important aspect in fabricating media with magnetic properties lying within a narrow range about the designed values. In manufacturing, for a specified magnetic property specification, the coercivity H_c can often be controlled by the substrate temperature and the underlayer thickness, which in turn are set effectively by the heater power and the underlayer sputtering powers, respectively. The product of remanent magnetization M_r and magnetic layer physical thickness δ is controlled by the layer thickness and the squareness of the hysteresis loop. Depositing films under conditions of higher adatom mobility tends to form magnetic films with the *c* axes oriented in the film plane, which increases loop squareness and, therefore, increases the M_r of the medium. These deposition conditions also help establish a desirably small switching-field distribution (SFD), or equivalently large S^* (approximately $S^* = 1 -$ SFD), the coercivity squareness, which is a measure of the narrowness of the range of applied magnetic fields required to flip the magnetic moments in the film. Figure 11 shows the effect of process parameters on S^* of a CoCrPtTa alloy system.

Thin-Film Media Microstructures

Cobalt-based alloys with hexagonal close packed (hcp) structure have been developed for use as the current longitudinal recording media. However, to confer on them the required magnetic properties in the read–write recording process, an underlayer with a specific microstructure and crystallo-

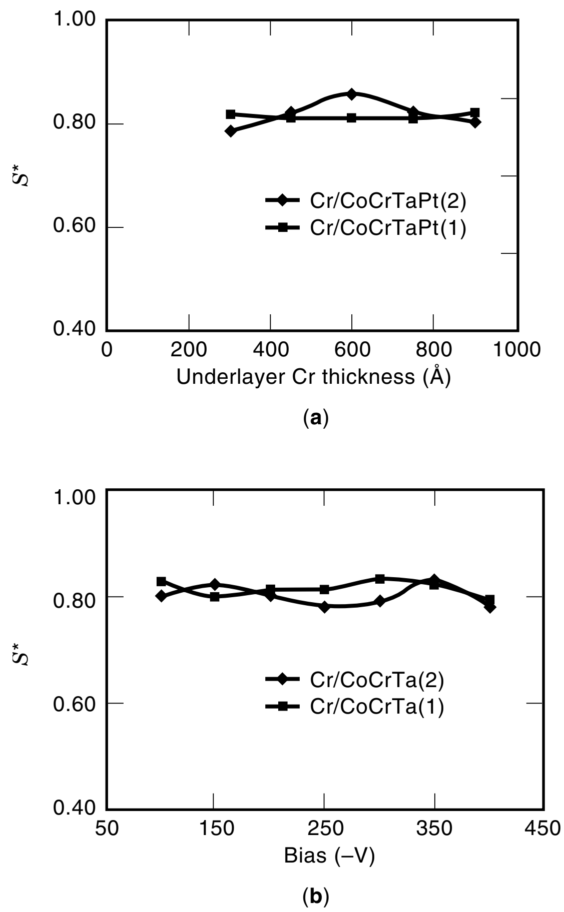


Figure 11. Process effects on coercivity squareness S^*. (a) Effect of the Cr underlayer thickness on CoCrTaPt media. (b) Effect of bias on the CoCrTa media on Cr underlayers. Curves 1 and 2 in each case refer to differing compositions within the same alloy systems.

graphic orientation is needed. Three decades ago, Lazzari, Melnick, and Randet (50) found that a Cr underlayer increased the in-plane coercivity of Co-based alloys.

It has been accepted for the last decade that the mechanism behind this coercivity increase is lattice-match-induced epitaxial growth of the magnetic film in a suitable crystallographic orientation. In a polycrystalline film with the easy magnetic axis of each grain oriented randomly, the magnetic anisotropy averages to zero and the film is isotropic. The only significant coercivity-enhancing mechanism then available is the shape anisotropy from the film itself and so it is difficult to obtain high coercivity and good hysteresis squareness. However, if an underlayer such as Cr, or a Cr alloy with B2 crystal structure in an appropriate orientation is deposited prior to the cobalt-based alloy, the crystalline orientation of Co- or Co-based alloys can preferentially be altered to enhance both the film coercivity and the hysteresis squareness. It is generally accepted that this underlayer effect is essential to ensuring alignment of the *c* axis of an hcp cobalt alloy structure in the film plane and so is critical in longitudinal recording.

Magnetic Layer Microstructure. To make a medium with square-hysteresis characteristic, which is highly desirable for better longitudinal recording performance, an appropriate magnetic microstructure is essential. The squareness of the hysteresis loop originates both from the intergranular interactions and from the distribution of easy *c* axes. Calculation shows that a three-dimensionally random distribution of the easy axes of a magnetic constituent, without counting the interactions among the grains, has a remanent M_r that is only half of the saturation magnetization M_s and that a two-dimensional random easy-axis distribution has M_r equal to $0.62M_s$ (51). Highly compact, sputtered grain structures with little grain separation usually result in strong magnetostatic interactions and so assist in achieving higher loop squareness. To obtain *c*-axis orientation in the film plane, the (11.0) or (10.0) planes of an hcp structure have to be grown parallel to the film plane. This can be done through control of the sputtering process but can most easily be achieved through epitaxial grain growth on top of an underlayer with the appropriate atomic structure, as discussed in the next section.

Crystalline Orientations of the Magnetic Layer and Underlayers. The most commonly used underlayer materials in current magnetic recording media are Cr, Cr-based alloys, or alloys with B2 crystal structure and similar atomic lattice constants (52). This structure is depicted in Fig. 12, which also lists atomic lattice constants. As we discussed in the preceding section, a specific orientation is needed for the desirable form of Co-based alloy film growth. Many studies have shown that having the (002) lattice orientation of the suitable B2 underlayer structure parallel to the film growth surface will induce epitaxial growth of an hcp Co alloy magnetic layer because of the close lattice match between the (11.0) plane of the Co alloys and the (002) plane of the Cr*X* (X = V, Mo, . . .) underlayer (50). This (11.0) orientation corresponds to *c*-axis alignment, or texture, in the film plane. Recent work has also shown that *c*-axis alignment or in-plane texture, in the magnetic layer could be promoted by epitaxial film growth on Cr (112) and (110) orientations of the surface planes of the underlayer (53). Figure 13 shows the atomic structure and orientation relationships.

Film Morphology, Grain Size, and Grain-Size Distribution. For good magnetic recording media, besides growing films with

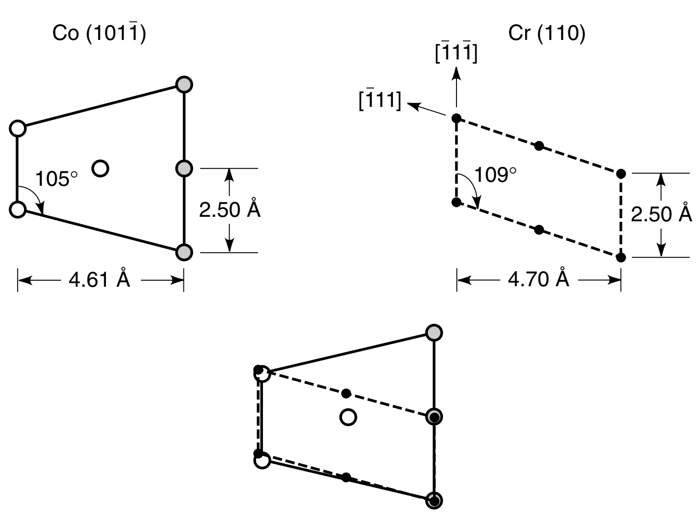


Figure 12. The crystal structure relationship of Cr and Co for Co(10.$\bar{1}$) crystal planes parallel to Cr(110) planes.

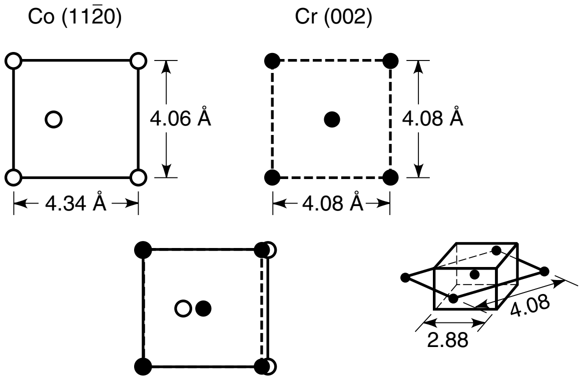
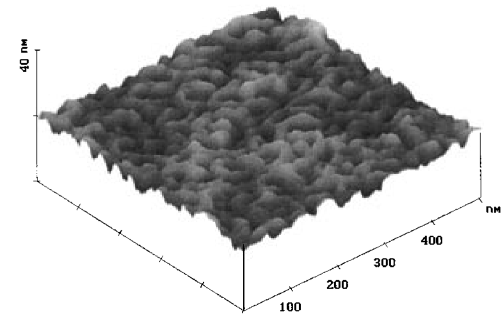


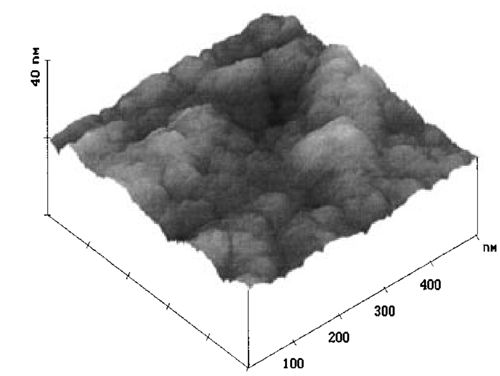
Figure 13. The crystal structures and relationship between Cr and Co, relevant to a Co(110)‖Cr(002) texture [i.e., with the Co(110) crystal planes parallel to the Cr(002) planes].

the correct atomic structure and crystalline orientation, it is also necessary to have uniform film morphology, small grain size, and narrow grain-size distribution. Studies have shown that, as the recording media layer is made thinner, the film growth technique becomes increasingly critical (54–57). Achieving two-dimensional film growth is preferable to three-dimensional growth—a surface and interfacial energy issue. A suitable substrate sublayer—for example, a NiP plated layer—can help establish a two-dimensional growth mode that improves the mechanical integrity of the subsequent layers. When the surface energy of a depositing layer has smaller surface energy than the existing surface material, the depositing adatoms tend to enlarge the existing surface layers by diffusing until they can be accommodated on the lower side of steps at the boundaries of the layers. This two-dimensional mode of growth therefore tends to form a continuous film by extension of the existing topmost layer in the plane of the surface. On the other hand, when the material of the depositing layer has a higher surface energy than the existing surface material, the depositing layer tends to grow in three dimensions by the formation of islands. For high-recording-density media, the layer-by-layer, two-dimensional film growth is particularly desirable since the magnetic film thickness must be very small and the mechanical integrity of the film is otherwise hard to maintain. Figure 14 illustrates the two types of film growth, which result in quite different recording performance (54).

