State-of-the-Art Magnetic Hard Disk Drives

I.R. McFadyen, E.E. Fullerton, and M.J. Carey

Abstract

Magnetic recording has progressed dramatically over the last 50 years, with an increase of almost eight orders of magnitude in the amount of information stored per unit area of disk space. Two key enablers of this progress have been the recording medium and the read-back head. This article reviews the current state of the art in multilayer thin-film longitudinal recording media and giant magnetoresistive (GMR) read heads, with particular emphasis on the nanostructured magnetic materials that are key to today's high-performance hard disk drives.

Keywords: *film, layered, magnetic properties, magnetoresistance, memory.*

Introduction

IBM introduced the 305 RAMAC computer in 1956. The system included the IBM 350 magnetic disk drive, which had a storage capacity of 4.4 Mbytes, was the size of two large refrigerators, and weighed two tons. Today, laptop computers commonly have disk drives that can store 20–100 Gbytes and are the size of a pack of cards. This represents an increase in the areal density (number of bits per square inch of disk surface) of almost eight orders of magnitude: from 0.002 Mbits/in.^{2} in 1956 to 100 Gbits/in.^{2} in today's state-of-the-art drives. Throughout this half-century of disk drive development, the basic recording principle—longitudinal magnetic recording (LMR)—has remained the same. However, today's high-capacity drives are nearly the ultimate realization of this recording scheme, and future drives will most likely use a scheme known as perpendicular magnetic recording (PMR), where the magnetization in the bits is perpendicular to the disk surface. As the recording industry transitions from LMR to PMR, it is worth reviewing two of the technologies that have allowed this remarkable increase in storage capacity, the thin-film disk and the giant magnetoresistive (GMR) read-back head.

Magnetic Recording

Figure 1 illustrates the basic concepts of longitudinal magnetic recording: writing, storage, and reading. The system contains a recording head, composed of separate read and write heads, which is supported by a self-generating air bearing in close proximity to the granular magnetic medium. The head is said to "fly" over the disk. The inductive write head is a miniature electromagnet: a time-varying current in a conductor wrapped around a ferromagnetic yoke provides a time-varying magnetic field in the gap of this yoke. This field, in turn, magnetizes regions of the disk as they pass under the gap. The data are stored as horizontal magnetization patterns, where the ones and zeros correspond to the presence or absence of magnetization reversals. It is from the in-plane, along-track orientation of magnetization on the disk that the term LMR is derived. The data is read back by measuring the stray fields (described in the section on GMR Heads) originating from the transitions between regions of opposite magnetization (not the magnetization directly). This analog signal is then processed to recover the digital information. While the basic physical processes for writing and storing information in LMR have not changed in any fundamental way, the read-back process and the materials that make up the components have changed radically.

As areal densities have increased, the dimensions of various components of the recording system have, necessarily, decreased. The amount by which they decrease can be estimated from basic scaling laws for magnetic recording, which are the same as the scaling of any three-dimensional magnetic system: the field configuration and magnitudes are not changed when all dimensions and currents are scaled by a factor s. Therefore, if you want to increase the areal density by s^2, all dimensions in the system should, to first order, be decreased by s. This assumes that the magnetic properties of the materials are not changed and also implies that the current density increases by $1/s$.

Comparing the IBM 350 with current disk drives, the areal density has increased by $s^2 = 5 \times 10^7$, implying that the critical dimensions have scaled by $s \sim 7000$. For the IBM 350, the thickness of the media t and the height at which the head flew over the disk were ~30 µm and ~20 µm, respectively. Assuming simple scaling, one

