MAGNETIC RECORDING HEADS

A crucial component of any magnetic storage system is the magnetic recording head. It writes, reads, and erases the information on the magnetic medium. Magnetic recording heads are used for both digital applications, as in computer hard disk drives, and for analog applications, as in audio or video recorders. Many of the recent advances in data storage are a direct result of improvements in materials and fabrication technology of recording heads. These advances have, in turn, spawned many of the remarkable new developments in software, entertainment, and communication applications available today. For a comprehensive review of recording and recording heads see Refs. 1–7.

BASIC OPERATION

Geometry of Storage Drives

The most common classes of magnetic recording systems currently available are tape and disk drives (Fig. 1). Recording heads used for tape applications are designed for either linear or helical formats. Linear tape heads have a rounded surface over which the tape is guided. The tape medium, generally a thin polyester ribbon on which a thin magnetic film is deposited, is in contact with the head and either the head or tape is moved back and forth to access different tracks. This configuration permits mechanisms utilizing parallel operation of multiple read, write, and erase heads either along or across the track. Tape heads vary from low performance audio heads, used in cassette recording, to high performance digital heads, used for information storage.

Helical scan drives are used in applications where high frequency signals are recorded, such as video cassettes. Multiple inductive heads are mounted on a rotating drum, and the head sweeps across the tape at a high velocity. The tape moves at a speed such that for each rotation of the drum, the tape has moved incrementally to the next data track. There are at least two heads on the drum with the write gaps at an angle relative to each other. Each successive track that is written partially overwrites the preceding track, and because adjacent tracks are written at different angles there is little interference between tracks. This is called azimuthal recording, used in high data rate applications. Typical track widths for video heads are 125 μm to 250 μm and head velocities relative to the medium are 25 m/s.

In rigid disk drives the recording medium is composed of ferromagnetic material deposited on a thin metal or glass disk. The recording head is mounted on a slider that effectively "flies" above the surface of the disk on an air bearing. The slider moves radially over the disk, to access data and servo tracks configured in concentric circles on the disk. Unlike tape heads, there is no intentional contact between the head and the medium. The slider has an air bearing surface (ABS) that rests against the disk when it is stationary (Fig. 2). As the disk comes up to speed, air is forced between the ABS and the medium, raising the slider above the disk surface. The flying distance between the head and the medium has decreased as storage densities have increased, since the recording system's areal density capability is determined in large part by this distance. At areal densities in disk drives today, 0.5 Gbit/in.^{2} to 2 Gbit/in.^{2}, the distance is in the range of 10 nm to 50 nm and is determined by the disk rotational rate (typically 5400 to 10,000 rpm) and the geometry of the rails on the slider.

Floppy disk recording heads share features of both disk and tape drives. The ferromagnetic recording medium is deposited on a flexible plastic disk. As in rigid disk drives, the head moves across a rotating disk to access the tracks. However, the head makes contact with the flexible medium (no air bearing), similar to a tape drive. The relatively low storage density of the standardized floppy format, coupled with the low cost of production of ferrite recording heads, has discouraged floppy drive manufacturers from advancing to thin film inductive technology.

Figure 2 shows the configuration of a disk drive. The recording element is located at the rear of the slider. A stainless

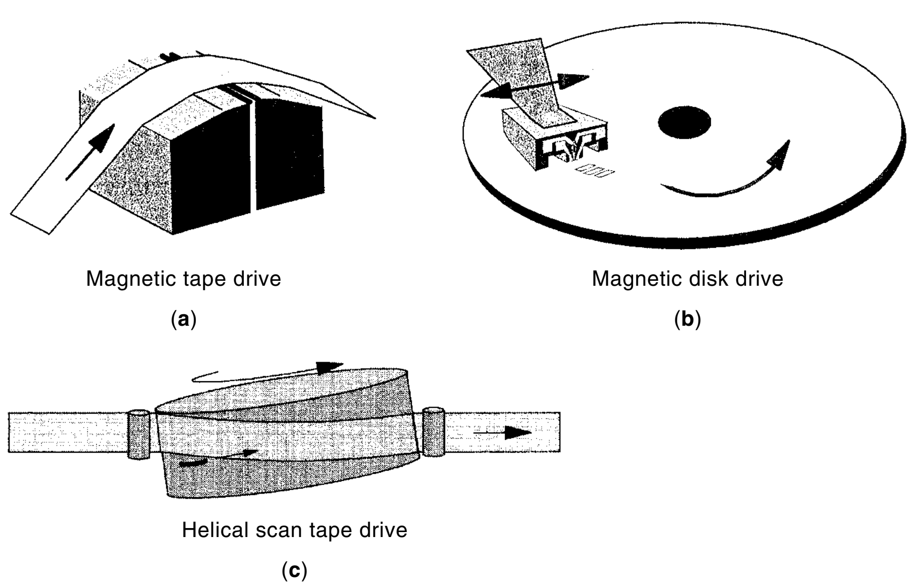


Figure 1. Schematic of magnetic tape and disk drives: Arrows indicate direction of movement. (a) The tape head in a linear drive is stationary as the ribbon medium moves across it, in contact with the head. (b) The tape head in a helical scan drive is mounted on a rotating drum which sweeps the head across the moving tape. (c) The disk recording head moves in a radial direction, flying above the surface of a rotating disk.

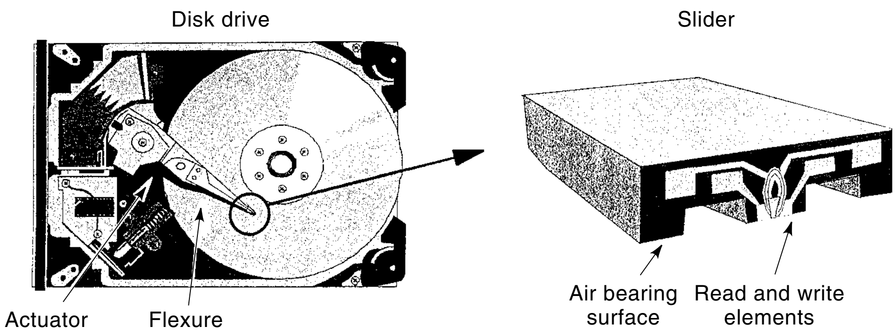


Figure 2. Schematic of a slider in a disk drive: Read and write elements are deposited on the slider, which has a machined air bearing surface. The slider is mounted on a flexure and the head is positioned over the medium by the actuator.

steel flexure connects the head to an actuator that moves the head to access the recorded tracks on the medium. A gimbal is used between the head and the flexure to allow a small amount of motion of the head (pitch and yaw) so as to follow the surface of the medium. Typical recorded trackwidths are 2 μm to 5 μm and the head velocity relative to the medium is 10 m/s to 25 m/s.

Writing Function

The basic mechanism of "writing" on magnetic media has remained unchanged since first developed in 1898 by Valdemar Poulsen (8). His invention, the telegraphone, recorded audio signals by switching the magnetization in a steel wire by using the magnetic field generated by a simple electromagnet. Contemporary write heads use the same principle. The head consists of wire coils wrapped around a ring-shaped magnetic core with a gap (Fig. 3). When the core is magnetized by passing a current through the windings (Ampere's Law), a magnetic fringing field extends beyond the gap. This fringing field is used to switch the magnetization of a small region on the ferromagnetic medium. In digital recording, data are written (or encoded) as regions of alternating magnetization in the ferromagnetic medium. In analog recording, the information is written using both the direction and the magnitude of the magnetization in the medium.

The geometry of the ring and the gap region determines the size of the ferromagnetic region switched in the medium, and hence determines how closely the switched regions can be placed together (the areal density). The coercivity of the medium itself will also determine how closely the regions can be placed, the higher the coercivity, the closer the possible spacing. Improvements in storage density have resulted from reducing the pole tip size (producing smaller bits), and generating larger fields (allowing higher coercivity media).

Reading Function

"Reading" information stored in the medium is achieved by sensing the transitions of the magnetic domains in the medium. These transitions produce fringing fields that extend above the surface of the medium. Reading is accomplished by using one of two principles: magnetic induction or magnetoresistance.

Inductive technology was the first to be developed. Inductive heads sense the time rate of change of the flux from the media, often using the same head that is used for writing [Fig. 4(a)].

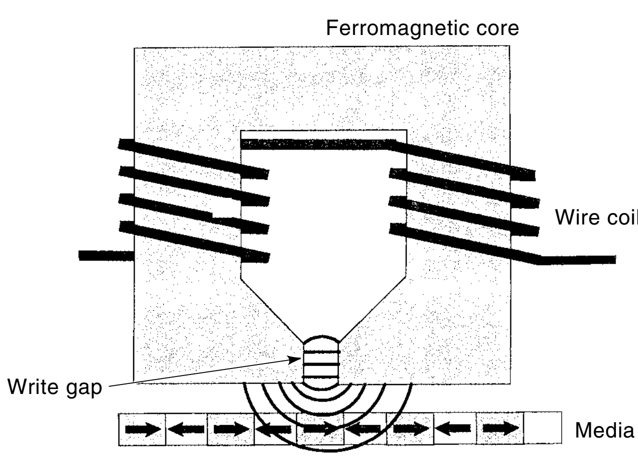


Figure 3. Write process: Current flowing in coils surrounding a soft ferromagnetic core induces a field within the core. Fringing fields emanating from the gap in the core magnetize the ferromagnetic medium, "writing" information on the disk.

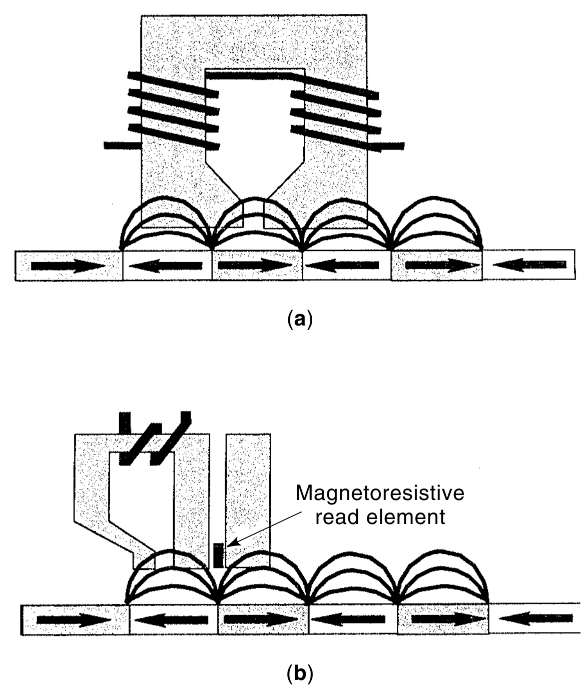


Figure 4. Read process. (a) Inductive heads sense the time rate of change of the magnetic flux emanating from the medium. Head components are as in Figure 3. (b) Magnetoresistive heads use a sensor to detect the field directly. A separate gap is needed for an inductive write head.

When the gap of the ring head is moved across the fringe fields emanating from the medium, a voltage is induced in the coils. This voltage is proportional to the time rate of change of the magnetic flux that circulates past the coils (Faraday's Law). The variation in the voltage is decoded to obtain the original information, either the data itself, or the servo information, which gives the position of the head relative to the data track.

