



Magnetic Information Storage Technology

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The cover page illustrates a hard disk drive used in modern computers. Hard disk drives are the most widely used information storage devices. The block diagram shows the principle of the state-of-the-art disk drives. Any information such as text files or images are first translated into binary user data, which are then encoded into binary channel data. The binary data are recorded in magnetic disks by a write head. For example, the magnetization pointing to the right (or left) represents "1" (or "0"). The magnetization pattern generates a voltage waveform when passing underneath a read head, which could be integrated with the write head and located near the tip of the stainless suspension. The voltage waveform is then equalized, i.e., reshaped into a proper form. This equalization step, along with a so-called maximum likelihood detection algorithm, allows us to detect the binary channel data with a high reliability. The trellis diagram shown with 16 circles and 16 arrows is the foundation of maximum likelihood detection. The detected binary channel data are then decoded back to the binary user data, which are finally translated back to the original information.

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Magnetoresistive Heads

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In the beginning of the 1990s the annual compound growth rate of areal densities in hard disk drives changed from ~30% to ~60%, largely thanks to the introduction of magnetoresistive (MR) read heads in drives. This revolution was first lead by IBM, and gradually followed by the entire data storage industry. Although inductive read head technology was extended to recording densities that were never thought possible, MR heads showed a clear advantage in read signal amplitude, and a demonstrated extensibility to much higher densities because of the discovery of giant magnetoresistance (GMR). It is now widely accepted that future growth in recording densities will be met by advanced MR heads and GMR heads.

This chapter examines the basic principle and designs of MR heads, with an emphasis on anisotropic MR (AMR) heads. The widely practiced biasing schemes to linearize the MR sensor and to eliminate Barkhausen noise are discussed. Small signal analysis of MR sensors will also be given. Reciprocity principle and transmission line model will be applied to MR heads. The practical engineering issues of MR heads such as side read asymmetry, readback nonlinearity, baseline shift, thermal asperity, and electrostatic discharge (ESD) sensitivity, and MR head fabrication process will be introduced. Since the GMR materials and head technology is still rapidly evolving, only a brief discussion is given. The chapter ends with an introduction to spin-dependent tunneling junction which may be used in the proposed tunneling MR (TMR) heads.

6.1 ANISOTROPIC MAGNETORESISTIVE (AMR) EFFECT

Due to spin-orbit coupling, some ferromagnetic materials display *anisotropic* resistivity, i.e., the resistivity is a function of the orientation between current and the magnetization.¹ Consider the configuration as shown

in Fig. 6.1. According to Ohm's law, the electrical fields parallel and perpendicular to the magnetization are as follows:

$$E_{\parallel} = \rho_{\parallel} j_{\parallel}, \quad E_{\perp} = \rho_{\perp} j_{\perp},$$

where

$$j_{\parallel} = j \cos \theta, \quad j_{\perp} = j \sin \theta.$$

The electrical field $\vec{E}$ is not parallel to the current density $\vec{j}$. Its component along the current direction is

$$E_j = E_{\parallel} \cos \theta + E_{\perp} \sin \theta = \rho_{\parallel} j \cos^2 \theta + \rho_{\perp} j \sin^2 \theta.$$

The resistivity along the current direction is

$$\begin{aligned} \rho_j &\equiv \frac{E_j}{j} = \rho_{\parallel} \cos^2 \theta + \rho_{\perp} \sin^2 \theta \\ &= (\rho_{\parallel} - \rho_{\perp}) \cos^2 \theta + \rho_{\perp} \\ &= \rho_0 + \Delta \rho_{\max} \cos^2 \theta, \end{aligned} \quad (6.1)$$

where

$$\rho_0 \equiv \rho_{\perp}, \quad \Delta \rho_{\max} \equiv \rho_{\parallel} - \rho_{\perp}.$$

The value of $\Delta \rho_{\max} / \rho_0$ is often called the magnetoresistance (MR) ratio. In general, the resistivity of an anisotropic MR material will vary according to a cosine square function if we rotate the magnetization with respect to the current direction or rotate the current with respect to the magnetization direction.

The MR ratio of a ferromagnetic film depends on film thickness and deposition method. The most commonly used MR sensor material today is the permalloy at a composition near 81% Ni and 19% Fe. It has near-zero magnetostriction, low crystalline anisotropy, and high-saturation magnetization, thus, it has a very high intrinsic permeability of >2000.

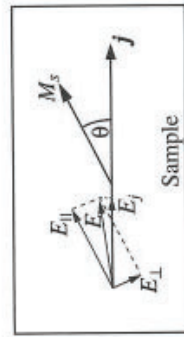


FIGURE 6.1. Electrical resistance anisotropy between the parallel and normal directions of magnetization.

The electrical and magnetic properties of permalloy, like many other magnetic materials, are dependent upon the film thickness and deposition method. For ion beam sputtered $\text{Ni}_{81}\text{Fe}_{19}$ alloy,² the typical MR ratios at selected thicknesses are listed in Table 6.1. The typical resistivity is 20–25 $\mu\Omega\cdot\text{cm}$, and it increases at very small thicknesses when surface scattering and grain size become important factors in electrical conduction. It is reported that ion beam deposited permalloy films have somewhat higher MR ratios than conventionally sputtered ones, particularly when the films are thinner than 200 Å.

6.2 MAGNETORESISTIVE READ HEAD AND BIAS SCHEMES

The concept of the MR head was first proposed by Hunt in 1971.³ A schematic of magnetoresistive (MR) head and its response to applied field (transfer curve) are shown in Fig. 6.2. The MR head is a magnetic flux-sensing device that responds to the vertical field above the magnetic medium averaged over the MR element height, D . If the sense current, I_s , is kept constant, then the change in resistance due to the vertical applied field results in a change in voltage across the element.

Note that the slope of the transfer curve at $H = 0$ is zero, namely, the MR element is not sensitive to an applied field. Therefore, a bias field of H_b is required for the MR element to operate at the maximum slope of the transfer curve. Since

$$\rho = \rho_0 + \Delta \rho_{\max} \cos^2 \theta,$$

$$\frac{\partial \rho}{\partial \theta} = -\Delta \rho_{\max} \sin(2\theta),$$

the bias angle should be $\theta_0 = 45^\circ$ for the slope to be maximum. The required bias field should be perpendicular to the easy axis and sense current, so this is called *transverse biasing*. The skirts in the transfer curve

TABLE 6.1. Typical MR Ratios, Sheet Resistance, and Resistivity of Permalloy Deposited on a Ta Seed Layer By Ion Beam Sputtering^a

Thickness (Å)	250	150	100	50
MR ratio $\Delta \rho_{\max} / \rho_0$ (%)	2.6	2.3	2.0	1.2
Sheet resistance R_s (Ω)	8.45	15.2	23.5	62.5
Resistivity $\rho_0 = R_s t$ ($\mu\Omega\cdot\text{cm}$)	21	23	24	31

^aTa sheet resistance is $\sim 450 \Omega$.

are due to nonuniform demagnetization field in the MR element and easy axis (EA) dispersion.

Compared with inductive read heads, one of the major characteristics of MR read heads is that it reproduces recording signals which are fundamentally independent of head-medium relative speed. Furthermore, an MR element in Fig. 6.2 will sense not only the transition underneath the element, but also the neighboring transitions. Therefore, the MR element need to be shielded by high-permeability shields. Here we will consider

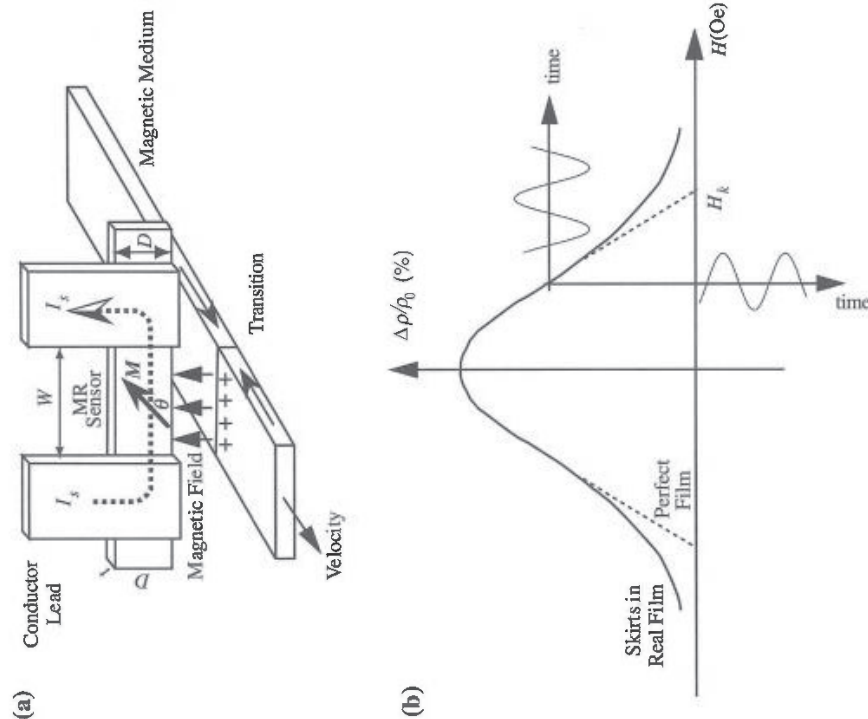


FIGURE 6.2. Schematic of MR head (a) and its transfer curve (b).

unshielded MR heads as shown in Fig. 6.2. The shielded MR heads will be discussed later in Section 6.3.