The magnetic layer grain size is another key parameter that affects the film magnetic properties and recording performance in several ways. Figure 15 shows the dependence of H_c on grain size—behavior that is observed by many researchers (58–61). The coercivity initially increases with increasing grain size and then drops for grain sizes larger than 40 nm. The recording performance is also closely related to the grain size and to the grain size distribution. The smaller grain sizes and narrower grain-size distributions result in lower media noise and higher media signal-to-noise ratio, since the media noise originates in zigzag domain-edge irregularities, whose dimensions are correlated with the grain sizes. Therefore, controlling the grain size and minimizing the width of the grain-size distribution are important goals for media makers. Approaches to these goals include (1) selection of materials with different surface energies, (2) selection of the underlayer or seed layer, and (3) optimization of the film



(a)



(b)

Figure 14. Two types of epitaxial growth of a Co-alloy magnetic layer on a Cr underlayer.

growth process. Grain-size control is closely related to the film morphology that we discussed earlier. When the grains are smaller, the film will of course present a smoother, more uniform morphology that can largely be retained throughout subsequent processing.

Magnetic Switching Volume. Studies have suggested that the magnetic film grain size and switching volume have im-

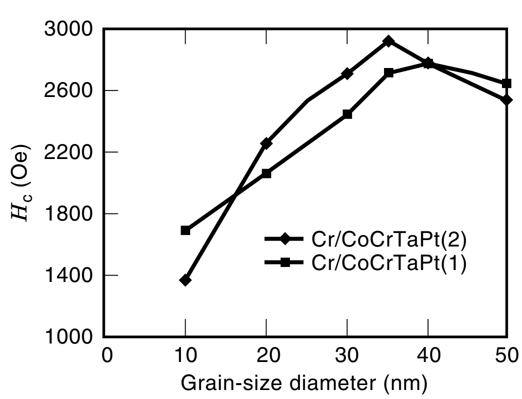


Figure 15. Grain-size effect on coercivity H_c.

portant effects on both the media performance and the thermal stability in high-density recording media (62–64). For low noise, as discussed previously, a small grain size is preferred. However, for sufficient thermal stability of the written information, the quantity $K_uV/(k_BT)$—the ratio of the energy associated with the magnetic anisotropy of the magnetic switching volume to the unit of thermal energy—must be sufficiently large (65). (In this ratio, K_u, k_B, T, and V are the magnetic anisotropy, Boltzmann's constant, the temperature, and the magnetic switching volume, respectively.) Thus, one would expect that there might be an optimal magnetic switching volume and so grain size, although these may not be identical quantities.

For a better understanding of the magnetization reversal process and the correlation between the reversal process and media noise, it is instructive to investigate the switching (activation) volumes and the physical grain sizes. It is known that these do not match for most materials, but the relationship is not fully understood at present. It is expected, however, that the medium noise should be related to the volume of the grains and/or the switching volume, since both quantities are relevant to the possible spatial resolution for recordings on these films.

Researchers have demonstrated that magnetization reversals do not imply switching volumes that are always identical with the physical grain size (66). In the simplest case, switching by homogeneous rotation of the magnetization, one would expect the physical grain and the switching volumes to coincide. The observed mismatch between physical grain and switching volumes has been known (67) and attributed to inhomogeneous magnetization reversals. Typically, for rather large particles, as occur in magnetic tape media, switching volumes are reported to be smaller than the particle volumes. Physically, this may be interpreted by assuming that the thermal energy k_BT can cause a change in the magnetization in only a certain fraction of the particle volume (i.e., the switching volume) in order to reverse the magnetization in that region of the particle. An example for such an inhomogeneous thermally assisted magnetization-reversal process was theoretically analyzed in Ref. 68. Experimental measurements imply that the magnetization-reversal process in "large" single-domain grains is inhomogeneous—most likely initiated at defect locations. On the other hand, when grains are too small to support a domain structure, they will switch entirely. Thus films with larger single-domain grains are expected to be noisy.

An additional factor that must be considered is magnetic interaction. Since magnetic interactions between grains must have an influence on the magnetization-reversal process, by affecting the external field at each nearby location they will affect the switching volume as well. Experimentally, it is found, however, that decreasing the grain size does not change the switching volume significantly. On the other hand, grain size controls the nature of the interactions in the magnetic media. One may speculate that making the grain and switching volume the same will result in a good design of recording medium.

Process Control of Thin-Film Microstructure. It is clear that selections of a suitable magnetic alloy and a suitable combination of underlayer and magnetic layer are essential. However, the film-deposition process is equally important for making good magnetic recording media. As discussed in the sections entitled "Thin-Film Media Magnetics" and "Thin-Film Media Microstructures," the film microstructure is strongly dependent on having the sputtering process yield a magnetic layer with its *c* axes in-plane and it is clear that this requires preferably an underlayer of B2 structure with [200] texture. In practice, this [200] orientation requires sputtering conditions that provide high adatom mobility. These conditions involve (1) high sputtering power, (2) high substrate temperature, (3) high substrate bias, and (4) low sputtering pressure. The [200] crystalline orientation has been grown on glass substrates by varying the substrate temperature (69). Figure 16 illustrates how [200] texturing can be achieved by varying the underlayer thickness and substrate temperature. The process conditions are critical for the underlayer but less so for the subsequent magnetic layer. It is observed that, even although higher-energy adatoms are required for formation of [11.0] or [10.0] orientation films of hcp Co-based alloys, once the [200] structure of underlayer is laid down, the epitaxial influence on subsequent growth is stronger than the influence of the process conditions.

Correlation of Thin-Film Microstructure with the Film Fabrication Process. The correlations between the microstructures, the morphology of deposited media films, and the film-growth-process parameters are demonstrated in Fig. 17 for CoCrPtTa media. High substrate temperature, high substrate bias, high power-density sputtering, and low working-gas pressure sputtering result in a film with well-defined grain morphology and with a strong tendency for the *c* axes to be aligned in the film plane. As an example, Fig. 17 shows the transmission electron microscope (TEM) images of films for a range of sputtering pressures and Table 2 gives the corresponding atomic structure change and the ratio of the *c* axis in the plane of the film to that out of the plane of the film. Since this morphology, the lattice structure, and the orientation variations are all results of sputtered adatom mobility, other sputtering process parameters that similarly affect the adatom mobility can be expected to change the film morphology and lattice structure in a similar way.

Thin-Film Media Structures and Configurations

Although thin-film media structures have evolved into several different configurations, illustrated in Fig. 18, since they were first used in the early 1980s, the basic structure remains the same. Basically, an underlayer, typically of Cr or Cr alloy, is deposited, followed by the magnetic layer(s), and finally a protective overcoat layer, typically a form of carbon. The whole sputtering deposition process is carried out within one vacuum chamber.

Conventional Magnetic Media. Conventional media structures always have an underlayer, a magnetic layer, and an overcoat. Commonly, the underlayers are Cr, Cr*X* alloys with *X* representing elements that primarily include V, Ti, Mo, Hf, Zr, and W in concentrations between 0 at.% and 30 at.%. The rationale for the *X*-element addition is first to alter the Cr lattice spacing while retaining the bcc crystal structure and second to inhibit development of larger underlain grains. The magnetic layer is now usually a quaternary CoCr*XY* alloy in which *X* and *Y* are Ta, Ni, Pt, Nb, and other elements. Ter-

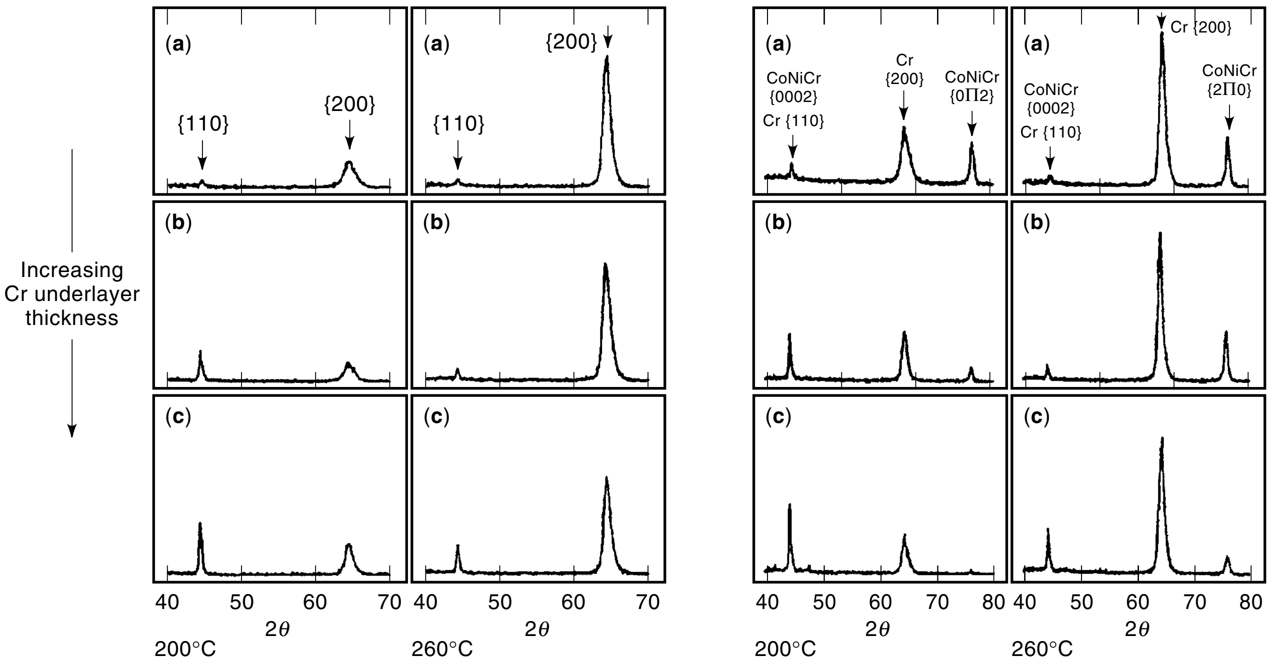


Figure 16. Influence of changes in Cr underlayer thickness and substrate temperature on film-growth texture observable through x-ray diffraction patterns, whose peaks reveal the major crystal planes parallel with the disk surface.

nary alloys without Pt were used in the early days for thin-film media with relatively low H_c (H_c < 2.5 kOe) but have been replaced by quaternary Pt-containing alloys for media requiring higher H_c. The addition of Pt linearly increases the coercivity at low concentrations and has resulted in coercivities as high as 4 kOe in thin film media. This dependence of coercivity on Pt concentration is quantified in Fig. 19. Carbon films have been used successfully as protective layers since the start of thin film media manufacturing. However, it has later been demonstrated that both hydrogenated and nitrogenated carbon films are even better than pure carbon films (70,71). Both CN_x and CH_y are currently in use by disk makers.