Since the signal from inductive heads is proportional to the time rate of change of the magnetic flux, a relatively large flux moving at a high velocity with respect to the head is required. Industry trends toward smaller drives, along with the relentless quest for higher areal density, have rendered the output from inductive heads insufficient. Smaller disks translate to lower disk velocity ($v = \omega \times r$, where r is the radius), and higher density results in smaller fringing flux from magnetic transitions in the medium.

In response to this challenge, head designers and manufacturers have incorporated magnetoresistive (MR) read elements into recording heads [Fig. 4(b)]. The signal output of an MR head is directly proportional to the flux from the medium's fringing fields, and is velocity independent. Consequently, increased sensitivity is obtained by the choice of materials in the MR element and not by the increased velocity of the medium. The trend toward smaller, high density media has spurred development of new magnetoresistive materials, and MR heads with much higher outputs than inductive heads have been developed and marketed.

TYPES OF RECORDING HEADS

Inductive Heads

Inductive heads are found in all types of magnetic storage systems. The head geometry is different in each application, depending on choices of either tape or disk media, high or low storage density, and analog or digital recording. However, there are two main categories based on the method of fabrication: either the heads are machined from bulk ferrite material and are called *ferrite* heads, or they are made from thin film processes and are called *thin film inductive* (TFI) heads.

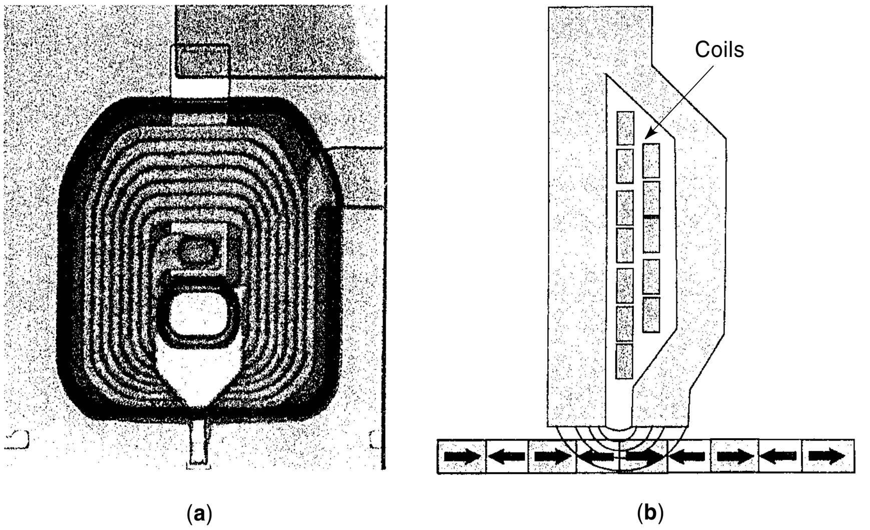
Ferrite heads historically came first, followed by thin film technology. Ferrite heads are machined directly from bulk ferrite and the wires are wound manually. Their primary advantage is that the heads can be made very inexpensively. However, it is difficult to machine narrow trackwidths. In addition, the large volume of the core material results in high inductance. This limits the storage density and data rates achievable by the heads.

A major step forward in recording-head technology was the development of thin film processing techniques for making both the core and the windings. Thin film inductive heads were first introduced in 1979 in IBM's 3370 disk drive (9). These heads consist of a ferromagnetic bottom pole, a coil and a ferromagnetic top pole, all defined with photolithography (Fig. 5). Thin film processing results in a number of improvements. The trackwidth, defined by the width of the pole tips, is now controlled by lithography rather than by a machining process. Also, the small size of the poles reduces the inductance, enabling use of the heads at higher frequencies. While the process of making the heads is quite complicated, the dimensional control achieved with lithography is much more reproducible than possible with machining. In addition, many heads are made simultaneously on each wafer, lowering manufacturing costs. Increasing the number of coil turns remains a processing challenge, and today's heads have three or four layers of stacked coils.

Anisotropic Magnetoresistive Heads

To keep pace with the increases in areal density driven by the hard disk market, alternative head technologies have been developed. A major improvement has been the replacement of inductive readback with magnetoresistive readback (10). MR heads have separate read and write elements (Fig. 6). An inductive thin film head is still used for writing, but a separate gap with a magnetoresistive sensor is used for reading the magnetic information. The MR sensor detects the flux from the medium directly. The resistance of the sensor varies with applied field and a sense current is used for detection. Figure 7 shows a view of an MR head from the air bearing surface.

The resolution of the head along the track is determined by the distance between two magnetic shields placed on either



(a) (b)

Figure 5. A thin film inductive head. (a) Plane view during wafer fabrication (b) Cross-sectional schematic showing coils surrounded by the magnetic poles. (a) courtesy Data Storage Systems Center, Carnegie Mellon University.)

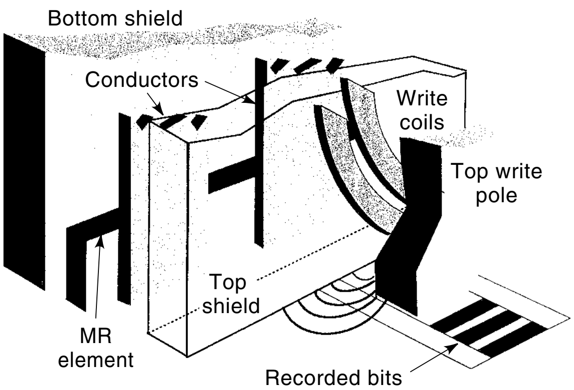


Figure 6. Anatomy of a magnetoresistive (MR) recording head: Elements are depicted in order of deposition: bottom shield, magnetoresistive device elements, conducting leads, top shield (also functions as bottom write pole), write coils, and top write pole. Elements are separated by a dielectric, typically Al_2O_3.

side of the element. A dielectric is used to separate the element from the shields. The total distance between the shields determines the achievable linear storage density. A common practice is to have one of the shields serve as the bottom pole of the inductive head reducing the total number of magnetic layers fabricated in the head. The resolution across the track, which determines the track density, is controlled either by the distance between the two conductors used to sense the resistance, or by the width of the magnetically active region of the magnetoresistive element.

One major advantage of MR heads is that the readback sensitivity is determined by the choice of the magnetoresistive material. Heads currently in production use materials based on the anisotropic magnetoresistance (AMR) effect. The resistance either increases or decreases depending on the relative orientation of the magnetization of the material to the current direction. The field response of a patterned AMR film

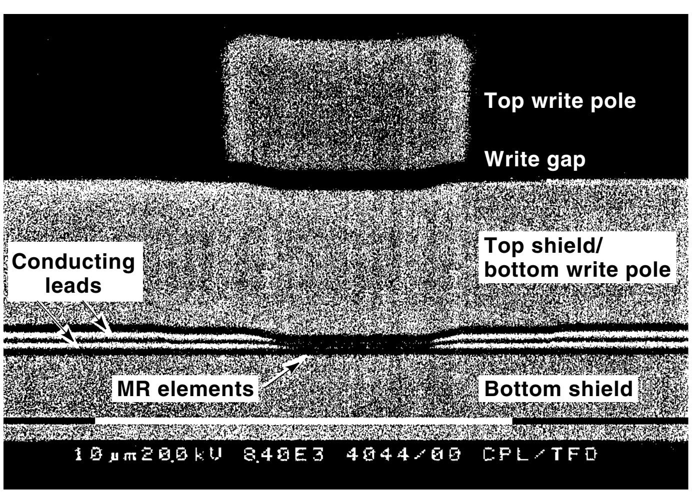


Figure 7. SEM photograph of a dual stripe MR head at the air bearing surface: The two MR elements are discernible in the bottom gap. The active area of the device is defined by the conducting leads.

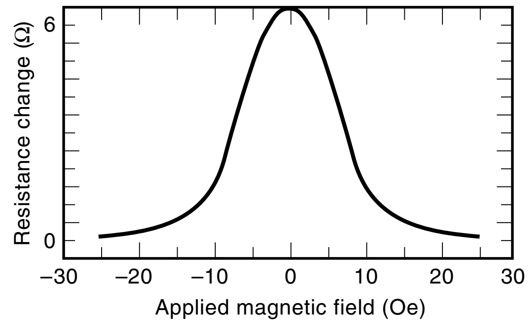


Figure 8. Anisotropic magnetoresistance response to an applied magnetic field: Data are taken from a patterned film, no biasing technique is applied. Current flows parallel to the zero field magnetization, and the field is applied transverse to this direction.

is shown in Fig. 8. The 10 nm to 20 nm thick AMR films commonly used have magnetoresistive effects on the order of 2.5% at low applied fields.

The physical origin of the magnetoresistance effect lies in spin orbit coupling. As the direction of the magnetization rotates, the electron cloud about each nucleus deforms slightly. This deformation changes the amount of scattering undergone by the conduction electrons when traversing the lattice (Fig. 9). A heuristic explanation is that the magnetization direction rotates the closed orbit orientation with respect to the current direction. If the orbits are in the plane of the current, there is a small cross-section for scattering, giving a low resistance state. If the orbits are oriented perpendicular to the current direction, the cross-section for scattering is increased, giving a high resistance state.

The response of a magnetoresistive element to an applied field is nonlinear. Thus, it is necessary to bias the MR material into a region that is linear (that is, offset the effect from zero field) such that the response is single valued with respect to the applied field, since both positive and negative fields are sensed from the medium. There are two pertinent methods currently used to bias the MR response for use in magnetic read heads: the soft adjacent layer (SAL) and dual stripe (DS) configurations.

Soft Adjacent Layer Heads. SAL heads use a thin film of soft magnetic material placed next to the MR element to bias the device into a linear region (11). The magnetization of this film is constrained to be transverse to the current direction, effectively applying a dc field locally to the MR element [Fig. 10(a)]. The field from the sense current is sufficient to rotate the magnetization of the SAL film to the transverse direction. When the SAL layer is magnetized, it produces a fringing field (H_F) that rotates the magnetization of the MR material with respect to the current. Since the change of resistance in an MR head goes as $\cos^2\theta$, where θ is the angle between the magnetization direction and the current, the optimum bias configuration is for the MR material's magnetization to be rotated near 45 degrees with respect to the current direction. This condition puts the zero field resistivity at a value midway between the maximum and minimum of the resistance. Thus the resistance will either increase or decrease when sensing positive or negative fields.

A difficulty with this biasing technique is that it leads to cross-track asymmetry. Since the magnetization of the sense

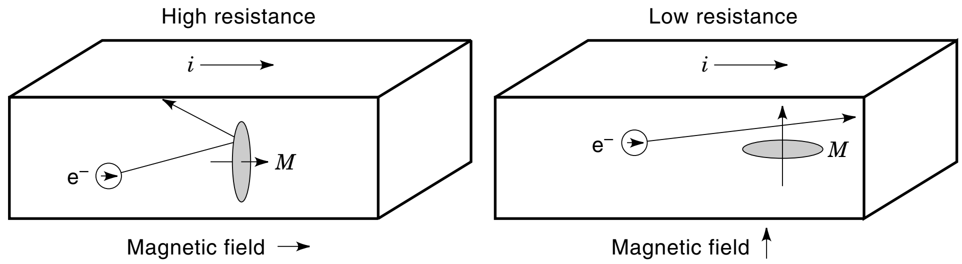


Figure 9. Schematic demonstrating the physical origins of anisotropic magnetoresistance: Current flows along the long direction of the bar. Dark gray ovals represent the scattering cross-sections of the bound electronic orbitals. For fields parallel to the current flow, electrons see a greater scattering cross-section than for fields perpendicular to the current direction.

film is rotated away from the long axis of the MR element, and since the flux flow in the element is perpendicular to the direction of magnetization, there will be an asymmetry in response of the head as it moves across the track. This asymmetry either needs to be taken into account when designing the tracking function of the head or it can be removed by more complicated head geometries.