The readback voltage of an MR head depends on the magnetic field in the MR element from a recording medium, which rotates the magnetization of the MR element. If the magnetic element is biased at an angle, θ_0 , then the readback voltage is

$$V(\vec{x}) = I \Delta R = JW \Delta \rho_{\max} (\cos^2 \theta - \cos^2 \theta_0), \quad (6.2)$$

where W is the length of the MR element (trackwidth) defined by the conductor leads, $\vec{x} = vt$ is the relative head-medium position, and J is the current density, assumed to be uniform across the MR element. Note that the physical width of the MR element must be equal to or greater than its trackwidth. Since θ and θ_0 are normally not uniform across the MR element, the readback voltage can be approximately represented by an average $\langle \rangle$ over the film plane (y, z):

$$\begin{aligned} V(\vec{x}) &= I \Delta R = JW \Delta \rho_{\max} \langle \cos^2 \theta \rangle - \langle \cos^2 \theta_0 \rangle \\ &= JW \Delta \rho_{\max} \cdot \Delta \langle \cos^2 \theta \rangle. \end{aligned} \quad (6.3)$$

For example, consider an MR element with a track width of $1 \mu\text{m}$ and a thickness of $150 \text{ \AA}$. The sense current density is $\sim 5 \times 10^7 \text{ A/cm}^2$ (mainly limited by the Joule heating and electromigration of the MR element). If $\Delta(\cos^2 \theta) = 1/4$, (which is a half of the maximum value to maintain linearity), then a zero-to-peak readback voltage of $\sim 575 \mu\text{V}$ is obtained.

The idea of the MR head is simple and elegant, yet the design and mass production of MR heads require sophisticated engineering work and micromagnetic (or finite element) modeling. For pedagogical reasons, we will focus on analytical analyses of MR heads in the following sections. *Quiescent analysis* in the absence of medium field signal is carried out to assess if the MR element is biased properly. *Dynamic analysis* in the presence of the medium field signal is necessary to evaluate the MR head response and performance. In this regard, *small-field signal analysis* near the bias point (as determined by the quiescent analysis) is particularly useful to obtain the field sensitivity of MR heads. Neal Bertram has used linear signal analysis to calculate MR head readback signal based on a proper extension to the small field signal analysis.⁴

The sensitivity of the MR head readback voltage to a small field signal H_{sig} is

$$\begin{aligned} \frac{\partial V(\vec{x})}{\partial H_{\text{sig}}} &= -2JW \Delta \rho_{\max} \cos \theta_0 \sin \theta_0 \frac{\partial \theta}{\partial H_{\text{sig}}} \\ &= -2JW \Delta \rho_{\max} \sin \theta_0 \frac{\partial(\sin \theta)}{\partial H_{\text{sig}}}. \end{aligned} \quad (6.4)$$

Then, the average small-signal sensitivity over the MR element is

$$\left\langle \frac{\partial V(\vec{r})}{\partial H_{sig}} \right\rangle = -2JW \Delta \rho_{max} \left\langle \sin \theta_0 \frac{\partial(\sin \theta)}{\partial H_{sig}} \right\rangle. \quad (6.5)$$

6.2.1 Transverse bias of magnetoresistive heads

In this section we will analyze the transverse biasing schemes and read-back sensitivity of unshielded MR heads.

Magnetoresistive heads can be transversely biased by a permanent magnet or a soft adjacent layer (SAL). Either biasing scheme generally produces nonuniform bias fields, but in simple analytical models we can approximate that a fixed average bias field acts on an MR element. If the external transverse field is H_t and the exchange coupling energy can be neglected, then the magnetic energy per unit volume for a very thin MR element ($t \ll D \ll W$) is

$$\begin{aligned} E &= -\mu_0 M_s H_t \sin \theta + K_u \sin^2 \theta + \frac{1}{2} \mu_0 \vec{M}_s \cdot \vec{H}_d \\ &= \mu_0 M_s \left(-H_t \sin \theta + \frac{1}{2} H_k \sin^2 \theta + \frac{1}{2} N_{dy} M_s \sin^2 \theta \right), \end{aligned} \quad (6.6)$$

where the first term is the magnetic energy due to the external field, the second term is the intrinsic anisotropy energy, and the last term is the demagnetizing energy. The orientation of the magnetization is determined by

$$\partial E / \partial \theta = 0,$$

which yields

$$\sin \theta = \frac{H_t}{H_k + N_{dy} M_s}. \quad (6.7)$$

If the external transverse field can be represented as a uniform signal field in addition to a bias field over the MR element:

$$H_t = H_{sig} + H_{bias},$$

then the magnetization orientation is ($H_{dy} \equiv N_{dy} M_s$)

$$\sin \theta = \frac{H_{sig} + H_{bias}}{H_k + N_{dy} M_s} = \frac{H_{sig} + H_{bias}}{H_k + H_{dy}}. \quad (6.8)$$

Transverse Demagnetizing Factor. Assuming that the MR element is very long in the z -direction (across track), the demagnetizing factor along the x -direction (down track, perpendicular to the thickness) is⁵

$$N_{dx} = \frac{1}{\pi} \left[\tan^{-1} \left(\frac{D-2y}{t} \right) + \tan^{-1} \left(\frac{D+2y}{t} \right) \right], \quad (6.9)$$

where D is the MR element height. Then the demagnetizing factor in the y -direction (height) is

$$\begin{aligned} N_{dy} &= 1 - N_{dx} \quad (\because N_{dz} \approx 0) \\ &= \frac{1}{\pi} \left[\tan^{-1} \left(\frac{t}{D-2y} \right) + \tan^{-1} \left(\frac{t}{D+2y} \right) \right]. \end{aligned} \quad (6.10)$$

At the center of MR element with a stripe height of $D = 1 \mu\text{m}$ and a thickness of $200 \text{ \AA}$, $N_{dy} = \frac{2}{\pi} \tan^{-1} \left(\frac{t}{D} \right) \approx 0.013$, $H_{dy} \approx 130 \text{ Oe}$.

The average demagnetizing factor along the MR element height (y -direction) can be calculated based on a micromagnetic model of the MR element.⁶ The MR element under bias reveals a nonuniform magnetization distribution. Namely, the magnetization near the edge tends to align with the film surface as if a portion of the MR element with a distance of Δ ($\sim 75 \text{ nm}$ for $200 \text{ \AA}$ NiFe) from each edge were "dead" with little response to an applied signal. Therefore, the average of N_{dy} is performed over $-D/2 + \Delta$ to $D/2 - \Delta$. Typically $t \ll D/2$, then

$$\begin{aligned} \langle N_{dy} \rangle &= \frac{1}{D} \int_{-D/2+\Delta}^{D/2-\Delta} N_{dy} dy \approx \frac{1}{\pi D} \int_{-D/2+\Delta}^{D/2-\Delta} \left(\frac{t}{D-2y} + \frac{t}{D+2y} \right) dy \\ &= \frac{t}{2\pi D} (\ln|y + D/2| - \ln|y - D/2|) \Big|_{-D/2+\Delta}^{D/2-\Delta} = \frac{t}{\pi D} \ln \left(\frac{D-\Delta}{\Delta} \right). \end{aligned} \quad (6.11)$$

For example, if $t = 200 \text{ \AA}$, $D = 1 \mu\text{m}$, $\Delta = 750 \text{ \AA}$, $M_s = 800 \text{ kA/m}$ for permalloy, then $\langle N_{dy} \rangle \approx 0.016$, and $\langle H_{dy} \rangle = \langle N_{dy} \rangle M_s \approx 12.8 \text{ kA/m} = 160 \text{ Oe}$. The average demagnetizing field is more than 20% greater than the demagnetizing field at the center of the MR element.

The demagnetizing field is much larger than the intrinsic anisotropy field of the permalloy film, so H_k can be neglected and Equation (6.8) becomes

$$\sin \theta \equiv \frac{H_{sig} + H_{bias}}{H_{dy}}. \quad (6.12)$$

The resistivity of the MR element is

$$\rho = \rho_0 + \Delta\rho_{\max} \left[1 - \left(\frac{H_{\text{sig}} + H_{\text{bias}}}{H_{dy}} \right)^2 \right], \quad (6.13)$$

where

$$H_{\text{bias}} \approx H_{dy} \sqrt{2} \text{ for } \theta \approx 45^\circ.$$

The small field signal sensitivity of the MR element is

$$\frac{\partial V}{\partial H_{\text{sig}}} = jW \frac{\partial \rho}{\partial H_{\text{sig}}} = jW \frac{\sqrt{2} \Delta\rho_{\max}}{H_{dy}}. \quad (6.14)$$

The average small-signal sensitivity over the MR element is

$$\left\langle \frac{\partial V}{\partial H_{\text{sig}}} \right\rangle \approx jW \frac{\sqrt{2} \Delta\rho_{\max}}{\langle H_{dy} \rangle} = \frac{\sqrt{2} jW \Delta\rho_{\max}}{\langle N_{dy} \rangle M_s}. \quad (6.15)$$

It is very important to recognize that the sensitivity of MR element is greatly influenced by the demagnetizing field, thus by the shape of the MR element.

SAL Transverse Bias. Another approach for transverse biasing is to use a SAL instead of a permanent magnet. This turns out to be the best method for single MR element read heads in engineering practices. As shown in Fig 6.3, the MR element and SAL are assumed to be uniformly magnetized, and they are also assumed to be electrically isolated from each other. The SAL experiences four sources of fields: a demagnetizing field (from its own magnetization), a signal field of H_{sig} , a field H_I due to the sense current, and a magnetostatic coupling field from the MR element. The last one is equal to

$$(1 - \alpha) H_{dy}^{\text{MR}} = (1 - \alpha) N_{dy}^{\text{MR}} M_s^{\text{MR}} \sin \theta_{\text{MR}}, \quad (6.16)$$

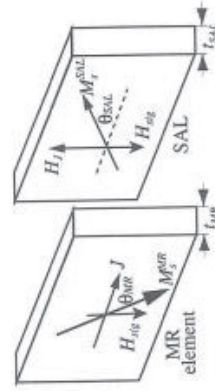


FIGURE 6.3. Schematic of MR element coupled with SAL.

where $(1 - \alpha)$ is the magnetostatic coupling coefficient, and α is the flux leakage factor between the MR element and SAL. From Equation (6.12), we obtain

$$\sin \theta_{\text{SAL}} = \frac{-H_{\text{sig}} + H_I + N_{dy}^{\text{MR}} M_s^{\text{MR}} (1 - \alpha) \sin \theta_{\text{MR}}}{N_{dy}^{\text{SAL}} M_s^{\text{SAL}}}, \quad (6.17)$$

where the minus sign of H_{sig} arises from H_{sig} reference direction being opposite to that of H_I . Likewise, we obtain a relation for the MR element (it is not subjected to a field due to current)

$$\sin \theta_{\text{MR}} = \frac{H_{\text{sig}} + N_{dy}^{\text{SAL}} M_s^{\text{SAL}} (1 - \alpha) \sin \theta_{\text{SAL}}}{N_{dy}^{\text{MR}} M_s^{\text{MR}}}. \quad (6.18)$$

In the absence of signal field, the MR element is supposed to be biased at $\theta_{\text{MR}} \approx 45^\circ$, and the SAL should be saturated, i.e., $\theta_{\text{SAL}} = 90^\circ$. If $\alpha = 0$, then Equation (6.18) leads to the following relation:

$$\frac{N_{dy}^{\text{SAL}} M_s^{\text{SAL}}}{N_{dy}^{\text{MR}} M_s^{\text{MR}}} \approx \frac{t_{\text{SAL}} M_s^{\text{SAL}}}{t_{\text{MR}} M_s^{\text{MR}}} \approx \sin 45^\circ = \frac{1}{\sqrt{2}}. \quad (6.19)$$

This equation can be understood as the magnetic flux along the y -direction is conserved between the MR element and SAL since zero flux leakage is assumed. If permalloy is used for both MR element and SAL, then the SAL thickness should be ~ 0.707 times the MR element thickness.