Seed-Layered or Double-Underlayered Media. It has been found that a double underlayer could result in better magnetic and recording performance for some alloys and certain underlayer materials (72–75). The first underlayer serves two purposes: It acts as a seed layer by initiating growth of smaller grains and by establishing a suitable epitaxial relationship in the deposition of the second underlayer. The second underlayer therefore grows both with the correct crystalline orientation and with a smaller grain size. This double underlayer approach has frequently been used for media, particularly in the pass-by type of sputtering system. The two underlayer materials need not be the same, but may be different, depending on the specific process, magnetic property requirement, and substrates used in the media design (57,76,77).

Flash Magnetic Layer and Double-Magnetic-Layer Media. Engineering of the working magnetic layer structures can also modify and improve the recording performance. The film coercivity can be increased substantially and the medium signal-to-noise ratio can be enhanced significantly by several process modifications: (1) using a flash magnetic layer before depositing the working magnetic layer (78,79), (2) depositing the same magnetic materials under successively different sputtering condition (49), or (3) using two different magnetic alloys to build one working magnetic layer (80).

Sandwich-Layered Magnetic Media. A nonmagnetic spacer layer sandwiched between two magnetic layers can reduce the effects of intergranular exchange coupling and of demagnetizing fields. Once the sandwich-layered construction was demonstrated to confer lower media noise and higher media SNR (81–84), sandwich-configuration media were produced at the time when the media still had relatively high $M_r\delta$. These layer-spacing effects are illustrated in Fig. 20.

However, producing media with dramatically increased areal density necessitated lower $M_r\delta$ and higher H_c and so required a reduced magnetic film thickness. This is incompatible with inserting a nonmagnetic spacer between two magnetic layers, since the film coercivity then suffers a severe drop and the distance between the outermost surfaces of the magnetic layers is increased. The coercivity decrease is grain-size related and, in fact, at low enough $M_r\delta$ one could reach the grain sizes at which the grains are no longer ferromagnetic—the superparamagnetic size limit. Therefore, sandwich media are only useful in applications for higher-$M_r\delta$ media, unless a new alloy with yet higher crystalline anisotropy is found.

Keeper-Layered Magnetic Media. Keeper-layered media were another early invention in the field of inductive media. The concept was to enclose a larger magnetic transition flux and so to boost the signal that had not been used in any commercial product. Since high-saturation magnetization materi-

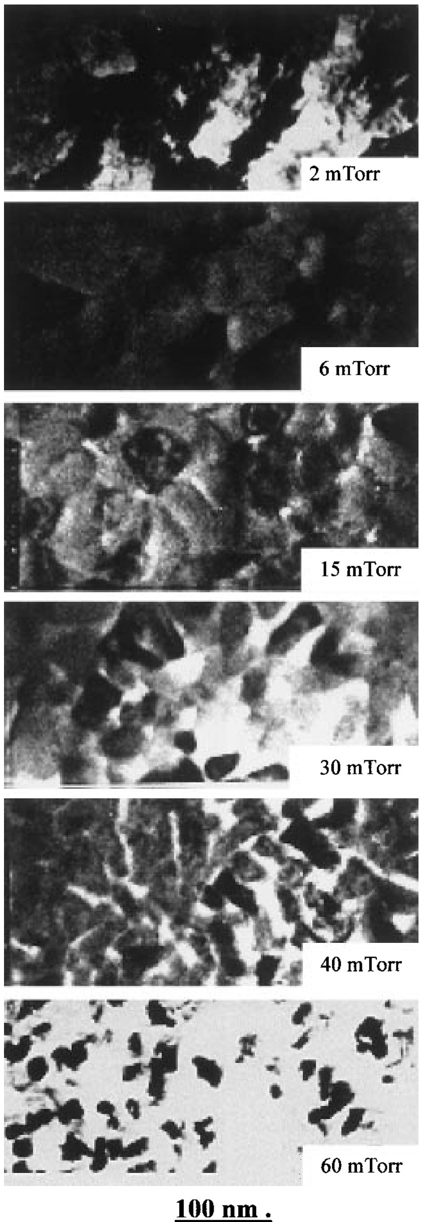


Figure 17. TEM micrographs showing the correlation between the film microstructures and sputter gas pressure for a thin film system.

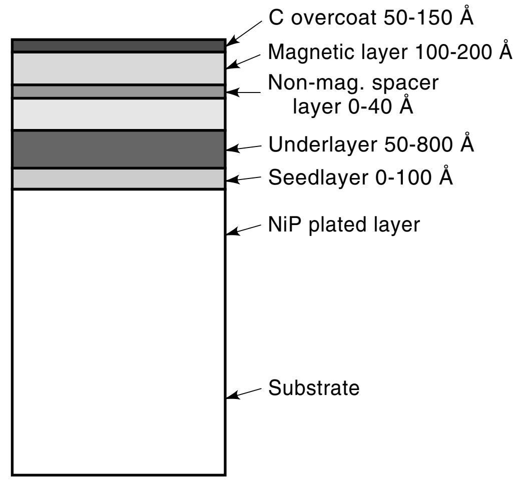


Figure 18. The configuration of a thin-film medium.

als must be used for the keeper layer, the results are higher demagnetizing fields and greater exchange coupling. Consequently, for keeper-layer media to be useful, the gain in signal amplitude must be balanced against the loss in media signal-to-noise ratio, as Yen, Richter, and Coughlin have demonstrated (88). Keeper-layer media therefore remain in the research laboratories but not in commercial production.

Recording Performance

Magnetic Transition Wavelength. During a magnetic head writing process, magnetic transitions are generated in the magnetic medium. The minimum repeat distance between the magnetic transitions is called the magnetic transition wavelength—the shorter the wavelength, the higher the number of magnetic transitions per unit distance. This transition length is illustrated in Fig. 21. Suppose the medium is dc erased (that is, erased with a constant applied field) and the magnetization is in the positive direction, with a value of M_r in the hysteresis loop. As the field of the head reverses and increases in magnitude, the magnetization reduces, following the hysteresis loop curve. At $H = -H_c$,, the minor hysteresis loop illustrates that there will still be a small remanent moment left. So, to take the remanence to zero the reversal field must be increased in magnitude to slightly more than H_c—to a field that is commonly called the remanent coercivity H_{cr}.

Assume that a medium is being written by a head that moves in the x direction—the direction of the field gradient in the gap in the recording head. Between media locations corresponding to points A and B in the hysteresis loop, there is a length a over which the transition occurs, and this can be estimated by

$$\frac{dM}{dx} = \frac{dM}{dH}\frac{dH}{dx} \tag{14}$$

If we can assume the slope of the hysteresis loop and the head field gradient are constant, we can integrate this to obtain

Table 2. Easy-Axis Orientation of Magnetic Film versus Sputtering Pressure

Pressure (mTorr of Ar)	2	6	10	15	20	30	40	60
Angles (deg)[a]	90	85	70	77	60	20	17	9
Interpretation[b]	In	Out	Out	Out	Out	Out	Out	⊥

[a] Easy axis angles are measured with respect to the film plane normal. Completely in plane corresponds to 90° and fully perpendicular to the plane is 0°.
[b] The interpretation of the angular orientation of the easy axes are in-plane (In), out-of-plane (Out), and perpendicular-to-plane (⊥).

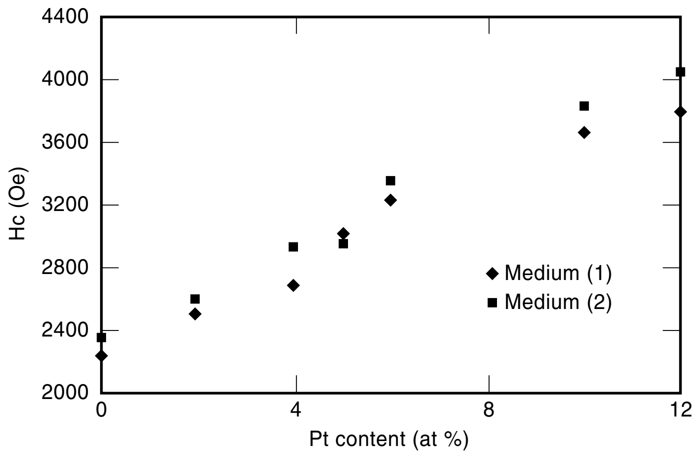


Figure 19. Pt concentration effect on coercivity H_c of CoCrTaPt media. Data sets 1 and 2 refer to differing underlayers.

$$a = M_r \bigg/ \frac{dM}{dH}\frac{dH}{dx} \tag{15}$$

which gives the importance of the squareness (through the slope dM/dx) of the hysteresis loop of the medium. The magnetic transition is most popularly assumed to have the shape of an arctangent function (89,90), which leads for film media to

$$a_{\min} = 2M_r\delta/H_c \tag{16}$$

where δ is the magnetic medium thickness. Consequently, for the shorter magnetic transition lengths required for high linear recording density, thin media with low magnetization and high coercivity are preferred.

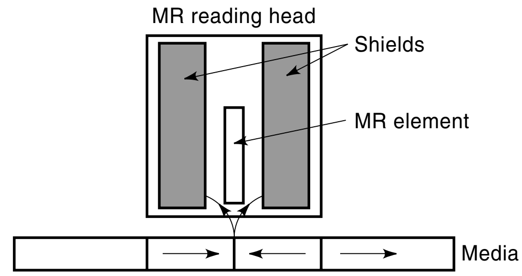


Figure 21. Transition length of a thin-film medium.