Dual Stripe Heads. A dual stripe head uses two MR sense elements that are electrically isolated from each other (12). The fields from the sense currents again rotate the magnetization, but in this case both elements are rotated equally and in opposite directions [Fig. 10(b)]. An advantage of the dual stripe design is that the response of the head is differential between the responses of the individual MR elements. The field from a transition in the medium rotates the magnetization of both head elements in the same direction, resulting in the resistance of one element increasing and the resistance of the other element decreasing. Because the nonlinearity of the two elements is essentially second order, the subtraction of the two parabolic responses linearizes the signal. The two elements are detected differentially, giving a greater response than a single element. Differential detection also removes any common mode signals originating from stray pickup or thermal noise. In addition, the cross-track asymmetry present in SAL heads is not present in the dual stripe design, since the asymmetry of one element cancels that of the other.

The greater readback signal of MR heads has enabled designs for higher storage density drives. However, design challenges have hampered the incorporation of MR elements into disk drives, evidenced by the time needed for the technology to advance to large scale production. Only in 1997, 26 years after the first MR head was demonstrated (10), have the majority of manufactured disk heads used MR technology. Problems that arise relate to the difficulties in obtaining the correctly biased state, in stabilizing the magnetic elements, and in obtaining high yield manufacturing processes. These topics will be discussed later.

Giant Magnetoresistive Heads

Giant Magnetoresistive Phenomenon. Giant magnetoresistance (GMR) was discovered in 1988 by Baibich et al. (13), in antiferromagnetically coupled multilayers of Fe/Cr. In this structure, thin layers of magnetic material are separated by layers of nonmagnetic material. The magnetic layers are coupled through the nonmagnetic layers either ferromagnetically or antiferromagnetically, depending on the thickness of the nonmagnetic layers. Magnetoresistance effects of up to ~50% were observed at low temperatures. This effect was subsequently found to occur in a number of multilayer magnetic film systems.

The GMR effect requires a method to change the relative orientations of the magnetization in adjacent magnetic layers, and requires that the thickness of the films must be less than the mean free path of the electrons. Figure 11 shows a schematic of the multiplayer structures. The GMR effect can be qualitatively understood on the basis of a two fluid picture of the conduction process in a magnetic metal.

The conduction electrons are divided into two classes: those with spin parallel to the local magnetization and those with spin antiparallel. The resistance of the material is determined by the scattering processes to which the electrons are subject. Strong scattering processes produce a short mean free path and large resistance, weak processes produce long mean free paths and lower resistance. GMR effects are produced when the scattering processes for one spin orientation of the conduction electrons is more effective than for the other spin orientation. In the two fluid picture, electrons with spin oriented parallel to the magnetization of the metal have a lower resistance than those with spin are oriented antiparallel. The high resistance state of the GMR materials occurs when the magnetic layers are antiferromagnetically aligned, so that electrons experience strong scattering where the magnetization of the material is opposite to the spin orientation. The low resistance state is obtained when a magnetic field strong enough to overcome the antiferromagnetic coupling is

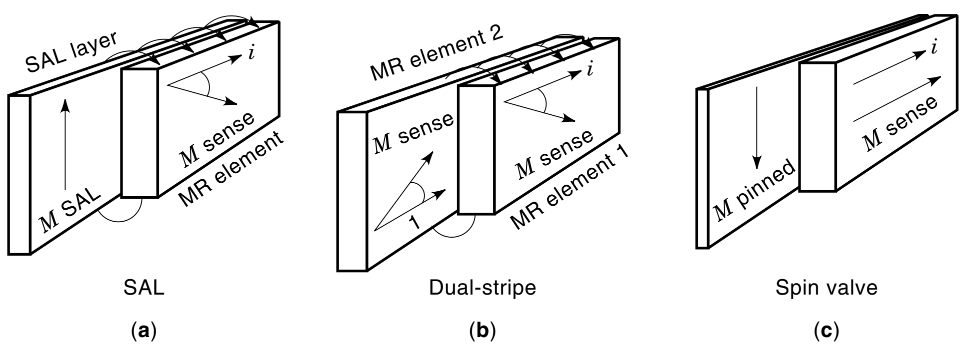


Figure 10. Biasing methods of three different MR heads. (a) The SAL MR head is biased by an adjacent magnetic film. (b) A dual-stripe head uses two sense elements. The current in each element biases the other element. (c) The spin valve head is self biased when the sense film is orthogonal to the pinned film.

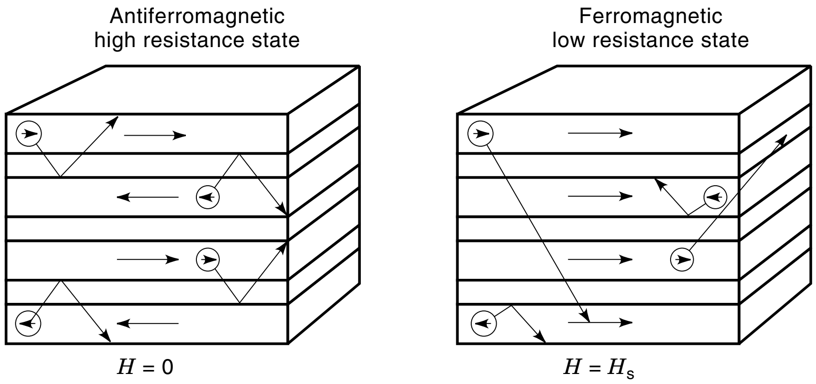


Figure 11. Schematic of the high and low resistance states of a GMR multilayer system: The magnetic layers, with arrows indicating the direction of the magnetization, are separated by nonmagnetic conducting layers. In zero applied field, the magnetic layers couple antiferromagnetically. Beyond the saturation field, the magnetization of the layers line up ferromagnetically. (See text for explanation.)

applied, and rotates the magnetization of the layers to a ferromagnetic configuration. When the magnetic layers are ferromagnetically aligned, only half of the conduction electrons experience strong scattering processes, while the other half experience weak scattering processes, with the net effect of reducing the overall resistance of the material.

For a multilayer to be attractive as an MR head sensor, it must have not only a large $\Delta\rho/\rho$, but also must have a large sensitivity to a magnetic field. The original Fe/Cr system requires extremely large fields (20 kG) to rotate the magnetization to the ferromagnetic configuration, and is therefore unattractive as a recording head device. Schemes have been developed, however, where *uncoupled* magnetic films can be switched from the antiparallel to parallel configuration. These devices have been termed *spin valve structures.*

Spin Valve Heads. Spin valves were developed to provide more control over the magnetics of the GMR multilayers (14). These structures contain two thin magnetic films separated by a nonmagnetic, conducting spacer layer. An antiferromagnetic "pinning" layer is exchange coupled to one of the magnetic films (pinned layer) in order to hold the orientation of the magnetization constant. The other magnetic layer (sense layer) is free to switch back and forth in the presence of a magnetic field. The principle for the magnetoresistance is similar to the GMR multilayer; that is, spin dependent scattering gives a low resistance state when the magnetic layers are ferromagnetically aligned, while a high resistance state is obtained in the antiferromagnetic configuration (Fig. 12).

The resistance in the spin valve structure depends on the angle between the magnetizations in the two magnetic layers, and is independent of the current direction, unlike the situation for AMR materials. The resistance varies as $\cos(\theta)$ where θ is the angle between the magnetization of the two layers. A typical value for the magnetoresistance in a spin valve material suitable for a recording head is 10%. To bias the structure in a recording head, the magnetization of the pinned film is oriented 90 degrees to the magnetization of the sense film [Fig. 10(c) and Fig. 13]. Optimizing the spin valve heads such that the many magnetic fields present in the structures (demagnetizing fields, exchange coupling fields, fields due to currents, anisotropy fields, stabilizing fields) are balanced requires extensive development and only recently have prototypes been demonstrated (15).

HEAD MATERIALS AND PROCESSING

The design of a magnetic recording head, and the selection of its constituent materials, are largely dictated by two key requirements of the recording system: areal density and frequency response (data rate). Head design (for example, choice of inductive or magnetoresistive technology) narrows the list of prospective materials, but even for a particular design the list of candidate materials can be quite large. Materials selection for recording heads plays an important role in the performance of the device, since critical parameters such as magnetic permeability, saturation magnetization, magnetostriction, and coercivity vary widely among ferromagnetic materials. The following section provides a description of recording head materials, as well as fabrication processes used in head construction.

Ferrite Heads

In current low end applications, a simple "ring" head often satisfies the density and frequency response criteria. Conven-

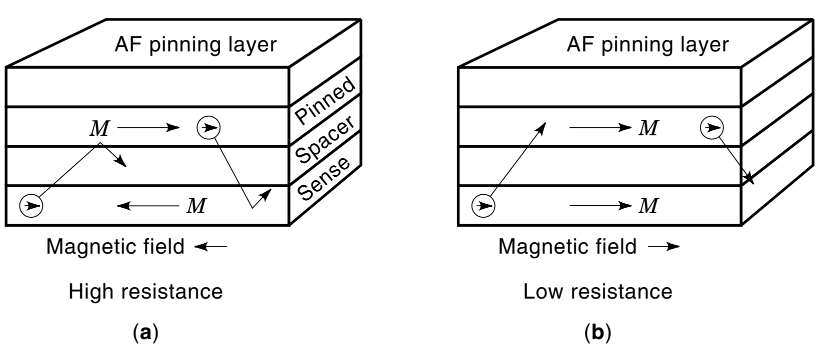


Figure 12. Principle of operation of a spin valve system. Two magnetic layers are separated by a nonmagnetic conducting spacer. The magnetization of the top layer is pinned by exchange coupling to an antiferromagnet layer, while the magnetization of the bottom magnetic layer (sense layer) is free to rotate in response to a magnetic field. (Not shown in the self biased state.)

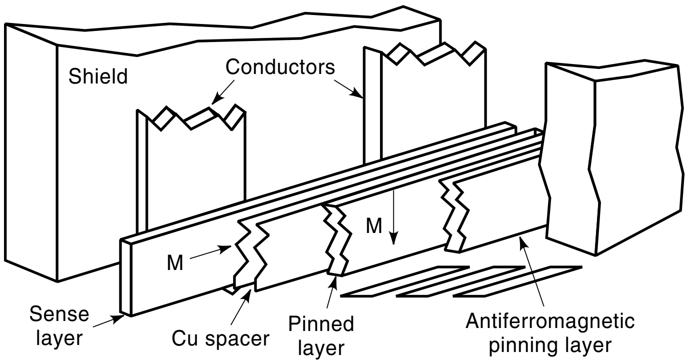


Figure 13. Anatomy of a spin valve read head: The magnetoresistive device consists of a magnetic sense layer, a Cu spacer, a magnetic pinned layer, and an antiferromagnetic pinning layer. The track-width is defined by the separation of the conductors. The device is deposited between magnetic shields.

tional ring heads are made of either iron alloy or ferrite cores. The cores are machined in two parts and bonded together to form the gap. The gap distance is typically 0.2–2.0 μm, and determines the resolution of the head along the length of the track. Fine Cu wire is wound around the core to complete this simple structure. A schematic of a ring head is shown in Fig. 3. One problem with ring heads made from iron alloy cores is the degradation of head performance at high frequencies due to eddy currents in the conductive magnetic cores. Eddy currents are reduced by lamination of iron alloy cores, or by use of high resistivity ($\rho > 0.1\ \Omega$ cm) ferrite cores. Materials requirements of the core include magnetic properties, such as high permeability, high saturation magnetization, and low coercivity; as well as mechanical properties, such as the ability to be easily machined and high hardness, which correlates to the wear resistance of the core material.