If the SAL does not stay in saturation, then we can solve θ_{MR} from the coupled equations of θ_{MR} and θ_{SAL} (6.17) and (6.18). Cancel θ_{SAL} we obtain an equation of θ_{MR} :

$$\begin{aligned} \sin \theta_{\text{MR}} &= \frac{H_{\text{sig}} + (1 - \alpha) [-H_{\text{sig}} + H_I + N_{dy}^{\text{MR}} M_s^{\text{MR}} (1 - \alpha) \sin \theta_{\text{MR}}]}{N_{dy}^{\text{MR}} M_s^{\text{MR}}} \\ &= \frac{\alpha H_{\text{sig}} + (1 - \alpha) H_I + N_{dy}^{\text{MR}} M_s^{\text{MR}} (1 - \alpha)^2 \sin \theta_{\text{MR}}}{N_{dy}^{\text{MR}} M_s^{\text{MR}}}. \end{aligned}$$

Note that $1 - (1 - \alpha)^2 \approx 2\alpha$ for $\alpha \ll 1$, then

$$\sin \theta_{\text{MR}} \approx \frac{H_{\text{sig}}}{2N_{dy}^{\text{MR}} M_s^{\text{MR}}} + \frac{H_I}{2\alpha N_{dy}^{\text{MR}} M_s^{\text{MR}}}. \quad (6.20)$$

Compared with the saturated SAL, the field sensitivity of the MR head with unsaturated SAL is reduced by a factor of 2 since the energy from the signal field is spent on rotating the magnetization in both MR element and SAL. This situation must be absolutely avoided in the design of the single element SAL-biased MR heads. This means that the sense current must

be large enough so that the SAL stays saturated. The required condition is

$$\frac{H_j + N_{dy}^{MR} M_s^{MR} (1 - \alpha) \sin \theta_{MR}}{N_{dy}^{SAL} M_s^{SAL}} \geq 1, \quad (6.21)$$

which, when MR element is biased at 45° leads to

$$H_j \geq \alpha N_{dy}^{SAL} M_s^{SAL} \approx \frac{2\alpha t_{SAL}}{\pi D_{SAL}} M_s^{SAL}. \quad (6.22)$$

According to Ampere's law, the maximum field generated by the sense current is

$$H_j \approx I t_{MR} / 2, \quad (6.23)$$

then

$$I \geq \frac{4\alpha t_{SAL}}{\pi D_{SAL} t_{MR}} M_s^{SAL}. \quad (6.24)$$

For example, if $\alpha \approx 0.2$, $t_{SAL}/t_{MR} \approx 0.7$, $D_{SAL} \approx 1 \mu\text{m}$, $M_s^{SAL} \approx 8 \times 10^5 \text{ A/m}$, the minimum required sense current density is $1.4 \times 10^{11} \text{ A/m}^2$ ($1.4 \times 10^7 \text{ A/cm}^2$), which is lower than the typical sense current density used in MR heads ($\sim 5 \times 10^7 \text{ A/cm}^2$).

Dual-Stripe Biasing. In another transverse biasing scheme called the *dual-stripe* MR head, two *identical* MR elements are closely spaced but electrically isolated. Transverse biasing is achieved through magnetostatic coupling between the two MR elements and sense currents, as shown in Fig. 6.4. Similar to the SAL MR heads, we have the following relations:

$$\begin{aligned} \sin \theta_{MR1} &= \frac{H_{sig} + H_j + N_{dy}^{MR} M_s^{MR} (1 - \alpha) \sin \theta_{MR2}}{N_{dy}^{MR} M_s^{MR}}, \\ \sin \theta_{MR2} &= \frac{-H_{sig} + H_j + N_{dy}^{MR} M_s^{MR} (1 - \alpha) \sin \theta_{MR1}}{N_{dy}^{MR} M_s^{MR}}. \end{aligned} \quad (6.25)$$

If both the MR elements are biased at $\theta_{MR1} \approx \theta_{MR2} \approx 45^\circ$, then the required condition is that

$$\frac{1}{\sqrt{2}} = \frac{H_j + N_{dy}^{MR} M_s^{MR} (1 - \alpha) / \sqrt{2}}{N_{dy}^{MR} M_s^{MR}},$$

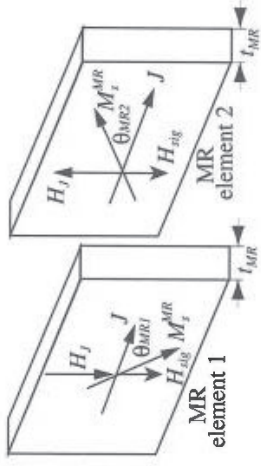


FIGURE 6.4. Schematic of dual-stripe MR heads.

or

$$H_j = \alpha N_{dy}^{MR} M_s^{MR} / \sqrt{2}. \quad (6.26)$$

Similar to the derivation in SAL MR heads, the required sense current density is

$$I \approx \frac{4\alpha}{\sqrt{2} \pi D_{MR}} M_s^{MR}. \quad (6.27)$$

If $\alpha \approx 0.2$, $D_{MR} \approx 8 \times 10^5 \text{ A/m}$, the required sense current density is about $1.4 \times 10^{11} \text{ A/m}^2$ ($1.4 \times 10^7 \text{ A/cm}^2$), which is the same as the minimum sense current density in the corresponding SAL MR heads shown earlier in Equation (6.24).

A major difference between the dual stripe head and the SAL head is that the former requires a certain level of sense current density. Excessive sense current density will "overbias" the two MR elements. In addition, two MR elements must be matched very well. Therefore, the design for dual stripe MR heads is more constrained than for SAL MR heads. On the other hand, the subtraction of the voltage drop of the two MR elements allows differential detection of magnetic field, which is advantageous in rejecting common mode signal and doubling field sensitivity.

6.2.2 Longitudinal bias of magnetoresistive heads

If the MR element is in a multidomain state, it will produce *Barkhausen noise* when subjected to an applied field. This is a major challenge in the manufacture of MR heads. To avoid Barkhausen noise, the MR head is

required to be in a single domain state. Therefore, a longitudinal bias field along the EA (current direction) of the MR element is needed. There are two popular longitudinal bias schemes for MR heads: *exchange bias* and *hard bias*.

The *design criterion of longitudinal bias* includes: (1) The bias field is large enough to ensure a stable single-domain state; (2) The bias field is small enough not to "stiffen" magnetization response to the applied field; (3) The materials used must be corrosion resistant; (4) Ease of fabrication.

Exchange Bias. Exchange bias utilizes the exchange coupling between a ferromagnet (MR element) and an antiferromagnet (or ferrimagnet) such as FeMn, NiMn, IrMn, NiO, and TbCo. When the antiferromagnet is properly deposited next to the ferromagnet, the hysteresis loop of the ferromagnet is shifted by H_{ex} , which is called the exchange bias field, as shown in Fig. 6.5. If the exchange bias field is large enough ($H_{ex} > H_c$), the ferromagnet will be in a saturated state, or single-domain state. For a MR element longitudinally biased by a *uniform exchange bias*, and transversely biased by a uniform field H_t , the magnetic energy per unit volume is

$$\begin{aligned} E &= -\mu_0 M_s^{MR} H_t \sin \theta + K_u \sin^2 \theta + \frac{1}{2} \mu_0 \vec{M}_s^{MR} \cdot \vec{H}_d - \mu_0 M_s^{MR} H_{ex} \cos \theta \\ &= \mu_0 M_s^{MR} \left(-H_t \sin \theta - H_{ex} \cos \theta + \frac{1}{2} H_k \sin^2 \theta + \frac{1}{2} N_{dy}^{MR} M_s^{MR} \sin^2 \theta \right). \end{aligned} \quad (6.28)$$

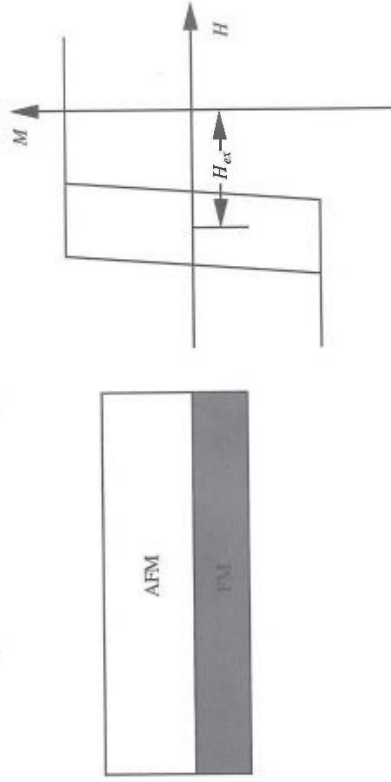


FIGURE 6.5. Exchange-biased ferromagnet (left) and its hysteresis loop (right). The unidirectional anisotropy is called exchange-induced anisotropy. (AFM = antiferromagnet; FM = ferromagnet.)