Readback Amplitude, Fundamental Signal of Thin-Film Media. The presence of the magnetization distribution in the recording medium generates a magnetic field flux that extends over the surface of the medium. Based on Faraday's law, when a coil cuts through this flux, or, as in the case of an inductive readback head, a coil flies above a moving magnetic medium, a current will be generated in the coil. This current can be used as a signal and is proportional to the fluctuation of the magnetic flux changes over the surface of the media. This is essentially the readback signal. When this phenomenon was first studied, it was assumed that the magnetization had a longitudinal sinusoidal form. With the additional assumptions that the reproducing head consisted of a semi-infinite block of high permeability material with a flat face spaced a distance d above the medium and that the magnetic flux distribution along vertical direction obeyed Poisson's equation, the flux per unit width Φ of the reproducing head was calculated to be

$$\begin{aligned}\Phi = \Phi_x &= \int_{d+\delta/2}^{\infty} B_x dy \\ &= -[2\mu/(\mu+1)]2\pi\delta M \sin kx[(1-e^{-kd})/k\delta]e^{-kd}\end{aligned} \tag{17}$$

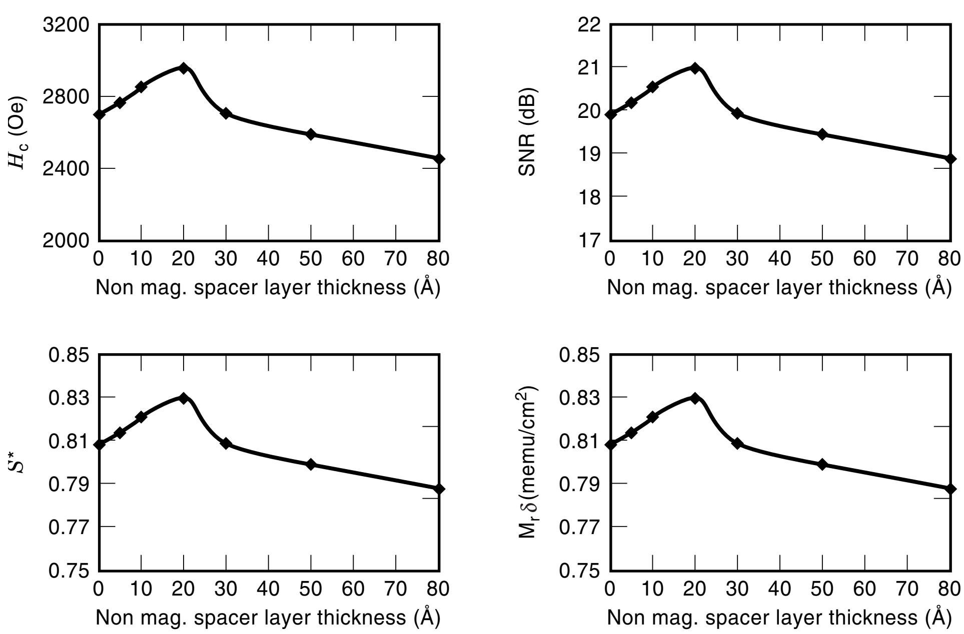


Figure 20. Effect of spacer layer thickness on H_c, SNR, S^*, and $M_r\delta$ in a double magnetic layer medium CoCrTa/Cr/CoCrPtTa system.

Using $x = vt$, where v is the linear velocity of the medium with respect to the head, t is time, and w is the width of the head, the time derivative of the flux Φ is

$$d\Phi/dt \propto 4\pi\, w\, v\, M[1 - \exp(-k\delta)]\exp(-kd)\cos\omega t \qquad (18)$$

Now if the head has a pickup coil with N turns and the efficiency of the head is q, the voltage generated by the head should be

$$V(t) = Nq\frac{d\Phi}{dt} \qquad (19)$$

Since the voltage is proportional to the flux time derivative, which is proportional to $\exp(-kd)$, the conclusions are (1) that there is a spacing loss that is dependent on d as

$$20\log_{10}[10\exp(-kd)] = -54.6(d/\lambda)\,\text{dB}$$

and (2) that there is a dependence of the readback signal on the medium thickness through the term

$$(1 - e^{-kd}) = k\delta = 2\pi\, d/\lambda = \delta\, w/v$$

Figure 22 shows Wallace's data of spacing loss and readback signal dependence on frequency. He experimentally confirmed the behavior just described by inserting spacers between a ring head and a rotating magnetic disk during readback.

This discussion is given here for a medium read by an inductive head (inductive media) but for a medium read by a magnetoresistive head (MR media), the starting point will be different. For MR media the readback signal is not proportional to the rate of the magnetic flux change but rather is proportional to the total intensity of the flux change. Thus any effort towards increasing the rotational speed of drive, the drive revolutions per minute, in the case of drives with magnetoresistive heads, is only for the purpose of increasing the data rate and not for improving the readback signal amplitude. The reader is referred to the excellent, detailed discussion appropriate to the MR media, written by Bertram (89).

To characterize the readback signal in media studies, average amplitudes are usually measured with high- and low-frequency tracks—that is, tracks, respectively, with high and low linear densities of magnetization transitions. The output from a sequence of transitions is a superposition of their individual amplitudes. In any sequence, two sequential transitions always have opposite signs. At a very high (spatial) frequency, the pulses are close together and tend to cancel each other, whereas at low frequency the pulses are completely separate and there is no interference between them. The readback process therefore exhibits nonlinearity at high frequency. Only the low-frequency amplitude is correlated unambiguously with the media $M_r\delta$ values. The high-frequency amplitude reveals information that includes the bulk magnetic property $M_r\delta$ and the sharpness of pulses, pulse width PW_{50}, which will be discussed in the next section.

Pulse Width PW_{50}. The recording signal pulse width is very much of interest in studies of magnetic recording media. The measure that is often used is PW_{50}—the pulse width at 50% of pulse amplitude—which describes the suitability of a medium for achieving high linear recording density. The smaller the PW_{50}, the greater the number of magnetic transitions that can occur both in the space domain and in the time domain. Therefore, the narrower the PW_{50}, the better the readback resolution will be.

Williams and Comstock (112), as well as Middleton, studied the pulse width and derived the relation between PW_{50} and the head gap width g, the head flying height d, the medium thickness δ, and the transition length a that is given in Eq. (7). Different studies have shown how PW_{50} varies as a function of head gap and flying height; their results are contained in Fig. 23. The variation in PW_{50} from the recording media point of view is given in Fig. 24, which shows the effect of media thickness δ and flying height for a fixed head gap and transition length.

Overwrite. Overwrite is an important measure of the effectiveness of writing one frequency signal over a previously written pattern that is most probably of a different frequency. The practical way of assessing the overwrite characteristics is first to write a pattern at frequency f_1 in the medium and measure the readback signal $V_0(f)$, then to overwrite another pattern of frequency f_2 (e.g., $f_2 = 2f_1$ or $4f_1$) and measure the residual signal $V_{Res}(f_1)$ at frequency f_1 as well, and finally to

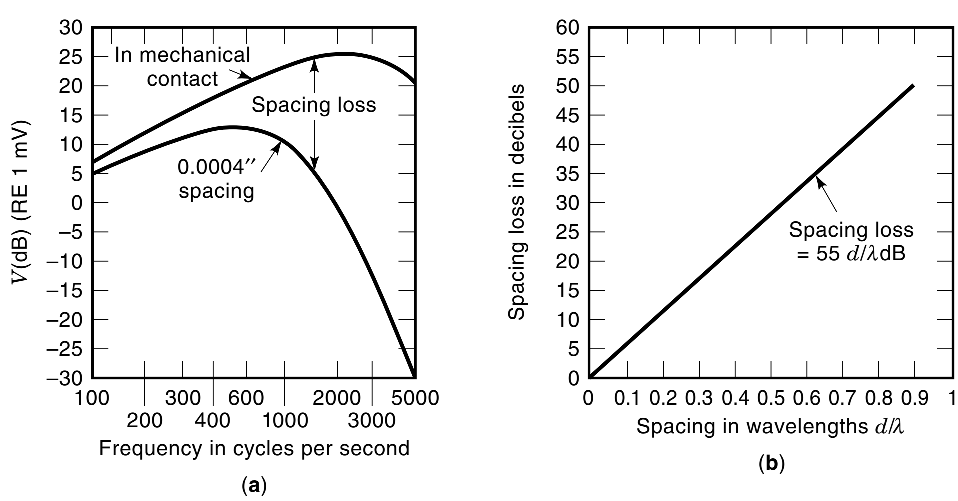


Figure 22. (a) Frequency effect on the read-back signal V (dB). (b) Dependence of the spacing loss (dB) on the ratio of the spacing d to recorded period of magnetization λ.

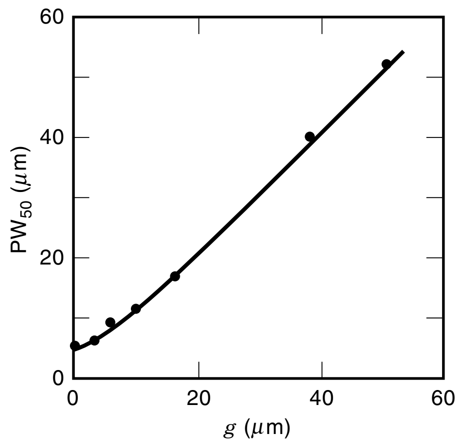


Figure 23. Correlations between PW_{50} and head gap g.

compute the overwrite OW as

$$OW = 20 \log \frac{V_0(f_1)}{V_{Res}(f_1)}$$

For high-performance thin films, this parameter should be at least over 30 dB.

In magnetic recording, the overwrite characteristics depend on both media and head properties. For example, increasing the writing field or decreasing the flying height of the head will improve overwrite performance. Here we discuss only the overwrite performance correlated to the media properties.

Overwrite is largely controlled by coercivity and $M_r\delta$. Overwrite can indicate whether the coercivity of a medium is excessively high. When the coercivity of a medium is high, the second set of magnetic transitions may not completely replace the old signals, thus reducing the overwrite. In high-density media, overwrite must be balanced against the need to have a short magnetic transition length and a small nonlinear transition shift (NLTS), which we discuss in the next section. This arises because a high-film coercivity is required for a short magnetic transition length and small NLTS, but lower coercivity is required for a good enough overwrite.

Nonlinear Transition Shift. At high recording density, magnetic transitions are nonlinearly distorted because the ratio of PW_{50} to the transition separation is increased. When two transitions are written too closely together, the demagnetizing field from the previous transition affects the writing of the next transition. This results in a shift of the location of the transition and is called the nonlinear transition shift. This shift depends on the transitions that are already written. From the magnetic flux view point, the origin of NLTS can be derived as follows.

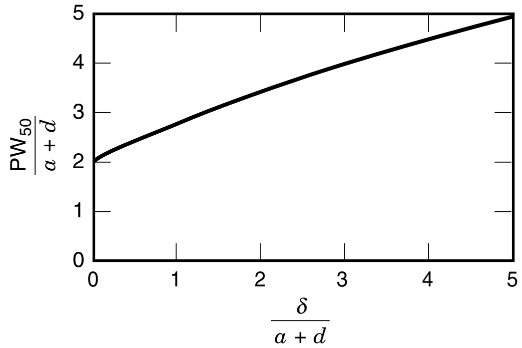


Figure 24. Correlation between PW_{50}, transition length, medium thickness, and head flying height.