Ferrites are alloys of the general form $MO(Fe_2O_3)$, where M is a divalent metal such as Mn, Zn, Ni, Co, or Fe. If M = Fe, then the chemical formula becomes Fe_3O_4, known as magnetite, or lodestone in ancient times. However, magnetite does not have sufficiently high permeability for use in most sensors, so Fe is replaced with Mn, Zn, or Ni, or some combination of these three elements. These mixed ferrites are manufactured by sintering particles of Fe_2O_3 and MO at high temperature and pressure. The magnetic properties of commonly used mixed ferrites are compared with lamination core materials in Table 1. One shortcoming of ferrites is low saturation magnetization, limiting the magnitude of the write field the head can produce. Manufacturers of ferrite heads have addressed this problem by depositing a layer of high moment material on either side of the gap. Such heads are called metal-in-gap (MIG) heads, and combine the best attributes of ferrite and high moment lamination materials. The marriage of ferrite and high moment materials in the form of MIG heads has extended the life of wire-wound core heads. However, another more fundamental deficiency of machined ring heads remains: the difficulty in manufacturing heads capable of high density recording using mechanical machining. Recording heads in modern disk drives read and write information at track densities of nearly 350 tracks/mm, corresponding to write pole widths of less than 3 μm.

Thin Film Inductive Heads

In 1979 researchers at IBM applied advanced semiconductor processing techniques to the fabrication of magnetic recording heads, and the thin film inductive (TFI) head was born. With this new technology hundreds, if not thousands, of heads are processed simultaneously on a single substrate using thin film deposition and photolithographic pattern definition. The feasibility of this approach required identifying a ferromagnetic material that is both amenable to thin film process techniques and is able to satisfy the stringent requirements of the recording transducer. Permalloy, an alloy of $Ni_{81}Fe_{19}$ (atomic percent), is particularly well suited for the thin film core since it can be deposited by electroplating, and has very attractive magnetic properties, as shown in Table 1.

The process of fabricating a TFI head is understood by referring to Fig. 5(b). First, the bottom half of the core is defined on the substrate by electroplating permalloy into a photoresist stencil, followed by sputter deposition of a dielectric gap (typically Al_2O_3 or SiO_2). Next, a Cu spiral coil is plated on top of the bottom core and gap, and this coil is completely encapsulated by an insulator, such as photoresist. Several layers of coils are added to generate sufficient inductive sig-

Table 1. Magnetic Materials Used in Magnetic Cores of Inductive Recording Heads: Initial Permeability (μ_0), Coercive Field (H_c), Saturation Magnetization (M_S), Resistivity (ρ), and Vickers Hardness

Material	μ_0	H_c (Oe)	M_S (kG)	ρ ($\Omega \cdot$cm)	Vickers Hardness
Mo permalloy[1]	20,000	0.025	8	100×10^{-6}	120
Alfenol[2]	8,000	0.038	8	150×10^{-6}	290
Sendust[3]	10,000	0.025	10	85×10^{-6}	480
NiZn ferrite[4]	300–1500	0.15–0.35	4–4.6	10^5	900
MnZn ferrite[4]	3,000–10,000	0.15–0.20	4–6	5	700
MnZn ferrite[5]	400–1000	0.05	3–5	>0.5	
Plated $Ni_{45}Fe_{55}$	1700	0.4	16	48×10^{-6}	
Plated $Ni_{81}Fe_{19}$	4000	0.3	10	24×10^{-6}	

[1]4% Mo 17% Fe 79% Ni
[2]16% Al 85% Fe
[3]5.4% Al 9.6% Si 85% Fe
[4]Hot Pressed
[5]Single crystal
Source: Ref. 2, p 6.24 and Ref. 16.

nals for read head applications. Finally, the top half of the permalloy core is plated using another photolithographically defined stencil. A clear advantage of this approach over traditional machining process is that the density capability of the head is determined by distances defined by either film thickness (the gap) or photolithography (the plated cores). The dimensional control afforded by these processes is far superior to that of machined parts, enabling production of heads with core widths on the order of 1 μm. Another advantage of thin film processing is the relatively small inductance, and corresponding superior high frequency performance, of the small NiFe core as compared to that of machined blocks of ferrite or laminated iron alloy cores.

Permalloy has served as the industry standard pole material in thin film heads for more than ten years, but steadily advancing recording densities and data rates have begun to push NiFe to its limit. On the density front, coercivities of recording media in excess of 2500 Oe, a necessity for high density storage, are placing increased demands on the amount of flux needed from the head. In order to write effectively, the head must produce a field roughly twice as large as the coercivity of the medium. Permalloy has a saturation magnetization M_S of 10 kG, but losses in the head, particularly that due to the spacing between the head and the medium, reduce the field at the medium substantially. The need for larger write fields in plated thin films heads prompted the development of heads incorporating $Ni_{45}Fe_{55}$, the composition of peak magnetic moment (M_S = 16 kG) in the Ni–Fe system (16). This NiFe alloy is well-suited as the writing element in conjunction with magnetoresistive readout (later in this article), but its higher anisotropy and magnetostriction limit its use in TFI heads. High M_S alloys, such as Fe–N (17), FeTaN (18), FeAlN (19), each with saturation magnetization of about 20 kG, are being actively studied for writing on future generations of high coercivity media. Further improvement of the frequency response of NiFe is in jeopardy due to eddy current damping. Solutions to this problem are being addressed on two fronts: (1) laminating the pole material with dielectric spacer layers, and (2) investigating more resistive high moment alloys [such as amorphous CoZrTa (20)].

Magnetoresistive Heads

The addition of a magnetoresistive read element creates a more complicated device than the standard TFI head, since an inductive element is still required for writing. Referring to Fig. 6, standard construction of such a dual element head begins with the deposition of a ferromagnetic shield, followed by the bottom half of the read gap dielectric. The MR element and contacts are then defined, after which the top half of the read gap and top shield are deposited. In this merged pole structure, the top shield of the read head also serves as the lower core, or pole, of the inductive write element. Finally, the remainder of the TFI write head is fabricated on top of the top shield. Unlike the TFI head, where the thick (2 μm to 4 μm) ferromagnetic core and Cu coil are plated, the critical sensor materials in an MR head are deposited by sputtering (21).

Biasing techniques incorporated in MR heads were described previously, and now some of the associated materials considerations will be discussed. The soft adjacent layer, or SAL design, introduces additional materials into the read head; whereas the dual stripe design simply replicates an MR element. Both designs use permalloy for the MR element(s). Key attributes of the SAL film are: low $\Delta R/R$, high M_S, high permeability, low magnetostriction, and high resistivity. Ternary alloys NiFeX (22) (examples of X are Nb, Rh, or Zr) and amorphous Co-based alloys such as CoZrMo (23) are used for the SAL film. For proper biasing, the MR element and SAL film must be magnetically decoupled by interposing a thin layer of high resistivity metal (for instance, Ta) between them.

For the dual stripe biasing technique, one key materials challenge is maintaining electrical isolation between the two MR elements that are separated by a dielectric film of 50 nm or less. Fabrication of dual stripe heads also taxes the photolithographic alignment process, since overlaid elements are defined in separate patterning steps, and the track-widths must be lined up precisely.

In addition to its relatively large magnetoresistance ($\Delta\rho/\rho \sim 2\%$) and high permeability (μ = 2000), permalloy has another characteristic in its favor: zero magnetostriction. Magnetostriction is the dimensional change, or strain, a material undergoes when exposed to a magnetic field. The magnetostriction of permalloy is typically less than 1×10^{-6}, whereas that of many other ferromagnetic alloys can be in the 10^{-5} range. Conversely, if a magnetostrictive material is stressed, it develops magnetoelastic anisotropy energy density (E_a) according to the equation:

$$E_a = -3\lambda\sigma\cos^2\theta$$

where σ is the stress in dynes/cm^2, λ is the magnetostriction in units cm/cm, and θ is the angle of the magnetization relative to the axis of applied stress. If both σ and λ are of the same sign, then the magnetoelastic energy will tend to create an easy axis parallel to the applied stress, whereas, if the two are of opposite sign, the magnetostriction will contribute an anisotropy orthogonal to the applied stress. Since the magnetic anisotropy of NiFe is already quite low, additional magnetoelastic anisotropy can either destabilize or reduce the sensitivity of the MR element. Control of magnetostriction, primarily through permalloy composition (24), is very important for producing a stable MR transducer.

Unlike an inductive head, a magnetoresistive sensor operates as a parametric amplifier: the voltage output is proportional to the sense current. The maximum tolerated current is determined by the power dissipation in the head, which in turn dictates the operating temperature. Current densities of about 2×10^7 A/cm^2 are commonly used, resulting in a temperature rise of several tens of degrees above ambient. Smaller dimensions permit higher current densities, but introduce concerns over electromigration. Fortunately, NiFe is not very susceptible to electromigration, although the contact lead metallurgy may be. Common contact lead metals are W and Ta/Au/Ta.

Another aspect considered in the design and fabrication of MR heads is the propensity of ferromagnetic materials to form magnetic domains. Any free magnetic charges present near the edges of the device, or in defects generated in manufacturing, will produce demagnetizing fields which create magnetic domains in the sense element. These domains are a source of noise (Barkhausen noise) and must be eliminated in the active area of the sensor. Various techniques, used individually or in combination, are used to stabilize the sense ele-

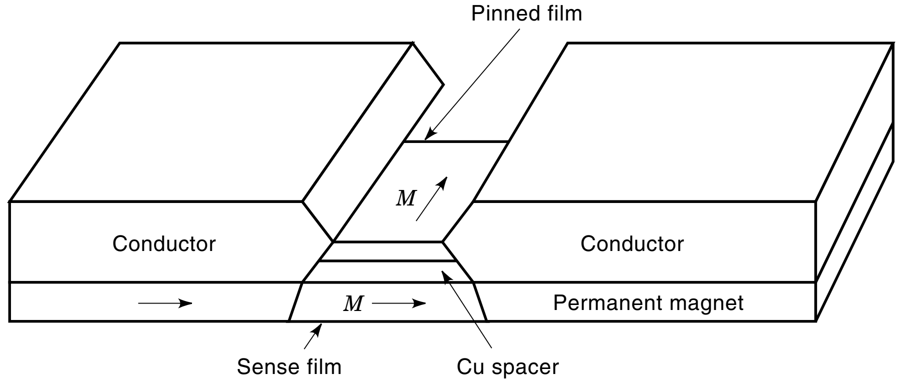


Figure 14. Permanent magnet stabilization: Permanent magnet thin films are deposited adjacent to the spin valve sense layer. The field from the permanent magnets creates a single domain sense element, greatly reducing noise in the response of the device.

ment. The material anisotropy is increased to overcome the destabilizing fields caused by magnetostatic effects at the ends of the MR element. The element height is reduced, producing a demagnetizing field constraining the magnetization direction along the long axis of the sense element. Antiferromagnetic (AF) exchange coupling pins the sense element magnetization at the track-edge, reducing the probability of multiple domains at the track-edge (25). Finally, thin permanent magnet films are fabricated at the track-edge (Fig. 14), providing a longitudinal stabilization field (26).