where θ is the angle between the magnetization and the easy axis (longitudinal direction), and H_d is the demagnetizing field in the MR element. The angle θ can be found by minimizing E :

$$-H_t \cos \theta + H_{ex} \sin \theta + \frac{1}{2} N_{dy}^{MR} M_s^{MR} \sin(2\theta) = 0, \quad (6.29)$$

where the intrinsic induced anisotropy H_k of MR element is neglected. Equation (6.29) will not yield a simple analytical expression for θ . To bias the MR element at $\sim 45^\circ$, the required transverse bias field is

$$H_{t,bias} = H_{ex} + N_{dy}^{MR} M_s^{MR} \sqrt{2}. \quad (6.30)$$

The corresponding small-signal sensitivity near $\theta = \theta_0$ of the exchange-biased MR element can be found by taking the derivative of Equation (6.29) with respect to H_{sig} :

$$\begin{aligned} -\cos \theta_0 + H_{t,bias} \sin \theta_0 \frac{\partial \theta}{\partial H_{sig}} + H_{ex} \cos \theta_0 \frac{\partial \theta}{\partial H_{sig}} \\ + N_{dy}^{MR} M_s^{MR} \cos(2\theta_0) \frac{\partial \theta}{\partial H_{sig}} = 0, \\ \frac{\partial \theta}{\partial H_{sig}} = \frac{\cos \theta_0}{H_{t,bias} \sin \theta_0 + H_{ex} \cos \theta_0 + N_{dy}^{MR} M_s^{MR} \cos(2\theta_0)}. \end{aligned}$$

If $\theta_0 = 45^\circ$, then the small-field sensitivity is

$$\frac{\partial(\sin \theta)}{\partial H_{sig}} = \cos \theta_0 \frac{\partial \theta}{\partial H_{sig}} = \frac{1/\sqrt{2}}{H_{t,bias} + H_{ex}} = \frac{1}{2\sqrt{2} H_{ex} + N_{dy}^{MR} M_s^{MR}}. \quad (6.31)$$

In contrast, in the absence of the exchange bias, the small-field sensitivity of the magnetization orientation is

$$\frac{\partial(\sin \theta)}{\partial H_{sig}} = \frac{1}{N_{dy}^{MR} M_s^{MR}}. \quad (6.32)$$

It is apparent that the excessive H_{ex} significantly reduces the sensitivity of MR element. The exchange bias H_{ex} aligns the magnetization along the positive EA ($\theta = 0$), while the demagnetizing field $N_{dy}^{MR} M_s^{MR}$ aligns the magnetization along the either direction of EA ($\theta = 0$ or π). This seems not drastically different, but uniform exchange bias "stiffens" MR magnetization response more than shape anisotropy by a factor of $2\sqrt{2}$. A clever scheme has been devised to bias MR element by *exchange tabs* at the two

ends of the MR element, as shown in Fig. 6.6, which minimizes the loss of sensitivity.⁷ The tail regions of the MR element under the exchange tabs are pinned to the right, and the middle region (the active read region) defined by the leads is forced into a single domain state due to magnetostatic and exchange interactions. In the absence of the transverse bias, the magnetization of the whole MR element is along the longitudinal direction in a single-domain state. When the magnetization in the middle region is biased at $\sim 45^\circ$, magnetic charges are created in the middle/tail region boundaries, producing a demagnetizing field pointing to the right. This demagnetizing field minus the magnetizing field due to the magnetic charges at the outer boundaries of the tail regions is the longitudinal bias field H_l , which affects the small field sensitivity of the MR element as the exchange field H_{ex} does in the case of uniform exchange bias. However, a proper design of the exchange tabs can make H_l much smaller than H_{ex} , thus enhancing the sensitivity of the MR element.

Hard Bias. A popular longitudinal bias scheme is the *contiguous or abutted junction hard bias*, as shown in Fig. 6.7, which utilizes two hard magnets abutting the MR element along the longitudinal direction.⁸ The hard magnets consist of a hard magnetic layer such as CoPtCr and appropriate

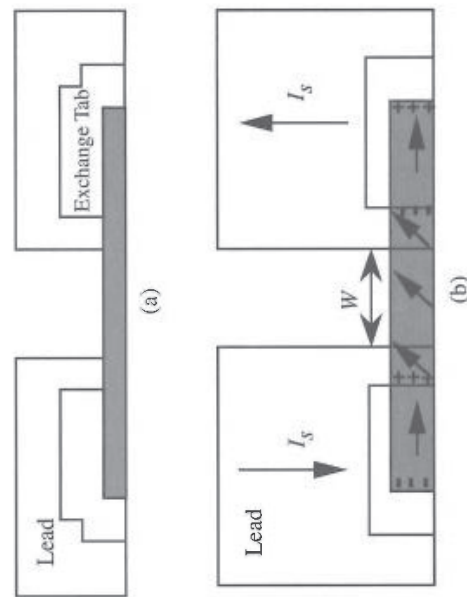


FIGURE 6.6. Cross section (a) and side view (b) of longitudinal bias with exchange tabs, including leads. The lead and exchange tab could be made flush to the middle active read region of the MR element.



FIGURE 6.7. Cross-sectional view of abutted junction hard bias.

under- and/or overlayer for desirable magnetic and electrical properties. The fabrication of the MR head with hard bias will be described later in Section 6.5. The hard magnets are electrically connected to the MR element. The magnetostatic field generated by the hard magnets in the MR element serves as the longitudinal bias field H_l . Similar to exchange-biased AMR head, the small field sensitivity of the abutted junction AMR head is

$$\frac{\partial(\sin\theta)}{\partial H_{sig}} = \frac{1}{2\sqrt{2}H_l + N_{dy}^{MR} M_s^{MR}} \quad (6.33)$$

The thickness and the magnetization of the hard magnetic layer are chosen such that H_l is sufficient to maintain the single-domain state of the MR element, but not excessive to sacrifice its sensitivity. This design is also advantageous in that the hard magnets will not respond to medium field, so side reading of MR element is greatly reduced (Section 6.4.1).

An alternative longitudinal bias scheme is the *overlay hard bias*,⁹ as shown in Fig. 6.8, where the trackwidth is again defined by the leads, similar to the case of exchange tab bias. The tail regions of the MR element are exchange coupled to the hard magnet such that they are pinned to the right. The longitudinal bias field in the middle active read region can be adjusted by controlling the thickness and the magnetization of the hard magnetic overlayer. A variation of this bias scheme is to have a thin



FIGURE 6.8. Cross-sectional view of overlay hard bias.

nonmagnetic spacer between the hard magnetic over-layer and the MR element so that the hard magnets and the MR element are magnetostatically coupled rather than exchange-coupled.¹⁰ The spacer layer helps to attain the large coercivity in the hard magnet, and allows better control of the longitudinal bias field.

6.3 MAGNETORESISTIVE HEAD READBACK ANALYSIS

In addition to proper longitudinal/transverse biasing schemes and a high sensitivity, MR heads must have high-permeability shields to realize a good linear resolution of closely spaced magnetic transitions. This can be simply illustrated in Fig. 6.9 where transition #2 is being detected by the MR element. An unshielded MR will pick up magnetic flux from all three transitions. Since the flux from transition #1 & #3 oppose that of transition #2, the MR signal will be greatly weakened. On the other hand, the shielded MR element will pick up only the flux of transition #2 unless the spacing between the transitions is very close compared with the shield-to-shield gap. Therefore, the shielded MR head has a much higher linear resolution.

As mentioned before, MR heads are *flux-sensing* devices while inductive heads are *flux-derivative-sensing* devices. The former would yield a readback voltage even if there is no relative motion between MR head and magnetic transition. To analyze the spatial variation of the readback voltage, which is completely neglected in *quiescent analysis*, we need to find out how a *shielded* MR head responds to a spatially varying signal

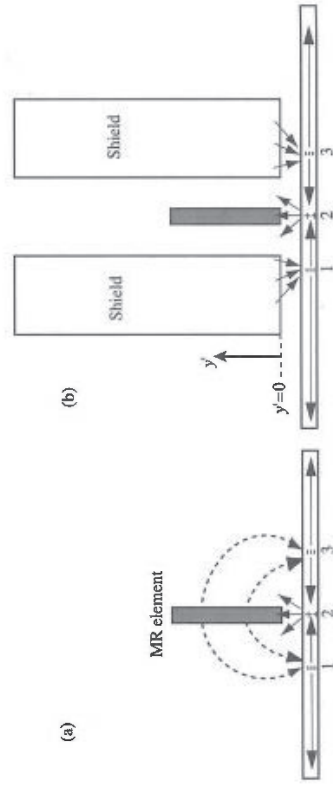


FIGURE 6.9. Unshielded (a) and shielded (b) MR heads.

flux from a magnetic medium. As shown in Section 6.2, the voltage of an MR element under external field is

$$\begin{aligned} V_{MR}(\bar{x}) &= I\Delta R = JW\Delta\rho_{\max} \langle \cos^2\theta - \cos^2\theta_0 \rangle \\ &= -JW\Delta\rho_{\max} \langle \sin^2\theta - \sin^2\theta_0 \rangle. \end{aligned} \quad (6.3)$$

where $\bar{x}$ is the relative position of magnetic medium vs. the MR head, and the average is over the whole active read region of the MR element. This is the formula one would use to calculate the readback voltage directly from the magnetization pattern in the recording medium by micromagnetic modeling or finite element modeling. However, here we do this analytically by using the *reciprocity principle* as we did in analyzing the inductive read process. Note that the $-$ sign in Equation (6.3) depends on whether the bias angle is $+45^\circ$ or -45° . It is not critical in the context of single-pulse analysis.