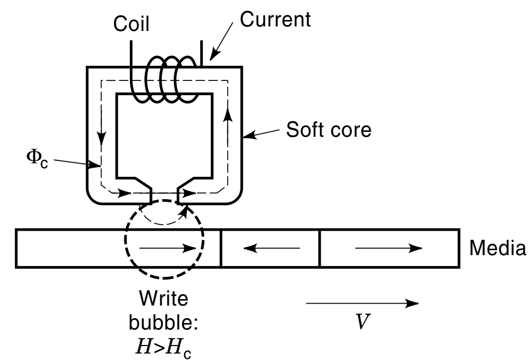


Figure 25. Writing a transition in a moving medium.

Since NLTS is a result of demagnetizing field H_{demag}, the medium sees the field from the head as $H_{eff} = H_{demag} + H_{head}$, in which H_{head} must exceed H_c in order to write a new transition.

Therefore, the transition is written not at a location x_0 but instead at the shifted location $x_0 + \Delta$, at which

$$H_{eff} = H_{demag} + H_{head}(x_0 + \Delta) > H_c \qquad (20)$$

Since the shift Δ is small, a Taylor-series expansion around the location x_0 enables the following expression to be derived (80):

$$\Delta X = \frac{4M_r\delta(d + \delta/2)^3}{\pi Q H_c B^3}\Bigg| \qquad (21)$$

where Q is a head-dependent parameter and B is the intertransition spacing. Therefore, the NLTS is proportional to both $M_r\delta$ and d, is inversely proportional to medium coercivity, and competes with overwrite. A balance must therefore be found between NLTS and overwrite when developing a high-performance medium.

Media Noise and Media Signal-to-Noise Ratio. There has been concern that media noise will finally limit the attainable increases in areal recording density. Media noise is caused by the randomness and uncertainty of magnetic transitions and results from the characteristics of the magnetic constituents in the media. Any spatial variation and magnetic fluctuation will produce noise. As the packing fraction of grains in thin film media approaches unity and the related intergranular exchange coupling increases, the media noise increases at the higher recording densities. Figure 25 shows a medium with transitions produced by a writing head. As we discussed in the section entitled "Magnetization Reversal," when all the grains reverse their magnetization independently under the influence of the externally applied field, there will be no uncertainty in the transition location other than a geometric grain-size effect and there will be less magnetization fluctuation. Therefore, the magnetization transition will be sharp, leading to low media noise and high media signal-to-noise ratio. On the other hand, if the magnetization reversal occurs in grains clustered and coupled tightly together, the magnetization transition will not be sharp, because its location conforms to the boundaries of the clusters of grains. This magnetic structure generates a so-called irregular or zigzag transition wall and results in media noise. The origin of the clustered grain reversal behavior lies mostly in exchange coupling but also in magnetostatic interaction.

As progressively higher areal densities are sought, media noise becomes more and more a problem. To make a medium with lower noise, different techniques and approaches have been reported. (1) *Physical grain separation:* Magnetic grains can be physically separated during the sputtering process by creating microvoids in the grain boundaries. This mechanism of physical isolation, which cuts the exchange coupling, is an effective way of reducing media noise (91). However, this technique has not really been applied in production, because, as discussed earlier, to make a porous medium, lower sputtering adatom mobility must be used and this slows down production throughput. (2) *Chemical segregation.* Studies have shown that the local chemical composition in the film could be varied during sputter fabrication. Surrounding or interlacing the magnetic grains with a nonmagnetic phase could also be effective in cutting down the exchange interactions and so lowering media noise (93). Techniques based on this idea have been widely used in the industry with quite remarkable results. However, new studies have shown that, at least for some media that exhibit low noise, neither physical separation nor chemical segregation could be detected. The only noticeable differences were the lower saturation magnetization and the extremely uniform and homogeneous film grain structure (94). This is, of course, of great current interest to disk makers.

Write Jitter. Peak jitter measurements are a valuable complement to the popular technique of integrating the frequency spectrum of media noise power. By using the standard peak jitter measurement algorithm described in Hewlett-Packard Application Note 358-3, the total peak jitter can be separated into write and read components. Under typical recording conditions, write jitter is known to be the dominant component of media noise. (Media noise also includes three variances associated with the readback waveform: peak jitter, PW_{50} fluctuations, and amplitude fluctuations.) By definition, write jitter is the standard deviation of the distribution of peak positions relative to their expected positions and is conveniently expressed in nanometers. If jitter measurements are performed at low recording density, in the absence of transition interference and NLTS, the peak write jitter is also the transition jitter. Transition jitter directly relates to the microstructure of the magnetic film.

Off-Track Capability. Unlike the other parameters we have discussed that characterize media performance, off-track capability (OTC), in units of length, refers to the performance change found when the readback head is positioned off the track center in a radial direction of the disk (94–96).

When a head is positioned over a specified track written on the magnetic disk, a certain positioning error is always present because the tract is written in one location and is later read with the head slightly shifted off the track center. As the track density is increased (for high areal density), neighboring tracks start to interfere with each other by generating a signal in the read head, particularly when it is off the center of the track.

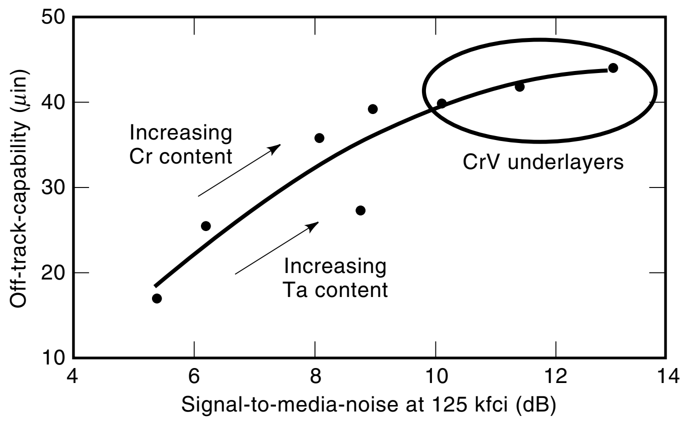


Figure 26. Off-track capability as a function of the media signal-to-noise ratio obtained by media composition and underlayer variation.

OTC characterizes how capable a medium is of allowing more tracks to be written in the fixed available radial dimension of a disk surface. OTC is mostly dependent media noise—the higher the OTC value, the greater the number of tracks that can be used per inch (TPI). The signal-to-noise ratio (SNR) and OTC give measures of a medium's recording density in two dimensions, the SNR revealing the range of linear recording densities along a track and OTC revealing the upper limits on the track number density. Figure 26 shows the correlations of OTC and media SNR. OTC always improves as SNR improves. Figure 27 shows the OTC curves of a group of samples that have different media SNRs (97). Interested readers are referred to the analysis by Taratorin (94).

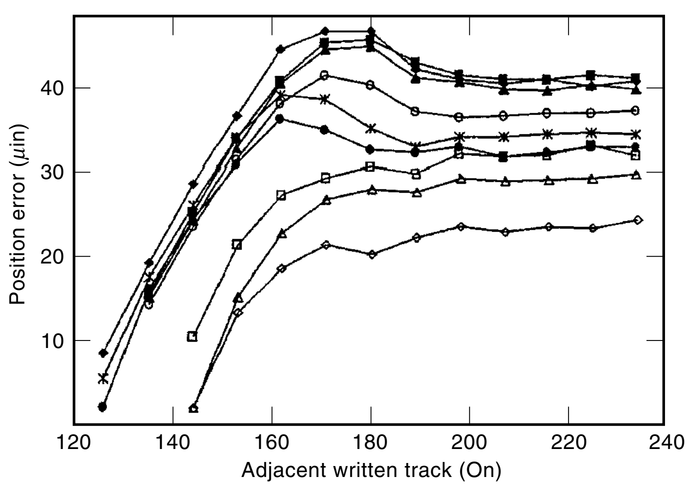


Figure 27. Off-track capability curves for a group of media of differing SNR as a consequence of differing underlayers and media compositions.

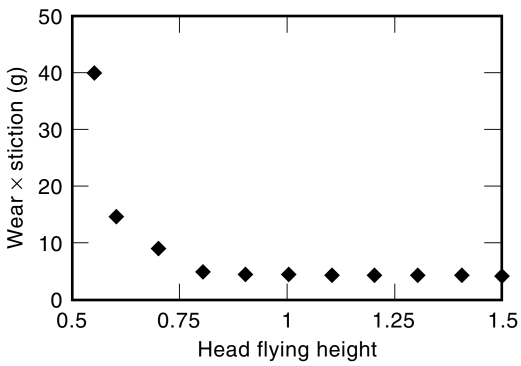


Figure 28. Head media products [(wear) × (stiction)] as a function of head flying height (in multiples of 1 μin., i.e., 25.4 nm).

Thin-Film Media Mechanics

Disk Tribology and the Head–Media Interface. Magnetic recording is realized by the relative motion between a recording head and a recording medium. To obtain a high signal at a high linear density with a narrow track pitch, according to the model of Williams and Comstock [Eq. (7)], the space between the head and the medium should be as small as possible. Therefore, the media surface needs to be made as flat and smooth as possible. However, smooth surfaces tend to lead to increased adhesion (stiction), friction, and thermal instability at the head–disk interface. A very small separation between the head and the media can indeed lead to greater friction and increased wear (98). Therefore, interface and media tribology is an important aspect of magnetic recording technology, recognized as critical in the magnetic recording media industry. Resolution of friction and wear issues involves appropriate selection of the substrate type and surfaces, the overcoat film, the lubricants, and the environment of the head–media interface and thus involves controlling the dynamics of the head and medium. The ultimate goal is to achieve contact recording with minimal friction and wear and with minimal adhesion between head and disk. Figure 28 shows the relationship between the product of wear and stiction as a function of recording head flying height. This behavior occurs because at a higher head-media flying height both wear and stiction can be very low, but as the head–media spacing is reduced both stiction and wear become large. The product of the two tends to infinity as the flying height tends towards zero, namely for contact recording.

Substrates. Conventional thin-film substrates are made from AlMg alloys containing about 5% Mg, since these have particularly high mechanical hardness. The substrates are stamp cut into circular plates and then electroplated with NiP film. This film further increases the surface hardness and also provides a base that can be highly polished. Aluminum substrates are widely used because they are good, easily made, and low in cost, but concerns have been raised about whether they can be made flat enough to permit ultralow head-flying heights and whether the hardness is high enough to withstand accidental head impacts without damage. For these reasons, glass, glass ceramic, and aluminum–boron-carbide have been considered as alternative substrate materials. Glass and glass ceramic substrates have now also been used in commercial products. However, advances in the technology of the conventional substrates have repeatedly extended the possibilities for AlMg. The best AlMg substrates have been made with flatness better than 3 nm and with local substrate surface roughnesses of only about 0.2 nm. Therefore, conventional AlMg substrates are still preferred in the industry.