The two most common domain stabilization techniques are (1) AF exchange coupling the sensor to an antiferromagnetic outside the active region, and (2) fabricating permanent magnetic films on both sides of the MR element patterned to exactly the desired trackwidth. Properties of MnFe, MnNi, NiO, and IrMn antiferromagnets used for stabilization are listed in Table 2, and will be described in more detail later. The permanent magnetic stabilization method uses CoPt-based alloys similar to those used in high coercivity magnetic disks. By controlling the product of magnetization and thickness of the permanent magnet film, the magnitude of the longitudinal stabilizing field is tailored according to sensor requirements.

One difficulty with MR heads is the possibility of shorting the element(s). Since a sense voltage is applied across the MR head, momentary contact between the head and the medium may short the element. Asperities may scratch the air bearing surface, possibly shorting the element to the shield. Asperities also produce thermal spikes in the element, causing a resistance variation in the head. These problems have been mitigated by overcoating the air bearing surface of the slider with a thin (<15 nm) protective film of amorphous carbon. Such overcoats also have dramatically improved the tribological characteristics of the interface between the head and the disk.

Table 2. Properties of Antiferromagnetic (AF) Materials in NiFe (25 nm)/AF Exchange Couples: Exchange Field (H_X), Blocking Temperature (T_B), Resistivity (ρ), and Corrosion Resistance

Material	H_X (Oe)	T_B (°C)	ρ ($\mu\Omega \cdot$ cm)	Corrosion Resistance
MnFe	50	150	130	poor
MnNi	120	>400	190	moderate
NiO	30	220	$>10^{10}$	good
IrMn	100	250	200	moderate

Magnetoresistive materials for use in recording heads have been the object of research since the early 1970s, and while scientists have searched for materials superior to NiFe, no obvious successor has been found. Alternate materials are elusive primarily because of the numerous properties they must possess in addition to large magnetoresistance: low coercivity, low magnetic anisotropy, low magnetostriction, and high permeability. However, in 1988 the field of magnetoresistive research was thrown wide open with the discovery of giant magnetoresistance (GMR) in multilayer films.

Giant Magnetoresistive Materials

Giant magnetoresistive materials were discovered only recently, but are already in the product plans of most head manufacturers. A common denominator of all GMR films is the interaction of at least two magnetic layers with magnetization vectors that can be rotated with respect to each other. As discussed previously, if the two regions are close enough (<10 nm), electrons can traverse the nonmagnetic spacer layer separating the ferromagnetic (FM) layers without loss of spin orientation. The electrons of one spin state will be scattered preferentially over electrons of the other spin state depending upon the relative angle between the magnetization vectors. A low resistance condition corresponds to parallel magnetization, and a high resistance to antiparallel magnetization, independent of the direction of current.

The GMR structure best suited for recording applications is the spin valve (14). Both the sense and pinned films are typically NiFe, Co, or bilayers of NiFe and Co, and in contrast to the SAL and DS sensors, the spacer material must be a low resistivity metal, such as Cu.

The magnetization in the pinned film is fixed by exchange coupling to an AF film. One of the primary challenges for the spin valve design is producing sufficiently large pinning field to ensure that the pinned film magnetization remains perpendicular to the sense layer magnetization, particularly in the operating environment of elevated temperature and alternating magnetic fields. A key attribute of AF exchange coupling is it produces a unidirectional anisotropy, meaning the pinned layer has a unique easy magnetization direction. In such a system, the magnetization direction of the pinned FM layer in zero field is independent of field history, an advantage for fabricating sensors with a predictable magnetization state. Two of the most important parameters of the AF/FM exchange couple are exchange field strength (H_X) and blocking temperature (T_B, the temperature at which the exchange field goes to zero). The exchange field should be as large as possible. The blocking temperature must be high enough to prevent loss of pinning at the operating temperature, but low enough to set the exchange field orientation without causing diffusion at the interfaces of the spin valve layers. Properties of some of the most widely used antiferromagnetic alloys are presented in Table 2.

Spin valves have been fabricated using each of the materials listed in Table 2 as pinning layers. Those with MnFe (27) suffer from sensitivity to corrosion and low T_B, which limits the operating temperature (i.e., current density) of the device. NiO-based spin values (28) have barely adequate exchange field strength, but otherwise have ideal attributes for use in a spin valve. An insulating antiferromagnetic is particularly advantageous since there is no shunt current loss. The chief disadvantage of MnNi is that high temperature processing ($T > 250°C$) is required to establish the AF phase (29), which can lead to degradation in magnetoresistance. IrMn is a relative newcomer to the list of exchange alloys in spin valve heads (30), but its properties appear to satisfy the requirements of a spin valve sensor.

An MR or spin valve head contains many materials other than the MR elements themselves that affect device performance and the manufacturing yield. The substrate, ferromagnetic shields, gap dielectric, magnetic stabilization and lead all play important roles in MR head performance. For instance, the insulator that electrically isolates the sensor from the shields is typically 50 to 100 nm of Al_2O_3. However, a dielectric with higher thermal conductivity would permit higher sense currents, improving the output of the head. The substrate material, forming the body of the slider, is generally a hard ceramic material such as $CaTiO_3$, SiC, or Al_2O_3–TiC, and is chosen based on its thermal, mechanical, and tribological properties. Lead metallurgy must be thoughtfully chosen to ensure that electromigration is not a problem and that device resistance is kept as low as possible.

THEORY OF OPERATION

The basic head requirement is to write and read the magnetization states in the magnetic medium. In many high density applications, the write and read elements are separate, and each is individually optimized for peak performance. Both head and media materials have comparable magnetic moments, but their coercive fields differ substantially. The head material is “soft,” returning to zero-magnetization state after removal of the applied field; whereas the medium material is hard, once pushed to a saturated state of magnetization it retains its magnetization state upon removal of the field. The medium thus has hysteretic characteristics, represented by such parameters as the saturation magnetization M_S, the coercive squareness of hysteresis loop S^*, and the coercivity H_c.

Write Modeling

Although the writing process is intuitively simple, analyzing it is quite complex. As the magnetic field from the head magnetizes the medium, the induced magnetization opposes the head field by generating a demagnetizing field. The head dimensions, and the separation between the ABS and the medium, are crucial parameters in writing. A simple but informative analytical method is first presented, followed by the incorporation of more complex behavior, and finally, a more realistic numerical approach is discussed.

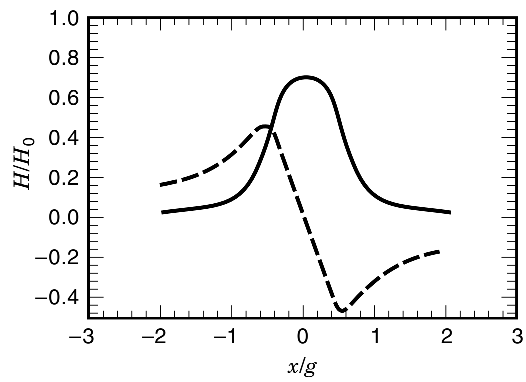


Figure 15. Calculated fields produced in the medium from an inductive head: Solid and dashed lines represent the x and y components, respectively, of the field induced in the medium. Results are derived from the Karlquist expressions, Equations (1) and (2).

In the simple analysis, assume the medium is very thin and only responds to the longitudinal component of the head field. The assumption of a very thin medium implies no perpendicular component of magnetization in the medium. Also assume that the head pole pieces are of infinite thickness. With these assumptions, the head field in the medium is given by the Karlqvist expression (31)

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

$$H_y(x, y) = \frac{1}{2\pi} H_o \log \left[\frac{\left(\frac{g}{2} - x\right)^2 + y^2}{\left(\frac{g}{2} + x\right)^2 + y^2} \right] \quad (2)$$

where H_x and H_y are the longitudinal and perpendicular components of the field seen by the medium, H_o is the magnetic field at the ABS of the head, and g is the gap distance. Figure 15 shows a plot of the longitudinal and perpendicular components of the head field at a distance of $g/4$ from the ABS of the head. If the medium was all negatively magnetized, and a large positive head current is suddenly applied to the head coil, the medium’s magnetization will become positive. Once the head moves away, or the head current is reduced to zero, the magnetization will relax to a point on the hysteresis loop vertical axis. Figure 16 shows a pictorial presentation of a head field contour and the hysteresis loop. As the head field goes to zero, different points in the medium return to different values of remanent magnetization, as depicted by different arrows in the hysteresis loop. The medium’s magnetization thus goes through a transition region. If the magnetization change is assumed to be linear, then the slope of magnetization, dM/dx, can be written as M_r/a_L, where a_L is called a transition parameter. A first estimate of the transition parameter is obtained from

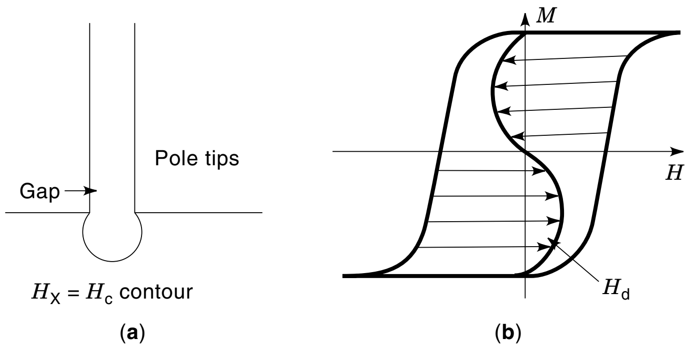


Figure 16. Effect of field contour on magnetic transition. (a) Shape of the fringe field contour below the gap of the write poles. (b) The medium transition will have a distribution of remanent magnetization, depending on the relative position of the point on the medium to the head contour field.

$$\frac{dM}{dx} = \left(\frac{dM}{dH}\right)\left(\frac{dH}{dx}\right) \tag{3}$$

and

$$a_L = M_r \Big/ \left(\frac{dM}{dH}\right)\left(\frac{dH}{dx}\right) \tag{4}$$

A small transition parameter, that is, a sharp change in magnetization in the medium, requires a low remanent magnetization, a square hysteresis loop (dM/dH), and a large head field gradient (dH/dx). Although Eq. 4 approximates the recording process, in reality, transitions are not linear and often have long tail sections. An arctangent or hyperbolic tangent are often better representations.