6.3.1 Reciprocity principle for magnetoresistive heads

The instantaneous magnetization, the quiescent magnetization, and the magnetization change (i.e., signal magnetization) due to signal flux of the MR element are, respectively,

$$M_y = M_s \sin\theta, \quad M_{y0} = M_s \sin\theta_0, \quad M_{y,\text{sig}} = M_y - M_{y0}, \quad (6.34)$$

where M_s is the MR element saturation magnetization. Substituting Equation (6.34) into (6.3),

$$\begin{aligned} V_{MR}(\bar{x}) &= -\frac{JW\Delta\rho_{\max}}{M_s^2} \langle (M_y + M_{y0})(M_y - M_{y0}) \rangle \\ &\approx -\frac{2JW\Delta\rho_{\max}}{M_s^2} \langle M_{y0}M_{y,\text{sig}} \rangle \quad (\text{if } M_{y,\text{sig}} < M_{y0}) \quad (6.35) \\ &= -\frac{2JW\Delta\rho_{\max}}{M_s^2} \frac{1}{D} \int_0^D M_{y0}(y') M_{y,\text{sig}}(\bar{x}, y') dy', \end{aligned}$$

where y' is the coordinate on the MR element. Because the MR element is very thin, we can assume that the signal flux is propagating along the y -direction into the MR element and is uniform in the x - and z -direction. Then it can be related to the signal magnetization as follows:

$$\Phi_{\text{sig}}(\bar{x}, y') = \mu_0 M_{y,\text{sig}}(\bar{x}, y') t W. \quad (6.36)$$

The readback voltage of the MR head becomes

$$V_{MR}(\bar{x}) = -\frac{2I \Delta \rho_{\max}}{\mu_0 D t M_s^2} \int_0^D M_{y0}(y') \Phi_{sig}(\bar{x}, y') dy'. \quad (6.37)$$

If the MR element is almost uniformly biased at $\sim 45^\circ$, $M_{y0}(y') \approx M_s \sqrt{2}$, then

$$V_{MR}(\bar{x}) \approx -\frac{\sqrt{2} I \Delta \rho_{\max}}{\mu_0 D t M_s} \int_0^D \Phi_{sig}(\bar{x}, y') dy'. \quad (6.38)$$

The signal flux $\Phi_{sig}(\bar{x}, y')$ into the MR element will decay from the air-bearing surface (ABS) ($y' = 0$) to the top of MR element ($y' = D$) due to flux leakage to the shields. The efficiency of the MR head can be defined as

$$E_{MR} \equiv \frac{\langle \Phi_{sig}(\bar{x}, y') \rangle}{\Phi_{sig}(\bar{x}, y' = 0)} = \frac{\int_0^D \Phi_{sig}(\bar{x}, y') dy' / D}{\Phi_{sig}(\bar{x})}. \quad (6.39)$$

where $\Phi_{sig}(\bar{x}) \equiv \Phi_{sig}(\bar{x}, y' = 0)$ is the signal flux injected into the MR element at the ABS. The MR head efficiency can be evaluated by a transmission line model which will be described in Section 6.3.5. The expression of the MR head readback voltage can be simplified as

$$V_{MR}(\bar{x}) = -\frac{\sqrt{2} I \Delta \rho_{\max}}{\mu_0 t M_s} E_{MR} \Phi_{sig}(\bar{x}). \quad (6.40)$$

Now the evaluation of the readback voltage boils down to that of the signal flux into the MR element at the ABS, which can be accomplished by the reciprocity principle.

The reciprocity principle as applied to a shielded MR head¹¹ can be demonstrated in Fig. 6.10a. The validity of the reciprocity principle does not depend on whether there is a real current in the coil or not. Imagine that a coil is wrapped around the MR element, then the MR head will generate a magnetic field if an *imaginary* current i is passed through the coil. Assume that the permeability of MR element and the shields is infinity and adopt the Karlqvist approximation similar to that of the inductive heads, then we can derive that the magnetic potential *above* the air-bearing surface (ABS) is given by Fig. 6.10b. Note that we have assumed that the MR element is located in the center of the shield-to-shield gap, so the deep gap fields in the two MR-element-to-shield gaps are the same in magnitude (H_g) but opposite in direction. The magnetic field, $H_x^{MR}(x, y)$, generated by the MR head at the recording medium, can then be calculated from the surface magnetic potential as done in Chapter 2.

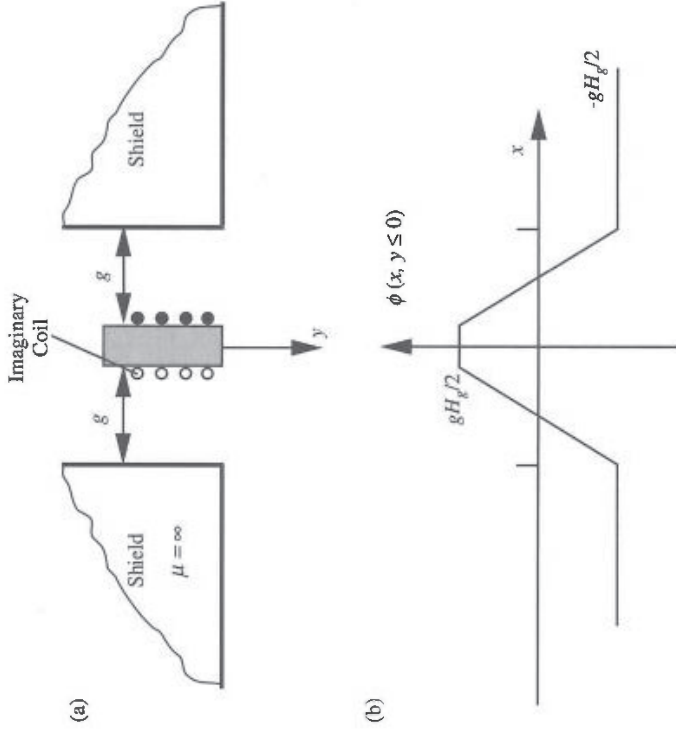


FIGURE 6.10. (a) Shielded MR head with imaginary coil. (b) Surface and deep gap magnetic potential under Karlqvist approximation.

Therefore, the signal flux into the MR element at the ABS can be expressed as

$$\Phi_{sig}(\bar{x}) = \mu_0 W \int_{-\infty}^{\infty} dx \int_d^{d+\delta} dy \frac{H_x^{MR}(x, y)}{i} M_x(x - \bar{x}, y), \quad (6.41)$$

where i is the current in the imaginary coil, H_x^{MR} is the MR head longitudinal field generated by the imaginary coil, and $M_x(x, y)$ is the medium magnetization. This equation is called the *reciprocity formula for MR heads*. If the MR head magnetic field potential is $\phi_{MR}(x, y)$, then

$$\begin{aligned} \Phi_{sig}(\bar{x}) &= \frac{\mu_0 W}{i} \int_{-\infty}^{\infty} dx \int_d^{d+\delta} dy \left[-\frac{\partial \phi_{MR}(x, y)}{\partial x} \right] M_x(x - \bar{x}, y) \\ &= \frac{\mu_0 W}{i} \int_{-\infty}^{\infty} dx \int_d^{d+\delta} dy \phi_{MR}(x, y) \left[\frac{\partial M_x(x - \bar{x}, y)}{\partial x} \right], \end{aligned} \quad (6.42)$$

where we did integration by parts, and used the fact that $M_x = 0$ at $x = \pm\infty$. In short, the reciprocity principle indicates that the signal flux picked up by an MR head can be expressed either as the convolution of its head field and medium magnetization or as the convolution of its head magnetic potential and medium magnetic charge.

Before using the reciprocity formula to derive the MR head readback voltage, we first introduce Potter's "short-cut" approach by recognizing that the shielded MR head is essentially composed of two inductive Karlqvist heads with gap centers located at

$$x = \pm \frac{g+t}{2}.$$

It follows that the readback voltage of the imaginary coil is

$$V^*(\bar{x}) = -v \frac{d\Phi_{sig}}{d\bar{x}} = V \left(\bar{x} - \frac{g+t}{2} \right) - V \left(\bar{x} + \frac{g+t}{2} \right), \quad (6.43)$$

where $V(\bar{x})$ is the readback voltage of a single gap inductive Karlqvist head with a gap length of g . For an *arctangent* magnetization transition, the inductive readback voltage at thin-medium limit is

$$\begin{aligned} V(\bar{x}) &= \frac{2\mu_0 v W H_g M_r \delta}{\pi i} \left(\tan^{-1} \frac{\bar{x} + g/2}{a+d} - \tan^{-1} \frac{\bar{x} - g/2}{a+d} \right) \\ &= C \left(\tan^{-1} \frac{\bar{x} + g/2}{a+d} - \tan^{-1} \frac{\bar{x} - g/2}{a+d} \right). \end{aligned} \quad (3.6)$$

Note that

$$\int \tan^{-1}(cx) dx = \frac{1}{c} \left[cx \tan^{-1}(cx) - \frac{1}{2} \ln(1 + c^2 x^2) \right],$$

and define a function

$$f_\phi(x) = x \tan^{-1}(x) - \frac{1}{2} \ln(1 + x^2), \quad (6.44)$$

then the signal flux injected into the MR element can be derived from Equation (6.43):

$$\begin{aligned} \Phi_{sig}(\bar{x}) &= -\frac{1}{v} \int V^*(\bar{x}) d\bar{x} = \frac{C}{v} (a+d) \\ &\left[-f_\phi \left(\frac{\bar{x} + t/2}{a+d} \right) - f_\phi \left(\frac{\bar{x} - t/2}{a+d} \right) + f_\phi \left(\frac{\bar{x} + g + t/2}{a+d} \right) + f_\phi \left(\frac{\bar{x} - g - t/2}{a+d} \right) \right] \\ &= \frac{2\mu_0 W M_r \delta}{\pi g} (a+d) f_V(\bar{x}), \quad (\because H_g g/i = 1) \end{aligned} \quad (6.45)$$

where $f_V(\bar{x})$ represents the expression in []. Therefore, the MR head readback voltage can be expressed as

$$V_{MR}(\bar{x}) = -\frac{2\sqrt{2}E_{MR} J W \Delta \rho_{max} M_r \delta (a+d)}{\pi i M_g} f_V(\bar{x}). \quad (6.46)$$