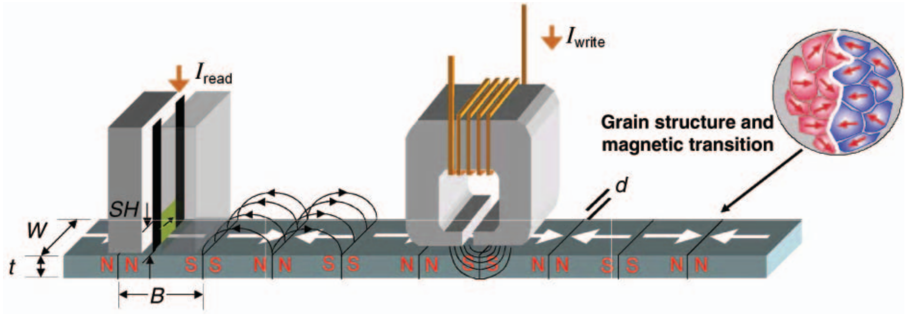

Figure 1. Schematic drawing of a longitudinal magnetic recording system, consisting of the recording medium and a recording head with separate read and write elements. The recording medium has a granular microstructure where the magnetic transition meanders between the 8-nm grains, as shown in the schematic at upper right. W *is the track width,* t *is the thickness of the medium,* SH *is the stripe height, and* B *is the bit length. Typical values are* W = *210 nm,* t = *14 nm,* SH = *100 nm, and* B = *30 nm. The head flies above the disk surface at a spacing of* d = *10 nm. Bits are written using an inductive head and are read back with a shielded magnetoresistive element.*

would expect the corresponding values in today's drives to be 4.3 nm and 2.9 nm, respectively. These values are surprisingly close to the current 14–20-nm media thicknesses and 10-nm fly height, and highlight two important factors of the current disk drives. First, many of the critical dimensions in modern disk drives are now on the nanometer scale. While the original disk drives used the bulk properties of materials, the physics of state-of-the-art drives is increasingly dominated by thin-film and interface effects and can be viewed as commercial implementation of nanotechnology. Second, the values of certain dimensions (e.g., media thickness and fly height), while small, are not scaling as fast as one expects. In fact, the thickness of the media has essentially not changed for the last five years, because thermal activation of nanoscale magnetic particles, known as superparamagnetism, precludes continued scaling, as will be discussed in the next section. This phenomenon is the main impetus for the transition to PMR, as outlined in the article by Richter and Harkness in this issue.

The evolution of the basic technologies for the write element, the read element, and the storage medium follows a common pathway. The early drives were bulk-processed: the magnetic medium was spin-coated onto disks and the coils of the heads were individually hand-wound. As dimensions decreased, there was a transition to thin-film deposition in the 1970s that evolved into the complex thin-film heterostructures in the 1990s that persist today. For example, the first write heads were laminated NiFe cores hand-wound with enamel-coated wires, while modern heads are electroplated CoFeNi yokes and Cu conductors fabricated with wafer-level processing. The technologies for storing information—the disk—and for reading the information—the read-back head—have changed even more dramatically.

Longitudinal Media

In LMR media, the signal-to-noise ratio (SNR) needed for high-density recording is determined by statistically averaging the contributions from a large number of weakly interacting magnetic grains per bit. The granular system limits the magnetic correlations and allows information to be written on a finer scale than is possible in a homogeneous magnetic film. As illustrated in Figure 1, the transitions generally follow the grain boundaries, and thus the storage density of the data is ultimately limited by the grain size. Scaling of magnetic media involves reducing the grain diameter in an attempt to keep the number of grains per bit constant, and reducing the media's magnetic thickness $M_r t$ (where M_r is the remanent magnetization and t is the thickness) to keep self-demagnetizing fields manageable. The original disk recording medium consisted of iron oxide particles in an organic binder that was spun onto the disk. This technology was in use until the 1980s, when the inability to scale particle size, and particle size distributions, was in part responsible for the introduction of sputtered thin-film CoCr alloy media. For these granular CoCr films, the Cr diffuses toward the grain boundaries during growth, resulting in a magnetic core of the grain with nonmagnetic or weakly magnetic grain boundaries. These films have evolved to the current media using CoPtCrB alloys. Alloy developments, along with considerable improvements in underlayers, allowed the grain size and media thickness to scale appropriately to grain diameters D on the order of 8 nm.