As the medium is magnetized, the regions of magnetization variation accumulate magnetic charge which produces another component of magnetic field called the demagnetizing field (H_d). The demagnetizing field is obtained from the Maxwell equation

$$\nabla \cdot H_d = \nabla \cdot M$$

When the written track-width is large compared to the dimension in the longitudinal direction, and the medium's magnetization is arctangent, then the previous expression can be solved for the demagnetizing field. If the transition is represented by an arctangent transition, then the longitudinal and the perpendicular components of the demagnetizing field are given by (32). Figure 17 shows the shape of the arctangent transition and the associated demagnetizing field.

$$H_d^x(x,y) = -\frac{M_r}{\pi} \times \left[\arctan\left(\frac{a+y+\frac{\delta}{2}}{x-x_o}\right) + \arctan\left(\frac{a-y+\frac{\delta}{2}}{x-x_o}\right) - 2\arctan\left(\frac{a}{x-x_o}\right)\right] \tag{5}$$

$$H_d^y(x,y) = \frac{M_r}{2\pi}\log\frac{\left[a+\frac{\delta}{2}-y\right]^2 + (x-x_o)^2}{\left[a+\frac{\delta}{2}+y\right]^2 + (x-x_o)^2} \tag{6}$$

Once the head field and the demagnetizing field are understood, the transition parameter can be determined. In Eq.(3) the total field can be written as

$$H = H_h + H_d$$

where H_h is the applied head field, given by Eqs. (1) and (2), and H_d is the demagnetizing field given by Eqs. (5) and (6). Referring to Eq. (3), the slope of the hysteresis loop at the coercive field can be written as

$$\left.\frac{dM}{dH}\right|_{X_o} = \frac{M_r}{H_c(1-S^*)}$$

where S^* represents the squareness of the loop at the coercivity point. At this point, there is enough information to solve Eq. (3) for any head field, spacing and loop shape. In 1971, Williams and Comstock published a now widely used paper on an analytical expression of the transition width (33). Eq. (4) implies a large head field gradient is required to obtain a sharp transition. The Williams–Comstock analysis assumes the transition occurs at the point of maximum head field gradient. That is, for every head-medium spacing the head current is adjusted so that it reaches a value slightly larger than the coercivity (called the remanent coercivity, H_r) at exactly the same spatial point where the head field gradient is also maximum. With this assumption, the following expression is obtained for the transition parameter.

$$a = \frac{(1-S^*)\left(d+\frac{\delta}{2}\right)}{\pi Q} + \sqrt{\left[\frac{(1-S^*)\left(d+\frac{\delta}{2}\right)}{\pi Q}\right]^2 + \frac{M_r\delta\left(d+\frac{\delta}{2}\right)}{\pi Q H_c}}$$

In the previous expression Q is a function of head field gradient and its value varies very slightly around 0.75. For a high moment, thin, longitudinal recording medium, the last term in this expression dominates and the transition parameter re-

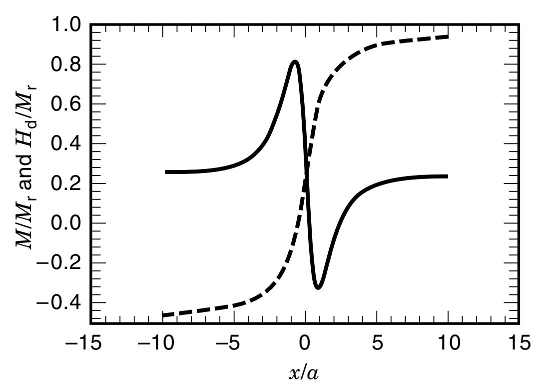


Figure 17. Calculated longitudinal component of the demagnetizing field and the resulting transition shape: Variation of magnetization in the transition region (dashed) and longitudinal component of the demagnetizing field (solid) normalized to the remanent magnetization (M_r) is plotted as a function of position normalized to the transition width a.

duces to

$$a \cong \sqrt{M_r\delta\left(d+\frac{\delta}{2}\right)\Big/(\pi Q H_c)}$$

or equivalently,

$$\frac{a}{\delta} = \sqrt{\left(\frac{M_r}{H_c}\right)\left(\frac{d}{\delta}+0.5\right)\Big/(\pi Q)}$$

The transition parameter is thus a strong function of M_r/H_c and d/δ. For a state of the art longitudinal recording, M_r/H_c is close to 5 and d/δ is close to 2.5. For these values a/δ is about 2.5 and for typical thin film longitudinal media the transition parameter is only 50 nm.

Although we have outlined the basic principles through simple analysis, actual operation is much more complex. The hysteresis behavior of the medium itself is still the subject of active research. One method of simulating the hysteretic behavior of the medium has been through a phenomenological model called the Preisach model, in which the medium is assumed to comprise an assembly of idealized particles. With a proper switching density distribution of these particles and careful consideration of the switching history of the particles, the major and minor loops can be modeled quite effectively. Also, the arctangent magnetization assumption breaks down for most cases, and one must perform a numerical analysis that involves finding a self-consistent solution. In this iterative method, the magnetization and field are carefully computed until the solutions converge. A two-dimensional application has been reported by Bhattacharyya, Gill, and Simmons (34). A more elaborate and careful three-dimensional work has been done by Davidson (35). In this work, Davidson uses the vector Preisach model for the medium, a three-dimensional head field through finite element analysis, and also an exhaustive self-consistent method to calculate the medium's magnetization. This work clearly shows that in thin film disks, there are substantial regions where the magnetization is not longitudinal and these regions can introduce distortions in cross-track characteristics which may limit recording density. Other methods for calculating the magnetization of the medium produced by the head fields are based on micromagnetics, and both two-dimensional (36) and three-dimensional (37) models have been developed.

Inductive Head Readback

When a magnetic medium with spatially varying magnetization moves under the inductive head, the time variation of flux through the windings of the coil generates a voltage according to Faraday's law of induction. Regions of alternating magnetization produce alternating, nearly Lorentzian, pulses in the head. The voltage produced in the coils can be written as

$$V(x) = -NWv\frac{d\phi}{dx}$$

where N, W, v, and ϕ represent the number of turns of the readback element, trackwidth of the head, velocity of the magnetic medium (head is conventionally stationary), and the flux linked by the windings of the head, respectively. In modern high density recording, the value of W has been reduced to increase the tracks per unit length and M_r has been reduced to lower the transition parameter and thus increase linear density of recording. Both of these factors reduce the readback voltage. The industry has tried to compensate by increasing the number of coils and the velocity of the medium.

To determine the flux linking the coils of the inductive head, a very useful formulation called reciprocity is used. The principle of reciprocity states that the flux linking the coil can be found through a correlation integral of the head sensitivity function (magnetic field produced in the recording medium for a total current of unity flowing through the coils of the head) and the medium's magnetization. For the head sensitivity function, the Karlqvist expression is used. The reciprocity relationship can be used to determine the flux per unit trackwidth

$$\phi(x,y) = NE\mu_0\int_{-\infty}^{\infty} dx' \int_{-\delta/2}^{\delta/2} h(x'+x,y')M(x',t')\,dy$$

where $h(x, y)$ represents the head sensitivity function, which is the head field for unit current, and E represents the efficiency of the head. After integration the readback voltage can be written as

$$V(x) = \frac{2}{\pi g}NWEv\mu_0 M_r\delta\left\{\arctan\left[\left(\left(\frac{g}{2}+x\right)\Big/(d+a)\right)\right.\right.$$
$$\left.\left.+\arctan\left(\left(\frac{g}{2}-x\right)\Big/(d+a)\right)\right]\right\}$$

The peak voltage is found by putting $x = 0$ in the above expression and the pulsewidth at half maximum (PW_{50}), an important parameter for determining the channel performance, is

$$PW_{50} = \sqrt{g^2 + 4(d+a)(d+a+\delta)} \tag{7}$$

where d is the head-medium separation and δ is the medium thickness. Note that in the PW_{50} expression, g^2 and the second term should be comparable in magnitude, and thus contribute almost equally to the pulsewidth. To reduce pulsewidth, one has to reduce the read head gap, as well as the flying height, medium thickness, and the transition parameter. For a 0.2 μm read gap, 50 nm transition parameter and 20 nm medium thickness, one achieves a pulsewidth of 297 nm.

The Karlqvist head field, though very useful, does not truly apply for thin film heads with narrow pole thicknesses. Thin film heads show distinct undershoots, which are not predicted by the above analysis. While the write analysis is still correct (the medium is not affected by the small change of field at pole edges), the readback is very sensitive to these effects. Lindholm has developed formulae for the head field applicable to thin film heads with finite pole tip thickness (38). This field, when correlated with the medium's magnetization, clearly shows the undershoots observed experimentally in thin film heads. Lindholm's expression is also used to investigate the writing at the edges of the track, where the magnetization often has a substantial transverse component. When the control of the head geometry is important finite element methods (FEM) are useful and many commercial packages are now available.

Magnetoresistive Head Readback

Analytic and Numerical Methods. The resistance of MR heads changes when a magnetic field rotates the magnetization of the sensor relative to the current direction. The magnetization rotation, measured from the easy axis of the film, can be written as

$$\sin\theta = \left(\frac{H_y}{H_k}\right)$$

where H_y is the perpendicular component of the field at the head and H_k is the crystalline anisotropy field of the MR element. The resistivity of the MR film is $\rho = \rho_o - \Delta\rho\sin^2\theta$, where ρ_0 is the zero field resistivity, giving the resistance variation with applied magnetic field as

$$\rho = \rho_0 - \Delta\rho\left(\frac{H_y}{H_k}\right)^2$$

For NiFe, the most widely used magnetoresistive material, $\Delta\rho/\rho_0$ is approximately 2% and H_k is 4 to 5 Oe.

For most practical applications, the magnetic read heads are in a shielded structure. This complicates the analysis, since the additional magnetic layers also conduct magnetic flux. In 1974 Potter (39) showed that a shielded MR head can be thought of as two Karlqvist heads connected back to back. Consequently, many of the expressions derived for inductive heads can be used with minor modifications for MR heads as well. An MR head with a shield to shield distance $2g$ has a PW_{50} identical to an inductive head with a distance between the top and bottom poles (write gap) of g.

The transmission line method correctly accounts for the decay of medium flux in the MR film. An application of the transmission line to SAL and DS MR films has been proposed by Bhattacharyya and Simmons (40). Although not completely analytical in nature, this paper derives a closed-form expression for the flux flow in the MR film for any shielded MR head. For an MR film of thickness t, located symmetrically between the shields of separation $2g$, the decay length of flux is $(\mu g t)^{1/2}$. This expression is in units of length, and is considered in determining the height used in high performance MR heads. Taller elements have material that is not influenced by the magnetic field of the medium, which only serves to shunt the current, reducing $\Delta R/R$. Small MR heights are desirable for high output voltages, but have difficulties in proper biasing and in reproducible manufacturing.

Micromagnetic Methods. While the transmission line method is useful in some respects, it does not include the crystalline anisotropy, ferromagnetic exchange, magnetostatic coupling between films, or magnetic saturation effects. Micromagnetic analysis accounts for these factors. In steady state micromagnetic analysis, one uses the torque equation: $\boldsymbol{M} \times \boldsymbol{H} = \boldsymbol{0}$. As applied to magnetic read heads, this equation becomes:

$$\hat{\boldsymbol{m}}(\boldsymbol{r}) \times \left[\boldsymbol{H}_{\mathrm{a}}(\boldsymbol{r}) + \boldsymbol{H}_{\mathrm{D}}(\boldsymbol{r}) + H_k m_z(\boldsymbol{r})\hat{\boldsymbol{z}} + \frac{2A}{M_{\mathrm{s}}}\nabla^2\hat{\boldsymbol{m}}\right] = 0$$

The first term within brackets includes the applied field due to current, the medium, and any other field such as permanent magnet or exchange stabilization. The second term is the demagnetizing field, the third, the crystalline anisotropy field, and the fourth, the exchange energy field. The medium flux is computed separately. One way to compute the medium flux is to find a suitable Green's function for the geometry, and then integrate the normal derivative of Green's function with the medium charges. A good reference for such work is a paper by Yuan, Bertram, and Bhattacharyya (41). Here the authors used the micromagnetic formulation to study the off-track asymmetry of shielded SAL MR heads, and showed the importance of proper biasing and MR film heights. The micromagnetic method has also been extended to analyze the mechanisms for domain nucleation in MR heads (42).