Now we will apply the reciprocity formula Equation (6.42) to the MR head directly. For a thin medium ($\delta \ll d$) and a *step* transition at $x = 0$,

$$\frac{\partial M_x(x - \bar{x})}{\partial x} = 2M_r \cdot \delta(x - \bar{x}), \quad (6.47)$$

$$\Phi_{sig}(\bar{x}) = \frac{2\mu_0 W M_r \delta}{i} \phi_{MR}(\bar{x}, d). \quad (6.48)$$

An *arctangent* transition is equivalent to a step transition with an effective magnetic spacing of $d + a$, so the corresponding signal flux from an *arctangent* transition at $x = 0$ is

$$\Phi_{sig}(\bar{x}) = \frac{2\mu_0 W M_r \delta}{i} \phi_{MR}(\bar{x}, d + a). \quad (6.49)$$

Under the Karlqvist approximation, the MR head field is the sum of the two inductive head fields:

$$H_x^{MR}(x, y) = H_x^{ind} \left(x - \frac{g+t}{2}, y \right) - H_x^{ind} \left(x + \frac{g+t}{2}, y \right),$$

where the negative sign arises from the fact that the head gap fields are opposite. Based on Equation (3.6) and the definition of f_V , we obtain

$$\begin{aligned} \phi_{MR}(x, d + a) &= -\int H_x^{MR}(x, d + a) dx \\ &= -\int dx \frac{H_g}{\pi C} \left[V \left(x - \frac{g+t}{2} \right) - V \left(x + \frac{g+t}{2} \right) \right] \\ &= \frac{H_g}{\pi} (a + d) f_V(x). \end{aligned} \quad (6.50)$$

This leads to identical expressions for the signal flux and MR head readback voltage in Equations (6.45) and (6.46).

To see what the MR head readback pulse looks like, let us examine an example. When $a = 15$ nm, $g = 50$ nm, $d = 25$ nm, and $t = 10$ nm,

the isolated pulse is as plotted in Fig. 6.11 (solid line). Note that its shape is not the same as a Lorentzian pulse (dashed line), although they do look similar. The dashed line is plotted using the small gap limit readback pulse expression derived in Section 6.3.2 [Equation (6.55)].

6.3.2 Small gap and thin medium limit

The readback voltage of the inductive head can be rewritten as

$$V(\bar{x}) = C \tan^{-1} \left[\frac{g(a+d)}{(a+d)^2 - (g/2)^2 + \bar{x}^2} \right]. \quad (6.6)$$

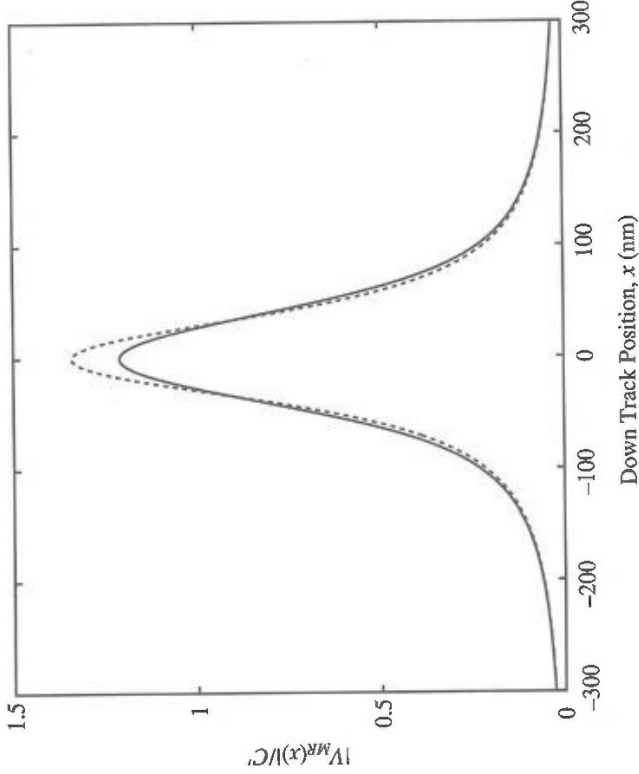


FIGURE 6.11. Isolated pulses of MR head, where the normalization constant is $C' = 2\sqrt{2}E_{MR}/W\Delta\rho_{\max}M_r\delta/\pi M_s$. The dashed line represents small gap read pulse.

Under the small gap limit ($g + t \ll a + d$), we can approximate the following Taylor expansions up to the first-order term of $g + t$:

$$V\left(\bar{x} - \frac{g+t}{2}\right) \approx V(\bar{x}) + \frac{dV(\bar{x})}{d\bar{x}} \left(-\frac{g+t}{2}\right),$$

$$V\left(\bar{x} + \frac{g+t}{2}\right) \approx V(\bar{x}) + \frac{dV(\bar{x})}{d\bar{x}} \left(+\frac{g+t}{2}\right).$$

Therefore,

$$V\left(\bar{x} - \frac{g+t}{2}\right) - V\left(\bar{x} + \frac{g+t}{2}\right) \approx -\frac{dV(\bar{x})}{d\bar{x}} (g+t).$$

This leads to

$$-\frac{dV(\bar{x})}{d\bar{x}} (g+t) = -v \cdot \frac{d\Phi_{sig}(\bar{x})}{d\bar{x}}, \quad (6.51)$$

$$\Phi_{sig}(\bar{x}) = \frac{g+t}{v} V(\bar{x}).$$

For the MR head under the Karlqvist approximation, $gH_g/i = 1$, then

$$\Phi_{sig}(\bar{x}) = \frac{2\mu_0 WM_r \delta g + t}{\pi} \frac{g}{a+d} \left(\tan^{-1} \frac{\bar{x} + g/2}{a+d} - \tan^{-1} \frac{\bar{x} - g/2}{a+d} \right). \quad (6.52)$$

The readback voltage of the MR head biased at $\sim 45^\circ$ becomes

$$V_{MR}(\bar{x}) = -\frac{2\sqrt{2}E_{MR}JW\Delta\rho_{\max}M_r\delta g + t}{\pi M_s} \frac{g}{a+d} \left(\tan^{-1} \frac{\bar{x} + g/2}{a+d} - \tan^{-1} \frac{\bar{x} - g/2}{a+d} \right). \quad (6.53)$$

This is a negative-going isolated pulse, and its shape is the same as that of an isolated pulse of an inductive head with a gap of g . The negative sign arises if the MR element transverse bias and the signal flux has the same direction. In this case, the signal flux into the MR element will rotate the magnetization further away from the current direction, so the resistance and voltage drops. On the contrary, if the signal flux opposes the MR element transverse bias, it will drive the resistance and voltage higher, resulting in a positive-going isolated pulse.

It follows that the half-amplitude pulse width of the MR readback voltage from an arctangent transition is

$$PW_{50} \approx \sqrt{g^2 + 4(a+d)^2}. \quad (6.54)$$

In other words, under the small gap and thin medium limit, the shielded MR head with a shield-to-shield spacing of $2g + t$ has a pulse width like an inductive Karlqvist head with a gap length equal to $\sim 50\%$ of $2g + t$.

In the extreme case of zero gap limit, $g \sim 0$, the MR head read pulse becomes

$$V_{MR}(\bar{x}) = -\frac{2\sqrt{2}E_{MR}JW\Delta\rho_{\max}M_r\delta}{\pi tM_s}(g+t)\frac{(a+d)}{\bar{x}^2 + (a+d)^2}. \quad (6.55)$$

This is a Lorentzian pulse, and the pulse width is

$$PW_{50} = 2(a+d).$$

Under more general circumstances, it can be shown by a conformal mapping method¹² that the MR head has a pulse width like an inductive Karlqvist head with a gap length equal to $\sim 60\%$ of $2g + t$:

$$PW_{50} \approx \sqrt{[0.6(2g+t)]^2 + 4(a+d)^2}. \quad (6.56)$$

Similar to the case of inductive read heads, one must design small magnetic spacing, small transition parameter, and small gap length, *simultaneously*, to achieve a narrow readback voltage pulse.

6.3.3 Advantage of magnetoresistive over inductive read head

When a MR head reads an arctangent transition written in a thin magnetic medium, the peak of the corresponding isolated pulse under small gap limit is

$$V_{MR}^{\text{peak}}(\bar{x}) = \frac{4\sqrt{2}E_{MR}JW\Delta\rho_{\max}M_r\delta}{\pi tM_s} \frac{g+t}{g} \tan^{-1} \frac{g/2}{a+d}. \quad (6.57)$$

As a comparison, assume that an inductive head has an efficiency of E_{ind}/g a gap length of g , and N coil turns, then its peak readback voltage is

$$V_{\text{ind}}^{\text{peak}}(\bar{x}) = \frac{4\mu_0 v W N E_{\text{ind}} M_r \delta}{\pi g} \tan^{-1} \frac{g/2}{a+d}. \quad (6.7)$$

Thus

$$\frac{V_{MR}^{\text{peak}}}{V_{\text{ind}}^{\text{peak}}} = \frac{\sqrt{2}J\Delta\rho_{\max}E_{MR}}{Nv\mu_0M_s} \frac{E_{MR}}{E_{\text{ind}}} \frac{(M_r\delta)_{MR}}{(M_r\delta)_{\text{ind}}} \frac{g+t}{t}. \quad (6.58)$$

For a state-of-the-art inductive head, $g \sim 1000\text{\AA}$, $v = 5\text{ m/s}$, $N \sim 50$. For a state-of-the-art MR head, $J \sim 5 \times 10^7\text{ A/cm}^2$, $\Delta\rho_{\max} \sim 4 \times 10^{-7}\text{ }\Omega\text{-cm}$, $t \sim 150\text{\AA}$, $\mu_0M_s = 1\text{ T}$. Since the MR element is much thinner than a

regular pole in inductive heads, we may assume $E_{MR}/E_{\text{ind}} \sim 0.5$. To avoid saturation of the MR element, the $M_r\delta$ product of the magnetic medium must be limited, while the $M_r\delta$ product of the magnetic medium for inductive read head is not limited by the saturation consideration. For the purpose of this simple analysis, assume that

$$(M_r\delta)_{\text{ind}} \approx 2(M_r\delta)_{MR}.$$

Then

$$\frac{V_{MR}^{\text{peak}}}{V_{\text{ind}}^{\text{peak}}} = \frac{\sqrt{2} \times 5 \times 10^{11} \times 4 \times 10^{-9}}{50 \times 5 \times 1} \times 0.5 \times 0.5 \times \frac{1150}{150} \approx 19.$$

This example clearly demonstrates a *major advantage of the MR heads over the inductive heads* that the former can generate much greater signal amplitudes. This is why MR heads have superseded inductive heads as one scales down magnetic recording bit size!