However, as was pointed out in 1997 by Charap et al.,[1] scaling of the media is limited by thermal instabilities when the grain volume V decreases to the point where the magnetic energy per particle $K_U V$ (where K_U is the magnetic anisotropy energy density) becomes comparable with thermal energies. The minimum energy needed to maintain stability for >10 years is $K_U V > 55\, k_B T$, where k_B is the Boltzmann constant and T is absolute temperature. Reductions in V can be countered by increasing K_U. However, K_U increases are limited by available write fields needed to overcome the media's coercive field, $\sim K_U/M_S$, where M_S is the saturation magnetization of the media. The combination of SNR requirements, write-field limitations, and thermal activation of small particles is commonly referred to as the superparamagnetic limit.[1,2]

Considerable effort has focused on layered heterostructures that can extend the limits of LMR media.[3–7] One such example is antiferromagnetically coupled (AFC) media.[3,4] A schematic of the AFC recording media structure in its simplest form is shown in Figure 2. The recording medium is made up of two ferromagnetic layers (upper and lower layers with $M_r t$ values of $M_r t_U$ and $M_r t_L$, respectively) separated by a ruthenium layer whose thickness is tuned to couple the layers antiferromagnetically via an indirect exchange mediated by the nonmagnetic ruthenium, a so-called "RKKY interaction."[8] For such a structure, the effective $M_r t$ of the composite structure is given by the difference between the $M_r t$ values of the two layers, $M_r t = M_r t_U - M_r t_L$. The effective energy barrier $K_U V_{\mathrm{eff}}$ for the composite is determined primarily by the upper layer, allowing the magnetic thickness to be scaled while maintaining thermal stability.[9]

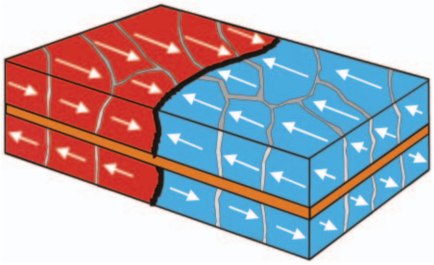

Figure 2. Schematic representation of an antiferromagnetically coupled medium. The medium has upper and lower media layers that are separated by a thin Ru layer whose thickness is tuned to couple the layers antiferromagnetically.

Although AFC media were introduced into products in 2001, a detailed understanding of them has only recently emerged. In current designs, the thicker upper layer is a magnetically hard, low-noise recording medium. In contrast, the thinner lower layer has a low coercivity and relatively high intergranular ferromagnetic exchange and would be superparamagnetic on its own.[10] During the write process, the recording head defines transitions in the upper layer first while the head field saturates the lower layer. The transition in the lower layer is only formed after the write head has passed, when the lower layer relaxes into its equilibrium configuration. The time scale for this process, which can be orders of magnitude longer than the nanosecond write times, and the resulting magnetic patterns of the lower layer depend on the strength of the coupling to the upper layer and the material parameters of the lower layer (e.g., K_U, $K_U V$, thickness, intergranular exchange, etc.). For certain lower-layer compositions and thicknesses, the average magnetization of the lower layer can orient orthogonal to the upper layer for high bit densities.[11]

Given the different process involved in forming the transitions in the two layers, understanding the resulting read-back signal and noise is nontrivial. In an AFC medium, the response can be viewed as a superposition of the signals from the upper and lower layers, S_U and S_L, respectively. In most cases, the lower-layer signal is opposite to the upper-layer signal such that the composite signal S is given by

$$S = S_U - S_L. \quad (1)$$

That is, the lower-layer signal subtracts from the upper layer signal. Similarly, there is noise originating from the upper and lower layers, given by N_U and N_L, respectively. The composite noise power N^2 may be expressed as

$$N^2 = N_U^2 + N_U^2 + 2cN_UN_L, \tag{2}$$

where c describes the degree of cross-correlation between the magnetization in the layers.[12] In the simplest case, where the two layers are antiparallel grain by grain such that $c = -1$, then the noise $N = N_U - N_L$; the noise of the lower layer similarly subtracts from the upper layer, giving a composite SNR that is independent of the lower-layer thickness. If the noise of the two layers is uncorrelated ($c = 0$), then the signals would subtract while the noise would add, yielding poor SNR.

The implications of Equations 1 and 2 can at times be counterintuitive. If the lower layer could be designed to have no noise ($N_L = 0$), then the SNR of the composite would be *worse* than the upper layer on its own, since you subtract signal without subtracting noise. Conversely, the SNR of the composite structure can, in principle, be improved by having poor SNR media in the lower layer. That is, you can possibly subtract more noise than signal, yielding an improved SNR for the composite. This is the basic principle of acoustic noise-canceling headphones and partly explains the excellent performance of AFC media where the lower layer is expected to be quite noisy on its own.[12] More generally, these ideas point toward general directions where multiple coupled layers are used to design media that go beyond simple statistical averaging of grains. An example of this approach is described in References 5 and 6 for laminated AFC media that combine both antiferromagnetic and uncoupled layers.