Micromagnetic analysis has been applied to spin valve devices (43). The magnetic configuration of a spin valve head is shown in Figs. 10(c) and 13. The pinned film's magnetization is held perpendicular to the ABS, whereas the sense film's magnetization is along the long axis of the head at zero field. The medium's field rotates the sense layer's magnetization in a transverse direction. Spin valves generate signals 2 to 3 times larger than SAL or DS MR heads. Spin valve design is more complicated than MR heads since the coupling field (between the pinned and free layer), the demagnetizing field, and the sense current field must sum to a net zero field in the sense layer. Figure 18 shows the magnetization patterns of the pinned and free films obtained from a three-dimensional micromagnetic analysis similar to that reported by Yuan et al. (41).

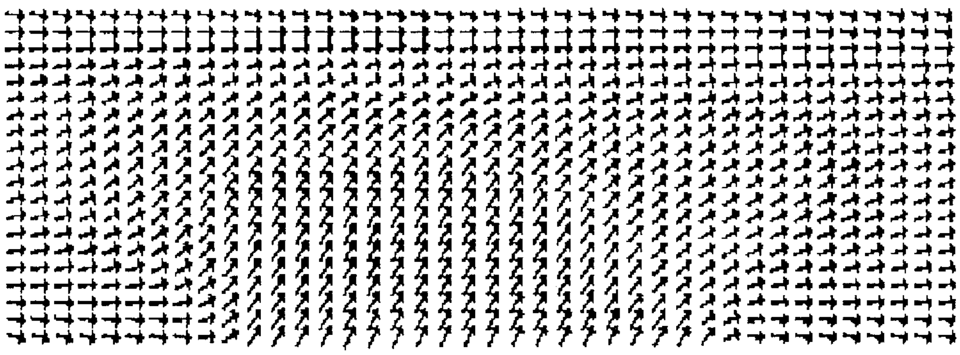
RECORDING HEAD TESTING

Recording heads are tested at various stages in the fabrication process. At wafer level, films used in the fabrication of the head are tested to determine if they have the required magnetic and mechanical characteristics. After devices are patterned, the devices or test structures can be measured to monitor their properties. After fabrication into heads, their output signals are analyzed using equipment similar to actual disk drives. In research and development of recording heads many advanced measurement tools are employed. These are often very labor intensive, and not done on a regular basis, but provide valuable insight into the functioning of prototype recording heads.

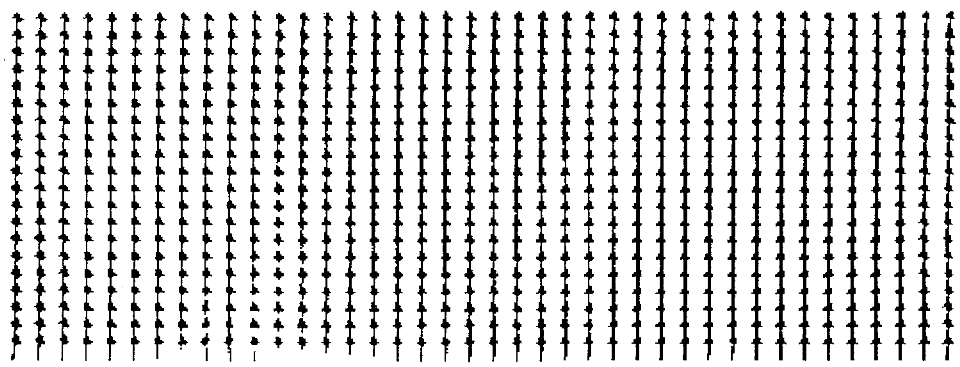
Wafer Level Testing

Sheet films of the head structure are tested using a variety of methods. The magnetization of the pole materials is measured either using an inductive B–H loop tester or a vibrating sample magnetometer. Parameters of importance are: saturation magnetization, related to the total field output of the head; coercivity, related to noise during readback; magnetic anisotropy, related to the efficiency of a write head and the sensitivity of a read head. Permeability is measured as a function of frequency to assess the high frequency capability of the pole materials. Other common measurements include resistivity, magnetostriction, stress, hardness, and film thickness.

For fabrication of an MR head, the magnetoresistance of the film is monitored by varying the drive field and monitoring the resistance of a long bar test structure. This shape gives a uniform direction of current flow in the material, im-



(a)



(b)

Figure 18. Result of a micromagnetic analysis: Micromagnetic models are used to calculate the distribution of magnetic flux in the magnetic layers of a read head. The arrows indicate the local direction of the magnetization in these films. (a) The magnetization of the sense film is rotated by the field emanating from the medium. (b) The magnetization of the pinned film is held perpendicular to the ABS.

portant since the magnetoresistance in an AMR head depends on the angle of the magnetization with respect to the current. A magnetic field often is applied in two orthogonal directions to fully characterize the response of the element. The hard axis curve is obtained for a field applied transverse to the direction of the material anisotropy (defined by device shape or induced anisotropy), and an easy axis curve is obtained for a field applied parallel to the direction of anisotropy. An example of the magnetoresistive response to an applied field for a spin valve film is shown in Fig. 19. In addition to magnetoresistance, such an *R-H* loop provides the coercivities of both the pinned and sense layers, as well as the exchange pinning field and magnetic coupling field between pinned and sense films.

After the films have been patterned into devices, the device response to an applied field is an important tool for determining final head performance. The amount of noise in the device, and the linearity of the response is evaluated. A field response curve is shown in Figure 20 for an unshielded spin valve device. Care must be taken in relating this response to that of a recording head sensing the medium, since the field from a transition excites the MR element in a manner that is different from a uniformly applied field. Nevertheless, this tool is useful to analyze the magnetic characteristics and ascertain whether the MR element is behaving as expected from modeling and if it is magnetically stable.

Fabricated Head Testing

A spin stand test bed is used to evaluate the performance of heads and media in a simulated disk drive operating environment. The heads are in the final assembled state, with the air bearing machined on the slider, and the slider mounted on the head gimbal assembly. The assembly is affixed to the flexure and the head is flown over the disk. Parameters tested include signal amplitude, resolution, signal to noise ratio, and so on. Measured parameters are discussed in detail below. Spin stand testing is used for verification of theory, testing new technologies, evaluating new head designs, assessing the quality of heads or media, and as a failure analysis tool.

A typical spin stand test bed is diagrammed in Fig. 21. The channel electronics include a preamplifier, amplifier and filter, and read write control electronics. With the increasing pressure for higher density and faster data rate, the channel electronics are also required to improve, resulting in stringent specifications for wide bandwidth and low noise. The migration to MR technology in disk drives precipitated the introduction of a new family of preamps with bandwidths beyond 100 MHz and input noise as low as 0.45 $nV/Hz^{1/2}$. The read channel electronics on the test stand can also include a filter, equalizer, and circuitry to provide signals for time domain measurements. Spin stand testers typically are able to do both parametric tests and bit error rates (BER). An example of an output waveform from a spin stand tester is shown in Fig. 22 for an isolated transition in the medium. The readback waveform for a series of isolated transitions is shown in Fig. 23.

Several types of tests were designed to determine the performance of either the disk or the head, although frequently the measurement results are the combination of both head

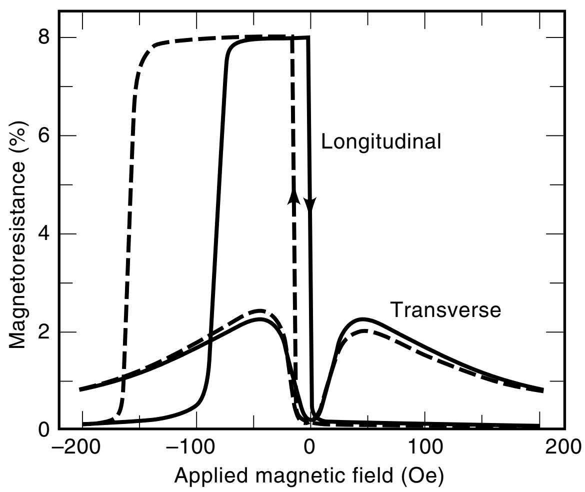


Figure 19. Uniform field response of a spin valve film: The percentage change in resistance is plotted vs. field, applied both parallel (longitudinal) and perpendicular (transverse) to the pinned layer's magnetization. Refer first to the longitudinal response. For negative fields greater than the pinning exchange field (here, $H_X \sim -125$ Oe), the magnetization of both layers are parallel to the negative field direction, and the resistance is low. As the field drops below H_X, the pinned layer's magnetization ($\mathbf{M}_{PL}$) switches back, while the sense layer's magnetization ($\mathbf{M}_{SL}$) still points in the negative field direction. $\mathbf{M}_{PL}$ and $\mathbf{M}_{SL}$ are antiparallel and the resistance is high. As the field becomes positive, the $\mathbf{M}_{SL}$ also switches. $\mathbf{M}_{PL}$ and $\mathbf{M}_{SL}$ are again parallel, resulting in the low resistance state. For the transverse curve, at low applied fields, $\mathbf{M}_{SL}$ rotates perpendicular to $\mathbf{M}_{PL}$. The magnetoresistance increases slower since $\mathbf{M}_{SL}$ is rotated perpendicular to the magnetic anisotropy direction; its magnitude is lower since the maximum angle between $\mathbf{M}_{SL}$ and $\mathbf{M}_{PL}$ is 90 degrees. The resistance decreases with higher fields as $\mathbf{M}_{PL}$ is also rotated, and the magnetizations become parallel again.

and disk properties. An example is the measurement of the PW_{50} of an isolated pulse. The PW_{50} is the width of the pulse at half amplitude [Eq. (7)] and depends on the read gap of the head, the transition parameter a, thickness δ of the medium, and also head and disk separation d. Separating the roles of the different parameters in determining the PW_{50} is a challenge for the experimentalist.

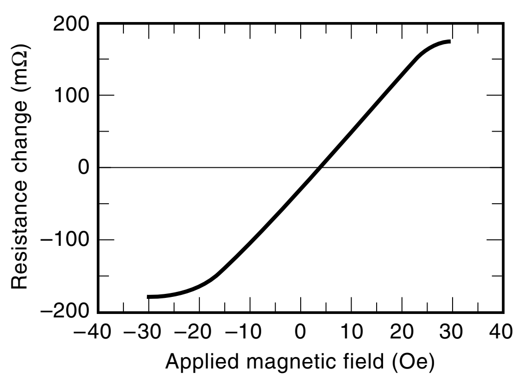


Figure 20. Transfer curve of a spin valve device: The change in resistance (in mΩ) of a spin valve head is plotted. The device is self biased: it has a linear response about zero field, and is single valued with respect to field orientation. The response saturates at low fields, ~25 Oe.