If a square wave recording pattern (all 1s) is reproduced by an MR head, the voltage amplitude will drop with increasing recording density due to linear superposition of pulses of alternating polarity. Similar to inductive heads, if the isolated pulse can be approximated by a Lorentzian pulse, then the 50% roll-off linear density D_{50} of MR head is related to PW_{50} by

$$D_{50}PW_{50} \approx 1.39. \quad (3.18)$$

A more rigorous simulation without using Lorentzian pulse approximation gives that¹³

$$D_{50}PW_{50} \approx 1.46, \quad (6.59)$$

which is quite accurate if $d/g > 0.2$. Like inductive read heads, the linear density resolvable by MR heads is approximately inversely proportional to the isolated pulse width.

6.3.4 Fourier transform of magnetoresistive head read signal

Under the small gap limit, the Fourier transform of the MR head isolated pulse $V_{MR}(\bar{x})$ resembles that of $V_{\text{ind}}(\bar{x})$:

$$V_{MR}(k) \propto V_{\text{ind}}(k) \propto e^{-k(a+d)} \frac{1 - e^{-k\delta} \sin(kg/2)}{k\delta}. \quad (6.60)$$

Likewise, the fundamental harmonic of the MR head readback voltage waveform from square wave recording pattern at a bit length of B is

$$V_{MR,rms} \left(k_0 = \frac{\pi}{B} \right) \propto k_0 e^{-k_0(a+d)} \frac{1 - e^{-k_0\delta} \sin(k_0 g/2)}{k_0 \delta} \quad (6.61)$$

The Fourier spectra are similar to those shown in Fig. 3.5, except that the normalization coefficients are different. In other words, MR heads also suffer from spacing loss, thickness loss, and gap nulls. Not surprisingly, the exact locations of the gap nulls experimentally observed are actually slightly shifted from $kg/2 = \pi, 2\pi, 3\pi, \dots$ since the Karlqvist approximation needs to be modified near gap corners.

6.3.5 Transmission line model of magnetoresistive heads

The efficiency of the MR head was defined earlier in Section 6.3.1, but we did not elaborate how it could be calculated. Similar to inductive head, MR head efficiency can be calculated numerically by micromagnetic modeling and finite element modeling, or analytically by transmission line modeling. For pedagogical reasons, we choose to introduce a simple two-dimensional transmission line model for MR heads.¹⁴

Consider the MR head shown in Fig. 6.12, where the MR element and the shields are assumed to be very long in the z -direction (across data track, i.e., normal to the page) and have a very large relative permeability. The

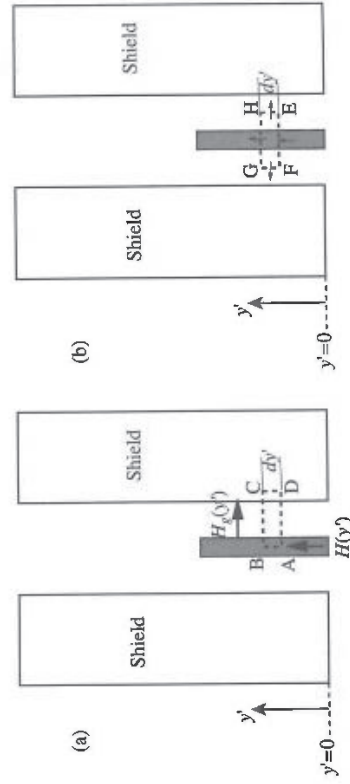


FIGURE 6.12. Transmission line model of shielded MR head: (a) applying Ampere's law, (b) applying Gauss's law, where the four arrows denote flux directions.

SAL layer is fully saturated, so it can be treated as air with a relative permeability of unity. Applying Ampere's law to loop ABCD in Fig. 6.12, we have

$$\begin{aligned} H(y') \cdot dy' + H_g(y') \cdot g - 0 \cdot dy' - H_g(y') \cdot g &= 0, \\ H(y') + \frac{dH_g(y')}{dy'} g &= 0. \end{aligned} \quad (6.62)$$

where $H(y')$ is the magnetic field in the MR element along the y' -direction, $H_g(y')$ is the magnetic field in the gap along the x' -direction, and the magnetic field in the shields are assumed to be negligible because of their large cross-sectional area.

Applying Gauss's law of flux conservation to closed surface EFGH, we obtain that

$$\begin{aligned} -\Phi(y') + \Phi(y') + dy' + 2\mu_0 H_g(y') \cdot W dy' &= 0, \\ \frac{d\Phi(y')}{dy'} &= -2\mu_0 W H_g(y'). \end{aligned} \quad (6.63)$$

where $\Phi(y')$ is the magnetic flux at height y' in the MR element propagating along the y' -direction. If the relative permeability of the MR element is μ , then

$$\Phi(y') = \mu \mu_0 H(y') \cdot tW. \quad (6.64)$$

Combining Equations (6.62)–(6.64), we obtain the following wave equation which describes the transmission (or propagation) of magnetic flux in MR element:

$$\frac{d^2 \Phi(y')}{dy'^2} - \frac{\Phi(y')}{\lambda^2} = 0. \quad (6.65)$$

where $\lambda \equiv \sqrt{\mu g t/2}$ is a characteristic length which describes how fast magnetic flux leaks out of the MR element.

The magnetic flux signal injected into the MR element at the ABS is $\Phi(\bar{x})$, and the magnetic flux signal at the top end of the MR element is approximately zero because it is next to air with a large terminating reluctance. Therefore, the boundary condition can be set as

$$\Phi(y' = 0) = \Phi(\bar{x}), \quad \Phi(y' = D) = 0. \quad (6.66)$$

Equations (6.65) and (6.66) lead to a simple expression of magnetic flux signal in MR element:

$$\Phi(\bar{x}, y') = \Phi(\bar{x}) \frac{\sinh[(D - y')/\lambda]}{\sinh(D/\lambda)}. \quad (6.67)$$

where $0 \leq y' \leq D$. For example, if $t = 15$ nm, $g = 100$ nm, $\mu = 2000$, then $\lambda \approx 1.2$ μ m. If $D \ll \lambda$, then the signal flux decays almost linearly along the y' -direction:

$$\phi(\bar{x}, y') \approx \phi(\bar{x}) \frac{D - y'}{D}. \quad (6.68)$$

The efficiency of the MR head can then be calculated as

$$E_{MR} \equiv \frac{\langle \phi(\bar{x}, y') \rangle}{\phi(\bar{x})} = \frac{\frac{1}{D} \int_0^D \phi(\bar{x}, y') dy'}{\phi(\bar{x})} = \frac{\lambda \cosh(D/\lambda) - 1}{D \sinh(D/\lambda)}. \quad (6.69)$$

The MR head efficiency versus MR element height D is plotted in Fig. 6.13. To achieve a high read efficiency, it is very important to control the MR element height to $D \lesssim \lambda$ during the mechanical lapping process.

6.4 PRACTICAL ASPECTS OF MAGNETORESISTIVE HEADS

Although MR head provides great advantages over inductive read head, it has proven to be a new art that is more difficult to master than many

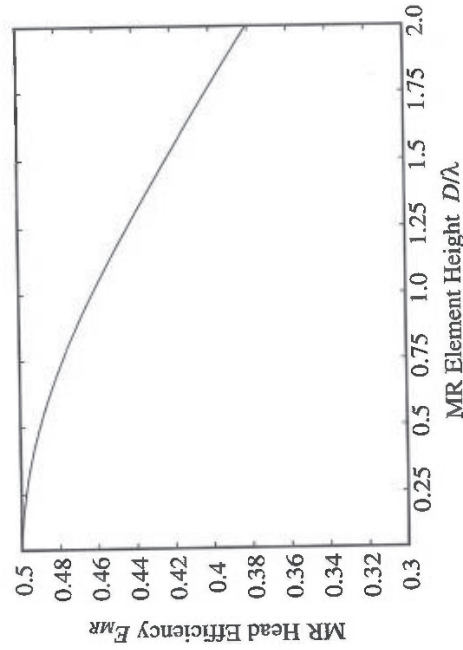


FIGURE 6.13. Efficiency of shielded MR head vs. normalized MR element height.

people had anticipated. In addition to proper biasing the MR element and controlling MR sensitivity as discussed previously, there are many engineering issues associated with MR heads, some of which will be presented here.

6.4.1 Side reading asymmetry

Side reading effect and read trackwidth of a magnetic recording head is often characterized by microtrack profiles. A microtrack is prepared by symmetrically erasing both edges of a full written track until the remaining track is substantially narrower than the read head to be analyzed. The width of the microtrack is limited by the mechanical precision of positioning head across the track and by the read signal amplitude needed to acquire meaningful track profiles. As shown in Fig. 6.14, a microtrack profile is obtained by measuring the readback amplitude as the read head is stepped across the microtrack while the fly height and disk speed are kept constant.

It has been recognized that side reading and the microtrack profile of MR heads tends to be asymmetric, mainly due to the anisotropic nature of flux propagation in the MR element.¹⁵⁻¹⁷ As shown in Fig. 6.14a, when a transition is next to the MR element at air bearing surface, the flux propagation paths (thick dashed lines) are perpendicular to the magnetization biased at 45° , because the flux along the magnetization is already saturated. According to the transmission line model of MR head, the flux almost decays linearly if the MR element height is much shorter than the characteristic length.