GMR Heads

Read-back head technology[13] has also changed markedly since the original disk drive, in which the same head was used for both inductive writing (time-varying current producing a time-varying field) and inductive reading (changing flux in the yoke due to the motion of the medium past the head, resulting in an induced current in the conductor wound around the yoke). As areal density increased, the signal from the recorded transitions decreased, and a more sensitive detection scheme was required. In the early 1990s, the magnetoresistive, or MR, head was introduced. This head is based on anisotropic magnetoresistance in a single Permalloy ($Ni_{80}Fe_{20}$) layer, which provides a change in resistance of about 2% as the magnetization in the layer rotates from parallel to perpendicular to the direction of current flow. By 1997, this technology was replaced by the spin valve, or giant magnetoresistive (GMR), head. The term "spin valve" refers to a structure where the relative orientation of the spins, or magnetization, in two adjacent layers controls the flow of current through the device. The name GMR refers to the effect in general, since the magnetoresistance was considered "giant" by comparison with MR sensors. Early GMR heads achieved 4% MR, but this value has steadily climbed to 15% today. The GMR head is a complicated stack of ferromagnetic, antiferromagnetic, and nonmagnetic metals, the details of which we will now discuss.

If one were able to look up at the read head from the media, the view would look like Figure 3. The GMR sensor is sandwiched between micrometer-thick magnetic shield layers. These shields provide down-track spatial resolution by absorbing the magnetic flux from nearby media transitions. The shield-to-shield spacing is currently about 50 nm. This puts a significant constraint on the materials that can be used in the GMR sensor, as will be discussed later in this section. The sensor itself is lithographically patterned to a width of approximately half the track width, W, which is about 100 nm today. As the track width scales to smaller dimensions, this is pushing magnetic recording past semiconductor processing in terms of the smallest feature size. The third dimension of the sensor, the stripe height, is discussed at the end of this section.

The basis of the GMR effect is contained in only three layers: a magnetic reference layer, typically a cobalt alloy; a nonmagnetic spacer layer, typically copper; and a second magnetic free layer, typically also a cobalt alloy. Current flowing in the magnetic layers becomes spin-polarized, and the probability of electrons scattering as they move between the magnetic layers depends on the relative orientation of the magnetization of these layers. The resistance is a minimum, R_0, when the free layer and reference layer moments are parallel. Spin-dependent scattering increases as the layers deviate from parallel.

In general, if θ is the angle between the free and reference layer moments, the resistance follows the form

$$R = R_0 + \Delta R \frac{1}{2}[1 - \cos(\theta)], \tag{3}$$

where ΔR is the maximum additional resistance due to GMR. The maximum resistance, $R_0 + \Delta R$, is obtained when the moments are antiparallel ($\theta = 180°$). Obviously, increasing the value of ΔR is a primary concern in the development of spin valves.

In a spin-valve read head, the magnetic moment of the reference layer points perpendicular to the medium surface. Without any field from the medium, the free layer moment points perpendicular to this direction ($\theta = 90°$). As the head passes over a magnetic transition in the medium, the direction of the free layer moment rotates, causing a change in resistance. The moment of the free layer is chosen such that θ makes only $\sim 10°$ deviations from $90°$ in response to the transition field. The output signal is, then, fairly linear with