Typical Test Parameters

- *Isolated pulse.* A simple measurement useful in determining the quality of the head/ medium system. The amplitude and PW_{50} are obtained from this measurement (Fig. 22). Pulse shape and the peak curvature are used to predict how the system will behave at higher density.
- *Track average amplitude (TAA).* An average of the readback signal strength from the head and related to parameters such as the head efficiency and the amount and distribution of flux from the recording medium.
- *Resolution.* Defined as the ratio of the 2*f* TAA to the 1*f* TAA. This test relates to the linear density along the track of a head/medium system. 1*f* and 2*f* refer to the frequencies used to write the data.
- *Overwrite (OW).* Measures the ability of the head/medium system to erase previous data by writing new data over it. Expressed in dB, the overwrite value is the ratio of the 1*f* signal before and after being overwritten with a 2*f* signal. This parameter is important because any remaining data will become coherent noise and will degrade the readback signal.
- *Roll off curve.* Multiple TAA measurements made over a range of linear density (Fig. 24) at sufficient write current to ensure saturation of the medium. The amplitude of the TAA decreases at higher transition densities because of interactions between adjacent pulses during both write and read processes.
- *Signal to noise ratio (SNR).* Relates to the medium noise in the disk. Figure 25 is an example of SNR measurement of a thin film disk. It shows the effect of noise increasing and signal decreasing as density increases.
- *Amplitude modulation.* The amount of low frequency modulation around the track, expressed as a percentage of TAA. It relates to the mechanical and magnetic circumferential uniformity of the disk.
- *Track profile.* The TAA measurement as the head is displaced across a written track. This test is to determine the track density ability of the head.

With the emergence of MR head technology, more extensive tests are required to ensure quality and performance. Problems specific to MR heads are: (1) baseline shift, where the reference voltage of the head shifts between measuring positive and negative pulses; (2) amplitude and baseline popping, where Barkhausen noise produces voltage spikes in the output; and (3) pulse height asymmetry of positive and negative signals, due to the nonlinear nature of the transfer curve.

The MR head is also sensitive to the field at the trackedge, and the response in this region is characterized by measuring the cross-track profile. The response of the head at the edge of the track is important for determining the position of the head during tracking, and a linear response as a function of cross-track position is desired. In addition, a more careful look at the cross-track profile, called the microtrack profile, gives information on the response uniformity of the sensor in the active area. These results indicate whether the MR element is in a single or multidomain state. For more details on these and other testing parameters, the reader is referred to standards published by the *International Disk Drive Equipment and Materials Association* (IDEMA) (44).

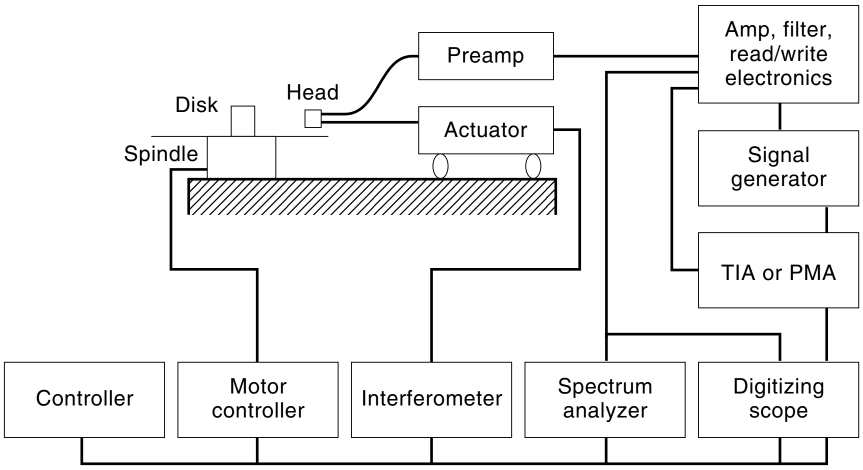


Figure 21. Schematic of a spin stand tester: The actuator positions the head over the disk, which is rotated by the spindle. The rotation speed is dictated by the motor controller, the head position is monitored by the interferometer. The head output is run through a preamplifier, amplifier, and filter. The signal generator is used to write information on the disk. The time interval analyzer (TIA) and phase margin analyzer (PMA) are used to assess the window margin of the bit error rate. The digitizing scope plots the output of the head, and the spectrum analyzer determines the features of the output pulses.

Advanced Measurement Methods

Magnetic properties and the signal readback are only two of the aspects monitored in characterizing recording heads. Comprehensive performance evaluation of a recording head also includes characterizing its flying behavior over the disk. The flying height, the spacing between the head and the medium, is measured using a method based on optical interferometry. Other optical techniques provide pictures of the curvature of the entire surface. Atomic force microscopy is used to provide detailed maps of the air bearing region. This gives important information on the amount of pole tip recession (how far the element is recessed relative to the encapsulating dielectric at the air bearing surface) that occurs during polishing of the head.

Characterization of magnetic domains in the write heads and the sense elements of MR heads is an area of continuing improvements in resolution and frequency response. Bitter fluid methods were initially used to decorate domain walls but this technique suffers from a lack of resolution, and is not dynamic. Kerr microscopy (45), where the polarization of reflected light is rotated by the magnetization of the domains, has long been a standard tool for imaging domains and for obtaining magnetization versus field information. However, this method is limited by the resolution of the light. This limitation has inspired novel measurement techniques based on electron microscopes to probe magnetic phenomena at smaller and smaller dimensions; for example, scanning electron microscopy with polarization analysis (SEMPA) (46), coherent Foucault imaging (47), and Lorentz microscopy (48). Methods utilizing synchrotron X rays are also being developed (49), providing not only high resolution but also element specific information.

New methods also have been developed to study the field distribution surrounding the write poles. By placing a thin magnetic film just above the ABS of a write head, Kerr microscopy can be used to sense the resulting magnetization pattern (50) when the write coil is energized. This method has been refined for use at high frequencies with pulsed lasers, and high resolution with solid immersion lenses. Another method uses microloops to sense the field inductively (51).

FUTURE DIRECTIONS

The growth in the areal density of storage products necessitates continuous improvements in recording heads. Scaling down the critical dimensions of the recording system will provide some improvement. Reduction in size will not be easy, as the dimensional tolerances become increasingly hard to maintain in manufacturing. For instance, a ten percent tolerance in read width, while easy to specify with trackwidths of ten

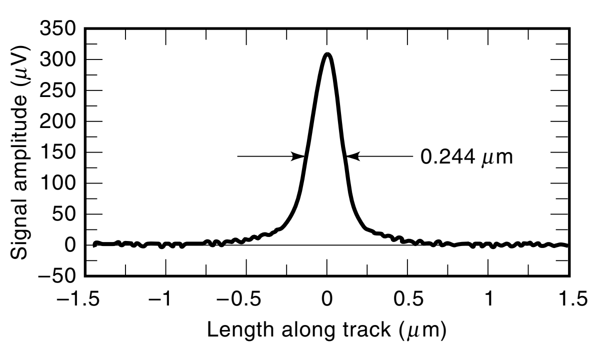


Figure 22. Response of a dual stripe MR recording head to a single transition in the medium: Signal amplitude (μV) is plotted vs. the length along the track (μm). The signal is averaged many times to remove medium and electronic noise. The pulse shape is nearly Lorenzian, with a PW_{50} of 0.224 μm.

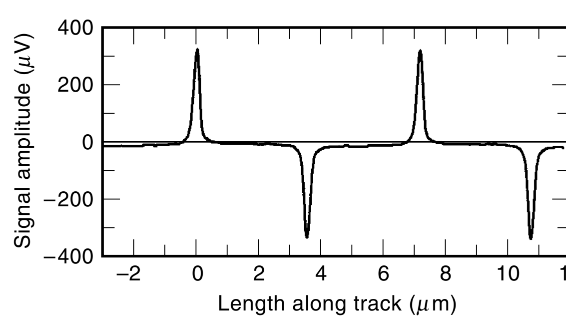


Figure 23. Response of a dual stripe MR recording head to multiple transitions in the medium: Signal amplitude (μV) is plotted vs. the length along the track (μm). Pulses for positive and negative field transitions are very symmetrical.

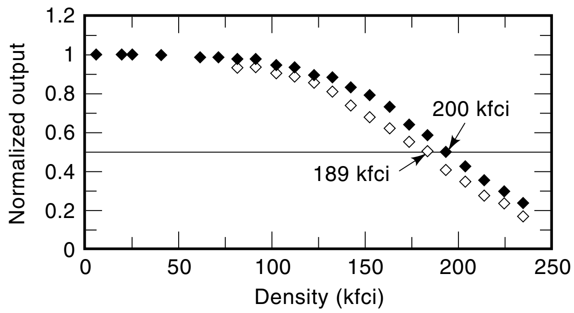


Figure 24. Roll off curve: Normalized signal output of the same head is plotted as a function of density (kilo-flux changes per inch) for two disks with differing coercivity and medium thickness. Heads operate in the region of 50% to 100% of maximum output. The density cutoff of a head depends on the media characteristics.

micrometers, becomes much more difficult at submicron dimensions. Advances in photolithography will be necessary to fabricate smaller and smaller heads.

New materials, such as the GMR materials, will provide some of the increase in head output required to read smaller bits. Major efforts are underway to invent new MR devices, such as ones based on colossal MR materials or on spin tunneling junctions (52). Detailed understanding of the magnetic properties of small structures is essential since the amount of magnetic material in either the sensor or in a recorded bit becomes minute. Averaging of properties is no longer sufficient to produce a clean response. Other active areas of research are on high moment and high frequency soft materials for write heads, and materials with high thermal conductivity and thermal stability for use at high current densities in read heads.

Reduction in the flying height of the recording head over the medium is reaching physical limitations. This eliminates the possibility of increasing areal density by reducing the bit length; as a result, increases in areal density will soon come from reducing the track width. This will provide challenges to servo techniques (methods used to stay on track), and new approaches will be needed. Some possibilities are based on micromachining servo tracks on the disk, or on merging technologies such as optical servoing with a conventional head.

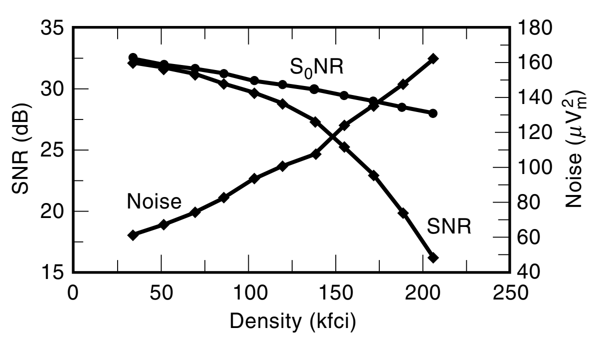


Figure 25. Effect of recording density on signal to noise ratio (SNR): SNR and noise are plotted vs. recording density. The signal amplitude decreases (see Fig. 24) as noise increases with density. The combined effect gives a precipitous drop in the SNR with increasing density. A parameter that is insensitive to the effect of the gap length and flying height is S_0NR and is the SNR as referenced to the maximum signal amplitude at low recording densities.

Magnetic media may evolve into new areas, resulting in redesigned recording heads. For instance, media with magnetization oriented perpendicular to the substrate plane are attractive at high densities. Alternatively, a patterned medium is attractive to overcome the interaction between bits. These changes have the potential to push recording densities to 100 Gbit/in.^{2} and beyond, necessitating novel approaches to positioning the head and reading and writing the information. The evolution of recording heads during the past several decades has been impressive. In the future, the demands of the information storage industry ensure that recording heads will continue to evolve into even more sophisticated devices.

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