Overcoat and Lubricant. There are two aspects to disk tribology in addition to substrate texturing: the overcoat and the lubrication technologies. Disks require an overcoat after magnetic layer deposition for two important reasons—to protect the mechanical integrity of the magnetic layer and also to prevent or at least minimize corrosion of the magnetic layer. Carbon, or carbon modified by being hydrogenated or nitrogenated, has been widely and effectively used as an overcoat in the industry.

To allow the head to fly freely over the disk surface and to minimize wear resulting from contact between head and media, a lubricant must be applied over the protective carbon layer. The lubricant is usually applied by dipping the disk into a solution containing the lubricant or its precursor. The thickness of lubricant on the disk surfaces is controlled by the rate at which the disks are pulled out of the solution. A good bond between the lubricant and overcoat is needed to prevent the lubricant from being squeezed out from any contact between head and media and to prevent the lubricant flying off the disk surface during drive operation. Sometimes, double lubrication or baking the disk in an oven between two lubrication steps can improve the bonding.

Studies have also shown that the molecular weight of the lubricant has a strong effect on the tribological performance (99). The class of lubricants that has been used extensively in disk industry are the perfluoropolyethers, including Fomblin ZDOL or Fomblin AM2001 lubricants. Perfluoropolyethers are long-chain fluorocarbon compounds, a desirable combination of properties that include good thermal and chemical stability, low surface tension, and low vapor pressure.

In addition to dip lubrication, vapor lubrication has been investigated by disk makers for media intended for ultralow head flying height. If successful, vapor lubrication could result in still lower cost and better performance of magnetic recording disk drives.

Substrate Texturing. Applying a layer of lubricant does reduce wear, but the meniscus force associated with the lubricant can cause serious stiction problems, sometimes resulting in the recording head sticking to the surface of the media and causing drive failure. To solve this problem, technology has evolved for substrate “texturing”—controlled introduction of slight variations from surface flatness. (Note that, confusingly, this texturing is not the same as the crystallographic idea of texture referred to in discussing underlayer and magnetic layer microstructure, in which similar crystallographic planes and directions in a polycrystalline material are more or less closely aligned. However, texturing of a substrate surface can indeed influence the crystallographic alignment, and therefore the crystallographic texture, of subsequently deposited layers.) Several different techniques are used for texturing disk substrates: (1) mechanical texturing, (2) laser bump texturing, (3) sputter texturing, and (4) intrinsic texturing.

(1) In mechanical texturing, a tape coated with hard particles such as diamond or Al carbide is used to abrade

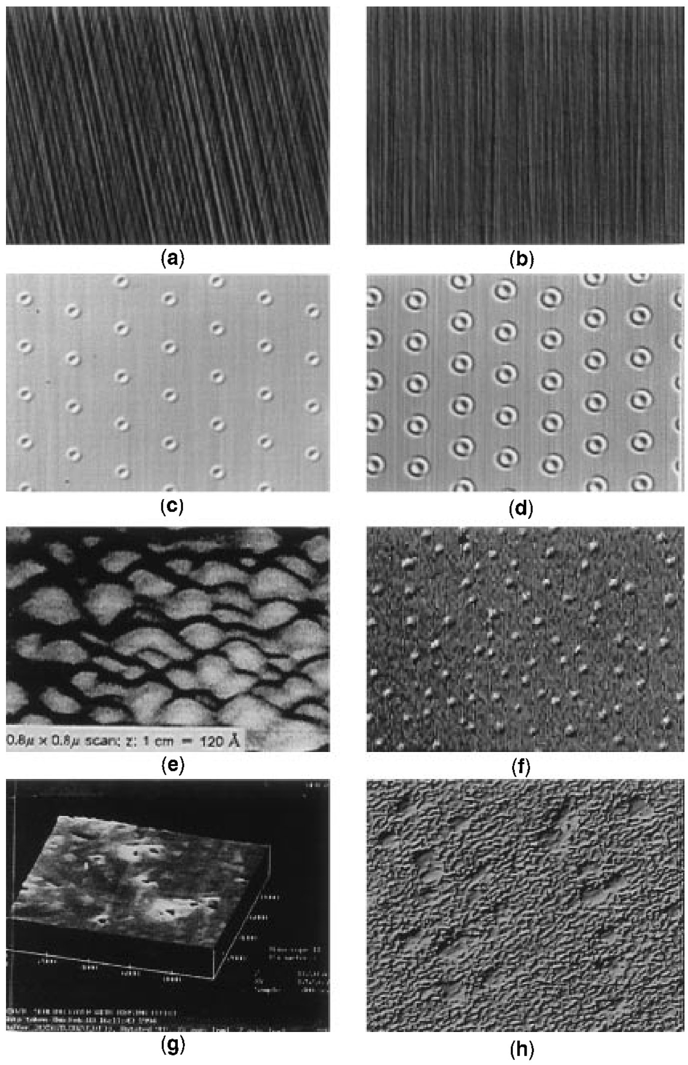


Figure 29. Images of different types of disk substrate texture; details given in the text.

the substrate surface mechanically in the circumferential direction. This technique has been very effective and widely used in the recording media industry for over 10 years. The circumferential texture not only minimizes head–media interface stiction problems, but also improves the recording performances because the circumferential texture induces anisotropic film magnetic properties (88). Figures 29(a) and 29(b) show two optical images of the circumferentially textured NiP/Al-Mg substrates. Figure 29(a) is of a pure circumferential texture and Fig. 29(b) is an optimized circumferential texture with cross-hatch markings that demonstrated to have greater tribological advantages.

(2) Laser bump texturing was first demonstrated by Ranjan et al. (100) and is now widely used in the magnetic recording media industry. A relatively high-energy laser beam is used to recrystallize the polished surface regions of the NiP layer and so to create bumps. Figures 29(c) and 29(d) contain images of two commonly used laser-created bump patterns. The bumps can be quite precisely controlled in their size, heights, and number density. The accuracy of creating bumps by this technique has allowed zone texturing of substrates—namely only laying bumps in the head landing or take-off zone to serve the tribological purposes and so leaving the data zone without texture. This is demonstrably a good strategy and is now widely used in the disk-making industry.

(3) Sputter texturing was probably one of the best low-cost methods. In this method, before the underlayer and magnetic layer are deposited, a sputter texturing layer is deposited using a film-growth technique that provides a rough film surface morphology. The subsequent underlayer and magnetic layer(s) then replicate the surface morphology of the texture layer and thus serve the required mechanical purpose.

Two types of materials have been used to create sputter textures, one by Mirzamaani and co-workers using lower melting point materials and the other by Gao and co-workers (101–103).

The first method relied on the concept of surface energy mismatch between the sputtered metal layer and the substrate. The relative surface energies play a central role in determining the film growth mode at thermodynamic equilibrium. If the deposited material has a larger surface energy than the substrate, it will tend to form three-dimensional structures, imparting a greater surface roughness that serves as substrate texturing. This is related to the wetting phenomenon that takes place between two materials that have different surface energies.

The second method relied on the concept of film stress and stress release. The substrate was held at high temperature during film deposition and then cooled at a controlled rate after the deposition, thus creating and then releasing the stress. The result of the stress release is to form hillocks or bumps. These bumps could be used as a means of substrate texturing technique. Figures 29(e) and 29(f) illustrate these two types of sputter-created bumps. The bump size, height, and the density of the bumps can be controlled to a certain degree. This type of texturing is simple and of low cost, but is not adaptable to zone texturing. However, a head flying height of 15 nm has been demonstrated without significantly increased stiction.

Sputter texturing has mostly been used with alternative substrates, although the technique has been demonstrated on several different types of substrates. Sputter textured glass substrates have been used in commercial disks.

(4) Intrinsic substrate texturing applies to alternative substrates, such as glass ceramic. The substrate blanks are made with a mixture of amorphous and crystalline phases that provides hard crystallites embedded in the amorphous matrix. If the amorphous phase is more easily removed, polishing leaves the harder crystallites protruding as surface bumps. On the other hand, if the crystallites can be pulled from the amorphous matrix, polishing may leave holes. Both types of surface serve the necessary mechanical purpose and have been used to provide texturing in the

industry. Figures 29(g) and 29(h) illustrate types of intrinsic substrate texture.

THE FUTURE OF MAGNETIC RECORDING MEDIA

The future for magnetic recording media is strong—it is estimated to be possible to develop media with a further order of magnitude increase to 40 or even 100 Gbit/in.^{2} in the areal data recording density, based on development of currently known technologies and ideas. As yet no other data recording technology can compete in the combination of cost, capacity, and speed. However, like anything else, magnetic recording media must face limitations, both fundamental and technological.

Magnetic Recording Media Limitations

It is worth discussing the approaches available for increasing the areal density and trying to understand its limits. The key limiting properties are: (1) media magnetic properties, particularly H_c and $M_r\delta$, (2) media noise, and (3) thermal instability.

In the sections entitled "Fundamentals of Magnetic Recording" and "Recording Performance," we have pointed out that PW_{50} must be small for high-density recording media and that this requires the media to have certain macromagnetic properties—high H_c and small $M_r\delta$. The coercivity of current CoCrTaPt alloys is about 2500 Oe to 3500 Oe and the new generation of media should have an H_c of 3500 Oe to 5000 Oe. For still higher H_c, the new media will require both a high intrinsic anisotropy and a microstructure optimized as discussed previously. As $M_r\delta$ is decreased, the read-back signal decreases and increased head sensitivity becomes important. Therefore, the conventional read head—an inductive or magnetoresistive head—has to be replaced by a more sensitive head, based on giant magnetoresistance (GMR) or colossal magnetoresistance (CMR).

When the recording areal density is increased significantly, the transition length is reduced and zigzag magnetic transitions become dominant because of the demagnetizing field. This will generate substantial media noise and lower the media signal-to-noise ratio (94). Although the use of signal processing techniques can significantly increase the sensitivity and the signal from media, media noise eventually will be an unavoidable limitation for magnetic recording media.

The smaller magnetic grains required for higher areal densities are more susceptible to thermally activated effects that alter the recorded magnetizations. Thermal activation not only causes the so-called superparamagnetic limit (104) but also leads to the transition decay of coercivity (105). The ratio K_uV/k_BT of the magnetic anisotropy energy to the thermal energy must exceed 60 to satisfy the requirement of thermal stability. [K_u, V, k_B, and T are the (intrinsic) magnetic anisotropy, grain volume, Boltzmann constant, and temperature, respectively.] This means that materials with the highest anisotropy are required and that control of the grain-size distribution is critical.

The areal density of longitudinal magnetic recording media has increased at a compound rate of about 60% per year in the last decade. Media are commercially available today with an areal density of 3 Gbit/in.^{2} to 4 Gbit/in.^{2}; 10 Gbit/in.^{2} media are predicted to be available within a few years. Roughly speaking, from 1980 to 1990 more attention was paid to raising the areal density by improving the macromagnetic properties H_c and $M_r\delta$ and since 1990 more attention has been devoted to reducing media noise by improving micromagnetic characteristics such as decoupling of the grains. Now, grain size and distribution control are becoming important aspects of media design. The areal density of recording media must have an upper limit, but Johnson (111) predicts that 100 Gbit/in.^{2} may be possible in future.