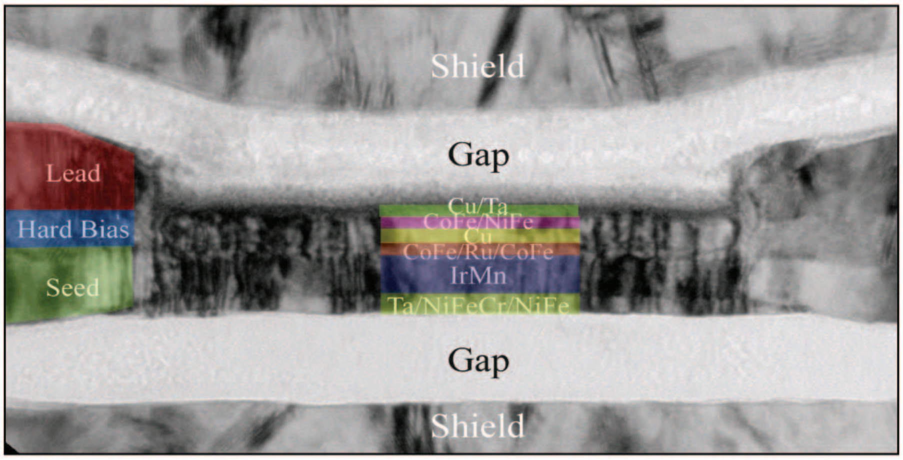

Figure 3. Transmission electron micrograph of a giant magnetoresistive spin-valve read head, viewed as if looking up at the head from the media. The 120-nm-wide sensor is a multilayer stack. In addition to providing the sense current, the leads contain a magnetically hard bias layer that applies a small magnetic field to the sensor. The magnetic shields ensure that the sensor detects only the field from a single transition at a time. (Image courtesy of P. Shang and W. Legg.)

field. This also ensures that the moment rotates without any discontinuous jumps, which would result in noise. This small angle limits the read head to use only about 20% of the total available MR. So, while a spin-valve film may have 15% GMR, the head uses only 3%.

The actual spin-valve read sensor is much more complex than this simplified three-layer structure. A useful way to explore the technology is to follow the construction of the device layer by layer.

The bottom shield is >1 μm thick and is deposited on the substrate by electroplating. Since the spin valve is composed of layers on the order of 1 nm thick, it is best to smooth the shield by chemical–mechanical polishing (CMP) before sensor deposition. A thin (~10 nm) alumina layer is deposited that electrically insulates the sensor from the conductive shield.

A typical underlayer structure is Ta(3 nm)/NiFeCr(3 nm)/NiFe(0.8 nm). The Ta provides good adhesion and promotes a ⟨111⟩ texture, which is beneficial for the magnetic properties of the free layer. The NiFeCr/NiFe layers are possibly the least appreciated recent advances in GMR technology. When the NiFe is deposited, the NiFeCr recrystallizes, increasing the grain diameter from about 5 nm to as much as 22 nm.[14] This decreases grain-boundary scattering, which can cause the electrons to lose spin information before undergoing the spin-dependent GMR scattering, and increases the output of current-generation spin valves by 20–30%.

The next layer is an antiferromagnet (in Figure 3, this is IrMn) which, having no net moment, does not respond to external magnetic fields. When a ferromagnetic layer is grown in contact with the antiferromagnetic (AF) layer, the AF layer "pins" the ferromagnetic layer's magnetic moment through a mechanism called exchange anisotropy.[15] This prevents the moment of the ferromagnetic layer rotating in moderate magnetic fields, making it useful as a reference layer. The key parameters of the AF materials are

- The interfacial exchange energy, σ, which determines how much field can be applied before the ferromagnetic layer's moment reverses, often called the exchange field, or $H_{ex} = \sigma/M_r t$. The value of σ depends not only on the AF material used, but also on the microstructure.
- The blocking temperature, T_b, at which σ decreases to zero, important for a device that operates at over 100°C.
- The critical thickness, T_{crit}, below which σ and T_b decrease due to thermal activation of the AF grains (analogous to the superparamagnetism discussed in the section on Longitudinal Media).

Table I shows typical values for these parameters for AF materials that have been or are being used in GMR heads.