The Outlook for Magnetic Recording Media

The current development of magnetic recording media is now highly advanced, but still offers considerable scope for increased data storage per unit area, available at high data transfer rate. The closest competition is likely to come from near-field optical recording, which was recently announced (106,107). Near-field optical recording has been successfully demonstrated and is claimed to offer a capacity that is an order of magnitude higher than that of magnetic recording media. The near-field data rate is potentially high, since it uses a great deal of hard-drive technology. However, even before the demonstration of the first near-field magneto-optical recording drive, several drive makers have already demonstrated 10 Gbit/in.^{2} in magnetic recording media. It is not clear when near-field magneto-optical technology will be ready to compete with magnetic recording technology in three key areas: (1) capacity, (2) cost, and (3) data transfer rate.

For future ultrahigh recording density media, novel magnetic alloy materials probably need to be developed. Film coercivity needs to be increased even while $M_r\delta$ is reduced. A higher media SNR and lower bit error rate is also required. The magnetic media will need to have an improved microstructure, with even smaller grain size and a much narrower grain-size distribution (108). A thinner overcoat or zone carbon overcoat will need to be developed to enable the head flying height to be reduced. Less or no substrate texturing will need to be used and dynamic head load–unload technology will need to be adopted.

Although the superparamagnetic size barrier will eventually limit magnetic recording densities, 100 Gbit/in.^{2} recording has been predicted (111) and, within the magnetic recording community, there is consensus that 40 Gbit/in.^{2} at least is attainable (99). Already, by the turn of the century, a magnetic recording medium drive with an areal density of 10 Gbit/in.^{2} is expected to be commercially available.

BIBLIOGRAPHY

1. P. P. Zapponi, U.S. Patent No. 2,619,454, 1952.
2. R. L. Comstock and E. B. Moore, Ferrite film recording surfaces for disk recording, *IBM J. Res. Develop.,* **18**: 556, 1974.
3. W. T. Maloney, RF-sputtered chromium-cobalt films for high-density longitudinal magnetic recording, *IEEE Trans. Magn.,* **MAG-15**: 1135, 1979.
4. T. Yamada et al., CoNiCr/Cr sputtered thin film disks, *IEEE Trans. Magn.,* **21**: 1429, 1985.
5. M. Ishikawa et al., Film structure and magnetic properties of CoNiCr/Cr sputtered thin film, *IEEE Trans. Magn.,* **22**: 573, 1986.
6. B. Lal, H. Tsai, and A. Eltoukhy, A new series of quaternary co-alloys for rigid-disk applications, *IEEE Trans. Magn.,* **27**: 4739, 1991.

7. Y. Cheng et al., Evaluation of the CoCrTaPt alloy for longitudinal magnetic recording, *J. Appl. Phys.,* **75** (10): 6138, 1994.
8. C. Gao, Seagate Recording Media, 1996, unpublished result.
9. Karlqvist, Calculation of the magnetic field in the ferromagnetic layer of a magnetic drum, *Trans. R. Inst. Technol., Stockholm,* **86**: 3, 1954.
10. M. H. Kryder, J. A. Bain, and M. Xiao, Advanced materials and devices for high density magnetic recording and readback heads, *Proc. 3rd Int. Symp. Phys. Magn. Mater. (ISPMM '95),* Seoul, Korea, 1995, p. 457.
11. K. G. Ashar, *Magnetic Disk Drive Technology,* Piscataway, NJ: IEEE Press, 1997.
12. Y. C. Feng, Ph.D. dissertation, Carnegie Mellon Univ., Pittsburgh, PA, 1995.
13. E. S. Murdock, Roadmap for 10 Gbit/in^2 media: Challenges, *IEEE Trans. Magn.,* **28**: 3078, 1992.
14. S. Y. Zhou et al., Single-domain magnetic pillar array of 35 Nm diameter and 65 Gbits/in^2 density for ultrahigh density quantum magnetic storage, *J. Appl. Phys.,* **76**: 6673, 1994.
15. M. Farboud et al., Fabrication of large area nano-structured magnets by interferometric lithography, *7th Jt. (Magnetism and Magnetic Materials (MMM) Intermagn. Conf.,* San Francisco, 1998, Paper 04.
16. C. A. Grimes, Li Chun, and M. F. Shaw, The magnetic properties of permalloy thin films patterned into rectangular picture frame arrays, *7th Jt. MMM Intermagn. Conf.,* San Francisco, 1998, Paper 06.
17. S. Y. Chou, P. R. Krauss, and L. Kong, Nanolithographically defined magnetic structure and quantum magnetic disk, *J. Appl. Phys.,* **79**: 6101, 1996.
18. L. Kong, L. Zhuang, and S. Y. Chou, Writing and reading 7.5 Gbits/in^2 longitudinal quantized magnetic disk using magnetic force microscope tips, *IEEE Trans. Magn.,* **33**: 3019, 1997.
19. G. Bate et al., *Proc. Int. Conf. Magn.,* Nottingham, England, 1964, p. 816.
20. Y. Suganuma et al., Production process and high density recording characteristics of plated disks, *IEEE Trans. Magn.,* **MAG-18**: 1215, 1982.
21. K. Yoshida, T. Yamashita, and M. Saito, Magnetic properties and media noise of Co-Ni-P plated disks, *J. Appl. Phys.,* **64**: 270, 1988.
22. M. Ishikawa et al., Effects of thin Cr film thickness on CoNiCr/Cr sputtered hard disk, *IEEE Trans. Magn.,* **26**: 1602, 1990.
23. R. D. Fisher, J. C. Allan, and J. L. Pressesky, Magnetic properties and longitudinal recording performance of corrosion-resistant alloy films, *IEEE Trans. Magn.,* **22**: 352, 1986.
24. B. B. Lal and A. Eltoukhy, High-coercivity thin-film recording medium and method, U.S. Patent No. 5,004,652, 1991.
25. M. F. Doerner et al., Composition effects in high density CoPtCr media, *IEEE Trans. Magn.,* **29** (6, pt. 2): 3667–3669, 1990.
26. S. Iwasaki, Y. Nakamura, and K. Ouchi, Perpendicular magnetic recording with a composite anisotropy film, *IEEE Trans. Magn.,* **MAG-15**: 1456, 1979.
27. J. H. Judy, Thin film recording media, *MRS Bull.,* **15** (3): 63, March, 1990.
28. K. Ouchi and S. Iwasaki, Recent subjects and progress in research on Co-Cr perpendicular magnetic recording media, *IEEE Trans. Magn.,* **23**: 2443, 1987.
29. S. L. Zeder et al., Magnetic and structural properties of CoNi thin films prepared by oblique incidence deposition, *J. Appl. Phys.,* **61**: 3804, 1987.
30. J. S. Gau and W. E. Yetter, Structure and properties of oblique-deposited magnetic thin films, *J. Appl. Phys.,* **61**: 3807, 1987.
31. J. A. Thornton, The macrostructure of sputter-deposited coatings, *J. Vac. Sci. Technol. A,* **4**: 3059, 1986.
32. C. Gao, R. Malmhall, and G. Chen, Quantitative characterization of sputter process controlled nano-porous film state, *IEEE Trans. Magn.,* **33**: 3013, 1997.
33. M. R. Kim and S. Guruswamy, Microstructural origin of in-plane magnetic anisotropy in magnetron in-line sputtered CoPtCr thin film disks, *J. Appl. Phys.,* **74**: 4643, 1993.
34. H.-C. Tsai, M. S. Miller, and A. Eltoukhy, The effects of Ni_3P-sublayer on the properties of CoNiCr/Cr media using different substrate, *IEEE Trans. Magn.,* **28**: 3093, 1992.
35. E. Teng et al., Dispersed-oxide seedlayer induced isotropic media, *IEEE Trans. Magn.,* **33**: 2947, 1997.
36. J. L. Vossen and W. Kern (eds.), *Thin Film Processes II,* San Diego: Academic Press, 1991.
37. M. Takahashi, A. Kikuchi, and S. Kawakita, The ultra clean sputtering process and high density magnetic recording media, *IEEE Trans. Magn.,* **33**: 2938, 1997.
38. T. Chen et al., Isotropic vs. oriented thin film media: Choice for future high density magnetic recording, *Intermag'96,* Seattle, WA, 1996, Invited Talk.
39. R. Nishikawa et al., Texture-induced magnetic anisotropy of Co-Pt films, *IEEE Trans. Magn.,* **25**: 3890, 1989.
40. T. Coughlin et al., Effect of Cr underlayer thickness and texture on magnetic characteristics of CoCrTa media, *J. Appl. Phys.,* **67**: 4689, 1990.
41. A. Kawamoto and F. Hikami, Magnetic anisotropy of sputtered media induced by textured substrate, *J. Appl. Phys.,* **69**: 5151, 1991.
42. Y. Hsu, J. M. Sivertsen, and J. H. Judy, Texture formation and magnetic properties of RF sputtered CoCrTa/Cr longitudinal thin films, *IEEE Trans. Magn.,* **26**: 1599, 1990.
43. T. Lin, R. Alani, and D. N. Lambeth, Effects of underlayer and substrate texture on magnetic properties and microstructure of a recording medium, *J. Magn. Magn. Mater.,* **78**: 213, 1989.
44. G. F. Hughes, Magnetization reversal in cobalt-phosphorous films, *J. Appl. Phys.,* **54**: 5306, 1983.
45. J.-G. Zhu and H. N. Bertram, Micromagnetic studies of thin metallic films, *J. Appl. Phys.,* **63**: 3284, 1988.
46. T. Chen and T. Yamashita, Physical origins of limits in the performance of thin-film longitudinal recording media, *IEEE Trans. Magn.,* **24** (6): 2700, 1988.
47. T. Y. Shiroishi et al., Magnetic properties and read/write characteristics of CoCrPtTa/CrTa/ (Cr-Ti, Cr), *J. Appl. Phys.,* **73**: 5569, 1993.
48. L. W. Song et al., Magnetic properties and recording performance of multilayer films of CoCrTa, CoCrPtTa, and CoCrPtTa with CocrPtb, *IEEE Trans. Magn.,* **30**: 4011, 1994.
49. D. J. Rogers, Y. Maeda, and K. Takei, The dependence of compositional separation on film thickness for Co-Cr and Co-Cr-Ta magnetic recording media, *IEEE Trans. Magn.,* **30**: 3972, 1994.
50. J. P. Lazzari, I. Melnick, and D. Randet, *IEEE Trans. Magn.,* **MAG-3**: 205, 1967.
51. B. D. Cullity, *Introduction to Magnetic Materials,* Reading, MA: Addison-Wesley, 1972.
52. D. E. Laughlin and B. Y. Wong, The crystallography and texture of co-based thin film deposited on Cr underlayers, *IEEE Trans. Magn.,* **27**: 4713, 1991.
53. D. E. Laughlin et al., The control of microstructural features of thin films for magnetic recording, *Scr. Metall. Mater.,* **33**: 1525, 1995.
54. E. G. Bauer and B. W. Dodson, Fundamental issues in heteroepitaxy, *J. Mater. Res.,* **5**: 852, 1990.
55. C. Gao et al., Sub-micron scale morphology effects on media noise of CoCrTa thin films on smooth substrates, *J. Appl. Phys.,* **81**: 3958, 1997.