The invention of the spin-valve head created an intense research effort into exchange anisotropy materials. The standard materials in use today—PtMn for its high σ and T_b, and, more recently, IrMn for its small T_{crit}—were still in early development when the first GMR heads were shipped in 1997. NiO, the antiferromagnet in the first spin valve, has relatively low σ and T_b. The invention that made the NiO antiferromagnet viable is contained in the "synthetic antiferromagnet" used in the next three layers in the spin valve: the pinned layer/AFC spacer layer/reference layer.[16] These layers are most commonly CoFe/Ru/CoFe. The CoFe layers are strongly coupled through the spacer layer via an RKKY interaction, leading to a reduced net moment similar to that described for AFC media. Since H_{ex} is inversely proportional to the net moment, making the net moment close to zero can make the reference layer stable against field perturbations. The second advantage comes in biasing the spin valve. As noted after Equation 3, the free and reference layer moments are perpendicular to each other. When the sensor is patterned, the free and pinned layers couple magnetostatically, which favors an antiparallel configuration of their moments. The strength of this antiparallel coupling is again proportional to the net moment. By keeping this value close to zero, it is much easier to keep the free layer moment perpendicular to the reference layer.

If the free layer contacts the reference layer, the magnetic coupling will restrict its ability to respond to a magnetic field. A nonmagnetic layer is required to physically separate these magnetic layers. The Cu spacer layer not only separates the magnetic layers, but, since its band structure closely matches that of CoFe, it also allows electrons to pass with little spin-independent scattering, a key feature for GMR transport.

The free layer is made up of two magnetic layers: CoFe and NiFe. The CoFe layer is ~1 nm thick and is in contact with the Cu spacer. CoFe gives high GMR, but doesn't have optimal magnetic properties. The combination of CoFe/NiFe is magnetically softer (responds more readily to low fields) than CoFe alone. Also, by adjusting the composition of the NiFe, one can minimize the effects of strain (magnetostriction) on the free layer. A further advantage comes from the fact that Cu and CoFe do not alloy, making for sharp interfaces, which also improves the GMR.

The spin valve is capped with a Cu/Ta bilayer structure. Electrons can pass through the free layer and into the Cu layer with minimal scattering and loss of spin. This increases GMR by lowering R_0 without changing ΔR. The free layer effectively "filters" the electrons, creating a polarized electron current that flows through the nonmagnetic Cu layer.[17] The Ta layer protects the spin valve from oxidation during the processing.

The spin valve, from the seed layers to the cap, is created in one deposition without breaking vacuum and must be patterned afterwards. Due to the small dimensions of the sensor, fine-line lithography techniques are already in use, and electron-beam lithography will likely be required in the future. Conductive leads are deposited on the patterned spin valve to provide the sense current. The "hard bias" portion of the leads (see Figure 3) are typically a magnetically hard CoPtCr alloy, and they are aligned with the free layer to provide a small magnetic bias field to stabilize the free layer, reducing noise.

To complete the read head, a top alumina gap and magnetic shield layer are added. The write head is then fabricated on top of this read head (this is a great oversimplification of the process involved). A single wafer contains approximately

Table I: Typical Physical Parameters for Antiferromagnetic Materials Used in Giant Magnetoresistive Read Heads.

Material	σ (erg/cm^2)	$H_{ex} = \sigma/M_r t$ (Oe*)	T_b (°C)	T_{crit} (Å)
NiO	0.06	150	225	400
PtMn	0.4	1000	325	225
IrMn	0.4	1000	275	80

Notes: σ = interfacial exchange energy; H_{ex} = exchange field; $M_r t$ = magnetic thickness of the pinned layer, where M_r is the remanent magnetization and t is the thickness; T_b = blocking temperature; T_{crit} = critical thickness.

*The strength of the magnetic field (in Oersted) that has to be applied to a film of 0.4 milli-emu cm to overcome the pinning from the antiferromagnet.

20,000 heads. The final step in the read-head fabrication is another very important yet underappreciated step. The heads are mechanically lapped to expose the read sensor and determine the stripe height (*SH* in Figure 1), which is ~100 nm. The stripe height, together with the track width, defines the shape of the GMR sensor. This shape is critical to the resistance of the sensor, the quiescent magnetic state produced by the magnetic bias, and the sensitivity of the sensor to the magnetic fields from the medium. In a technology dominated by thin-film deposition and precision lithography, lapping remains a key step in fabricating the final nanostructured device.

Of course, the read head and medium are just two parts of a highly complex system that makes up a hard disk drive. They are, however, two parts that show the incredible materials advances that have been made to improve the recording density by almost eight orders of magnitude in 50 years. They also highlight why so much of this advance has been made in just the last 10 years, as many of the important discoveries of thin-film magnetism have made their way into the marketplace.

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