56. T. Yeh, J. M. Sivertsen, and J. H. Judy, Effect of very thin Cr underlayer on the micromagnetic structure of RF sputtered CoCrTa thin films, *IEEE Trans. Magn.,* **26**: 1590, 1990.

57. Q. Chen, J. Zhang, and G. Chen, Thin film media with and without biscrystal cluster structure on glass ceramic substrates, *IEEE Trans. Magn.,* **32**: 3599, 1996.

58. H. Sato et al., Effects of grain size and intergranular coupling on recording characteristics in CoCrTa media, *IEEE Trans. Magn.,* **32**: 3596, 1996.

59. H. Mitsuya et al., Effect of grain size on intergranular magnetostatic coupling in thin film media, *Magnetism and Magnetic Materials (MMM'96),* Atlanta, GA, 1996, QQ-08.

60. H. S. Chang et al., Effects of Cr/Al underlayer on magnetic properties and crystallography in CoCrPtTa/Cr/Al thin films, *IEEE Trans. Magn.,* **32**: 3617, 1996.

61. Y. Nakatani and N. Hayashi, Effect of grain-size dispersion on read/write properties in thin film recording media affected by thermal fluctuation, *7th Jt. Magnetism and Magnetic Materials (MMM) Intermagn. Conf.,* San Francisco, 1998.

62. M. P. Sharrock, Time-dependent magnetic phenomena and particle-size effects in recording media, *IEEE Trans. Magn.,* **26**: 193, 1990.

63. P. I. Mayo et al., *J. Appl. Phys.,* **69**: 4733, 1991.

64. S. S. Malhatra et al., Magnetization reversal behavior in cobalt rare-earth thin films, *IEEE Trans. Magn.,* **81**: 1997.

65. P.-L. Lu and S. H. Charap, Thermal instability at 10 Gbit/in^2 magnetic recording, *IEEE Trans. Magn.,* **30**: 4230, 1994.

66. C. Gao et al., Correlation of switching volume with magnetic properties, microstructure, and media noise in CoCr (Pt)Ta thin films, *J. Appl. Phys.,* **81**: 3928–3930, 1997.

67. R. W. Chantrell, Magnetic viscosity of recording media, *J. Magn. Magn. Mater.,* **95**: 365, 1991.

68. H. B. Braun and H. N. Bertram, Nonuniform switching of single domain particles at finite temperatures, *J. Appl. Phys.,* **75**: 4609, 1994.

69. S. Duan et al., The dependence of the microstructure and magnetic properties of CoNiCr/Cr thin films on the substrate temperature, *IEEE Trans. Magn.,* **26**: 1587, 1990.

70. B. Marchon, N. Heiman, and M. R. Khan, Improvement of hydrogenated carbon overcoat performance, *IEEE Trans. Magn.,* **26**: 168, 1990.

71. B. B. Lal et al., Asymmetric DC-magnetron sputter carbon-nitrogen thin-film overcoat for rigid-disk applications, *IEEE Trans. Magn.,* **32**: 3774, 1996.

72. J. K. Howard, The effect of Cr and W nucleation layers on the magnetic properties of CoPt Films, *J. Appl. Phys.,* **63**: 3263, 1988.

73. L. L. Lee, D. E. Laughlin, and D. N. Lambeth, NiAl underlayer for CoCrTa magnetic thin films, *IEEE Trans. Magn.,* **30**: 3951, 1994.

74. Y. C. Feng, D. E. Laughlin, and D. N. Lambeth, Magnetic properties and crystallography of double-layer CoCrTa films with various interlayers, *IEEE Trans. Magn.,* **30**: 3960, 1994.

75. Y. Okuimura et al., Effects of CrNi Pr-layer on magnetic properties of CoCrTa longitudinal media, *IEEE Trans. Magn.,* **33**: 2974, 1997.

76. H. Mahvant, Oxidation of seed-layer for improved metal film performance, *IEEE Trans. Magn.,* **29**: 3691, 1993.

77. W. Xiong and H.-L. Hoo, Cr-Ta_2O_5 seedlayer for recording media on alternative substrates, *7th Jt. Magnetism and Magnetic Materials (MMM) Intermagn. Conf.,* San Francisco, CA, 1998.

78. L. Fang and D. N. Lambeth, CoCrPt media on hcp intermediate layers, *CMU Data Storage Syst. Cent. Rep.,* 1994.

79. N. Inaba et al., Magnetic and microstructural properties of CoCrPt/CoCrPtSi dual-layered magnetic recording media, *J. Appl. Phys.,* **75**: 6162, 1994.

80. B. Zhang et al., CoCrTa/CoCrPtTa double-layer films for magnetic recording, *IEEE Trans. Magn.,* **32**: 3590, 1996.

81. E. Teng and A. Eltoukhy, Flash chromium interlayer for high performance disks with superior noise and coercivity squareness, *IEEE Trans. Magn.,* **29**: 3679, 1993.

82. S. E. Lambert, J. K. Howard, and I. L. Sanders, Reduction of media noise in thin film metal media by lamination, *IEEE Trans. Magn.,* **26**: 2706, 1990.

83. E. S. Murdock, B. R. Natarajan, and R. G. Walmsley, Noise properties of multilayered co-alloy magnetic recording media, *IEEE Trans. Magn.,* **26**, 2700, 1990.

84. Y. C. Feng, D. E. Laughlin, and D. N. Lambeth, Magnetic properties and crystallography of double-layer CoCrTa thin films with various interlayers, *IEEE Trans. Magn.,* **30**: 3960, 1994.

85. B. Gooch et al., A high resolution flying magnetic disk recording system with zero reproduce spacing loss, *IEEE Trans. Magn.,* **27**: 4549, 1991.

86. T. M. Coughlin, B. R. Gooch, and B. Lairson, Keepered recording media, *Data Storage Mag.,* October 1996.

87. G. Mian and P.-K. Wang, Effects of a highly permeable keeper layer on transition shifts for thin film media, *IEEE Trans. Magn.,* **30**: 3984, 1994.

88. E. Yen, H. J. Richter, and T. Coughlin, Evaluation of keeper layer media, *Intermag'98,* San Francisco, CA, 1998.

89. N. Bertram, *Introduction to Magnetic Recording,* Cambridge, England: Cambridge Univ. Press, 1996.

90. R. M. White, *Introduction to Magnetic Recording,* New York: IEEE Press, 1985.

91. T. Yogi et al., Role of atomic mobility in the transition noise of longitudinal media, *IEEE Trans. Magn.,* **26**: 1578, 1990.

92. J. E. Wittig et al., Cr segregation in CoCrTa/Cr thin films for longitudinal recording media, *7th Jt. Magnetism and Magnetic Materials (MMM) Intermagn. Conf.,* San Francisco, CA, 1998, Paper CC-03.

93. C. Gao et al., Correlation of bulk saturation magnetization with magnetic properties and media signal-to-noise ratio of CoCrPtTa films, *J. MMM,* Sept. 1998 (in press).

94. A. Taratorin, *Characterization of Magnetic Recording Systems,* San Jose, CA: Guzik Technical Enterprises, 1996.

95. C. R. Paik et al., Magnetic properties and noise characteristics of high coercivity CoCrPtB/C media, *IEEE Trans. Magn.,* **28**: 3084, 1992.

96. P. I. Bonyhard and J. K. Lee, Magnetoresistive read magnetic recording head off-track performance assessment, *IEEE Trans. Magn.,* **26**: 2448, 1990.

97. C. Gao et al., Composition and underlayer effects on media noise and off-track capability in CoCrPtTa films, *IEEE Trans. Magn.,* **32**: 3569, 1996.

98. B. Bushan, *Tribology and Mechanics of Magnetic Storage Devices,* 2nd ed., New York: Springer-Verlag, 1996.

99. M. F. Doerner and R. L. White, Materials issues in magnetic-disk performance, *MRS Bullet.,* **21** (9): 28–34, 1996.

100. R. Ranjan et al., Laser texturing for low-flying-height media, *J. Appl. Phys.,* **69**: 5745, 1991.

101. M. Mizamaani, C. V. Jahnes, and M. A. Russak, Thin film disks with transient metal underlayers, *IEEE Trans. Magn.,* **28**: 3090, 1992.

102. C. Gao and D. Massey, *Thermally cycled metal layer deposition for substrate texturing,* U.S. Patent pending [a]9450174, 1995.

103. C. Gao et al., Hillocks formation, a new approach for sputter texturing disk substrates, *IEEE Trans. Magn.,* **25**: 3965, 1996.

104. M. Kryder, Ultrahigh-density recording technologies, *MRS Bull.,* p. 17, September, 1996.

105. K. Johnson, Thin-film recording media: Challenges for physics and magnetism in the 1990s, *J. Appl. Phys.,* **69**: 4932, 1991.

106. G. Knight, Terastor Inc., Near-field recording, *Diskon'97, Tech. Symp.* 1997.

107. Near-field recording, technology update, *Data Storage Magazine,* 1997, p. 8.

108. E. G. Bauer, Fundamental issues in heteroepitaxy, *J. Mater. Res.,* **5**: 852, 1990.

109. M. P. Sharrock, Time dependence of switching fields in magnetic recording media, *J. Appl. Phys.* **76**: 6413, 1994.

110. R. W. Chantrell et al., Models of slow relaxation in particulate and thin film materials, *J. Appl. Phys.* **76**: 6407, 1994.

111. K. E. Johnson, Will media magnetics pace areal density?, in *Proc. DISCON USA '97, Int. Tech. Conf.,* Sept. 23–25, 1997, San Jose, CA.

112. M. L. Williams and R. L. Comstock, An analytical model of the write process in digital recording, *AIP Conf.,* Vol. 5, 1971, p. 738.

CHUAN GAO
Seagate Magnetic Recording

BRIAN W. ROBERTSON
University of Nebraska

Z. S. SHAN
HMT Technology