If the signal flux and the change in magnetization angle $\Delta\theta$ are small, then we can apply a simple small signal model to obtain the microtrack profile. The change in resistivity is

$$\Delta\rho \approx -\Delta\rho_{\max} \sin(2\theta_0) \Delta\theta, \quad (6.1)$$

where θ_0 is the quiescent bias angle. The resulting change in resistance of the MR element is

$$\begin{aligned} \Delta R &= \langle \Delta\rho \rangle \frac{W}{Dt} = \frac{1}{DW} \iint_{\text{flux path}} \Delta\rho dy' dz' \cdot \frac{W}{Dt} \\ &= -\frac{\Delta\rho_{\max} \sin(2\theta_0)}{D^2 t} \iint_{\text{flux path}} \Delta\theta dy' dz' \\ &\approx -\frac{\Delta\rho_{\max} \sin(2\theta_0)}{D^2 t} \frac{\Delta\theta_{\text{air}} w L(z)}{2}. \end{aligned} \quad (6.70)$$

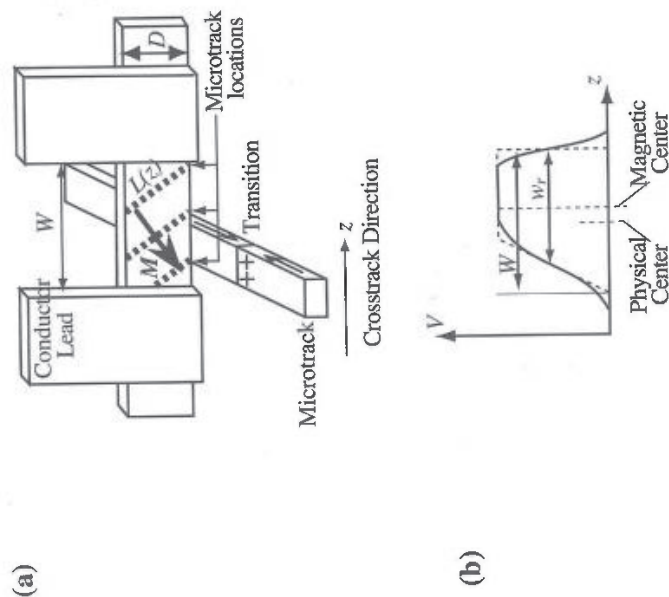


FIGURE 6.14. (a) Microtrack measurement, and anisotropic signal flux propagation in MR element. (b) Schematic microtrack profile and magnetic center.

where $\Delta\theta_{\text{air}}$ is the value of $\Delta\theta$ at the ABS edge of the MR element, $L(z)$ is the length of the flux propagation path varying with the microtrack location z , and w is the width of flux paths, which should be somewhat larger than the microtrack width.

When the microtrack is beyond the active region of the MR element, the flux propagation path disappears. Strictly speaking, this active region is defined by hard bias or exchange tabs rather than by the conductor leads, if they do not flush. Therefore, it is a good idea to flush conductor leads and hard bias (exchange tabs) to reduce side reading. In Fig. 6.14a, as the microtrack moves to left from the right edge of the MR element active region, the flux path length is constant at first and then diminishes linearly when it is interrupted by the hard bias layer or exchange tab under the conductor. Consequently, the resulting microtrack profile is shown as the dashed line in Fig. 6.14b, where the solid line is the actual

microtrack profile observed. The broadening is due to the finite width of microtrack, the finite magnetic spacing between head and disk, etc.

Having explained why side reading of MR head is asymmetrical, it is useful to introduce a number of important concepts. The *physical center* of the MR head is the center of its active region. In contrast, the *magnetic center* is defined as the equal-area line which divides the microtrack profile. In other words, either side of the magnetic center generates equal voltage signal. Both magnetic center and physical center are denoted in Fig. 6.14b. It is very important to know the offset of magnetic center with respect to the physical center of the MR sensor and inductive writer to achieve an optimum track density (Chapter 14).

From the microtrack profile, we can also find the read width, w_r , defined as the microtrack width at half-amplitude. As shown in Fig. 6.14b, the read width is

$$w_r = W - (D/2) \tan \theta_0 < W, \quad (6.71)$$

which is valid only if $D \tan \theta_0 < W$. This equation indicates that the effective read width of AMR head is smaller than the physical trackwidth defined by the conductor leads. Since the magnetic center should be at the middle of the read width, the physical-magnetic center offset is then

$$W/2 - w_r/2 = (D/4) \tan \theta_0. \quad (6.72)$$

The magnetic center approaches the physical center as the MR element height is reduced.

For MR head designs with exchange-tab longitudinal biasing, microtrack profiles display a *cross-talk null*, as shown in Fig. 6.15a. The dip in the microtrack profile is due to the negative contribution of the x-component of signal flux superimposed on the y-component of signal flux, which

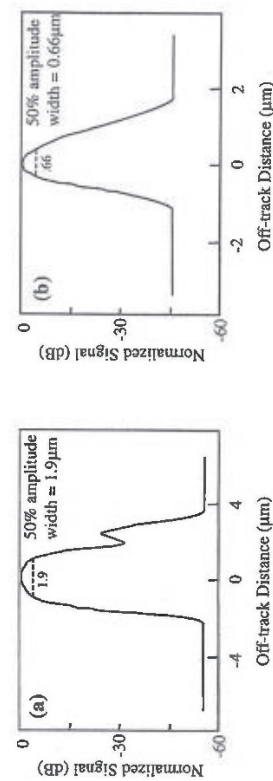


FIGURE 6.15. Microtrack profiles (schematic) of (a) 1 Gb/in.² AMR head (read trackwidth $\sim 1.9 \mu\text{m}$)¹⁸ and (b) 5 Gb/in.² AMR head (read trackwidth $\sim 0.66 \mu\text{m}$).¹⁹

may be picked up through the tail regions of the MR element under the conductor leads. Although the MR signals from the tail regions are shorted out by the leads, any magnetic rotation there can propagate to the central active region of the MR element because it is highly permeable. The undesirable side read, however, can be reduced by improving the exchange-tab biasing design, as shown in Fig. 6.15b, where the cross-talk null disappears. Alternatively, buttressed junction longitudinal bias can eliminate the cross-talk null by replacing the soft permalloy tails under the conductor leads with hard magnets, which are designed not to respond to magnetic excitations from the medium. In this sense, the longitudinal bias design is not only important for eliminating Barkhausen noise, but also critical for high-track density applications.

6.4.2 Readback nonlinearity

The transfer curve of MR element is intrinsically nonlinear. This nonlinearity does not show up if the dynamic range of the signal flux is small such that the transfer curve is effectively linear. However, when an MR head is driven into saturation or near-saturation, the MR head read response is no longer linear, as illustrated in Fig. 6.16. One of the consequences of MR read nonlinearity is that the positive peaks and negative peaks have

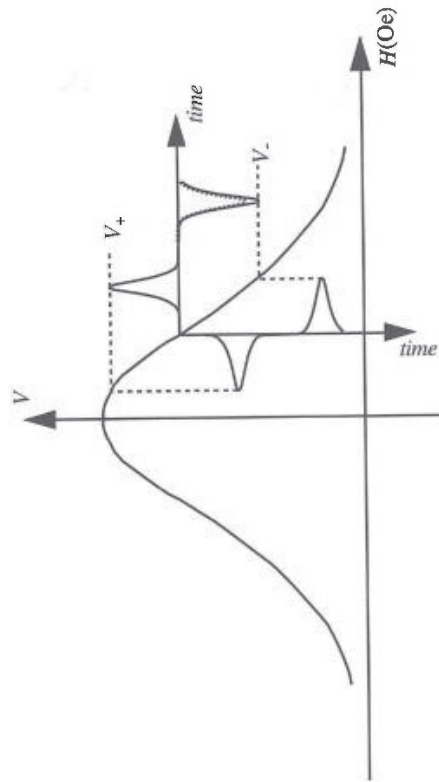


FIGURE 6.16. Amplitude asymmetry of MR head readback pulses. (The dashed negative pulse has no amplitude asymmetry.)

different amplitudes. The normalized peak asymmetry (PA) can be defined as

$$\%PA = \frac{|V_+| - |V_-|}{|V_+| + |V_-|} \times 100. \quad (6.73)$$

Another definition is

$$\%PA = \frac{|V_+| - |V_-|}{\max(|V_+|, |V_-|)} \times 100. \quad (6.74)$$

The latter is a factor of ~ 2 larger than the former definition. In both conventions, a positive peak asymmetry means a smaller negative-going peak.

In order to limit the peak asymmetry of MR head, we should choose the medium $M_r\delta$ product properly such that the MR element is not driven into saturation. In addition, we should neither overbias nor underbias (transversely) an MR head. Elaborate simulation and experiments have shown that asymmetric placement of MR element within the shield-to-shield gap can significantly affect peak asymmetry.²⁰

Generally speaking, MR readback nonlinearity is more serious for isolated pulses than for high-density pulses because the former is generated by the maximum signal flux level from a magnetic medium. Even though MR readback nonlinearity may not be a vital problem in high-density recording, it does interfere with the measurement of other write nonlinearities such as partial erasure and nonlinear transition shift. Therefore, several methods have been devised to characterize MR read nonlinearity.^{21,22} An in-depth discussion will be given in Chapter 10.

6.4.3 Baseline shift

Readback voltage waveforms normally display a flat baseline, i.e., the quiescent voltage level in the absence of magnetic transitions is expected to be zero. However, isolated transitions written with an untrimmed thin film inductive head and read with an MR sensor may exhibit a shift in baseline between readback pulses,²³ as shown in Fig. 6.17a. The normalized baseline shift (BLS) is defined as

$$\%BLS = \frac{V_2 - V_1}{V_{p-p}} \times 100, \quad (6.75)$$

where V_1 is the baseline voltage level of positively magnetized domains, V_2 is the baseline voltage level of negatively magnetized domains, and V_{p-p} is the peak-to-peak amplitude of the isolated pulses.

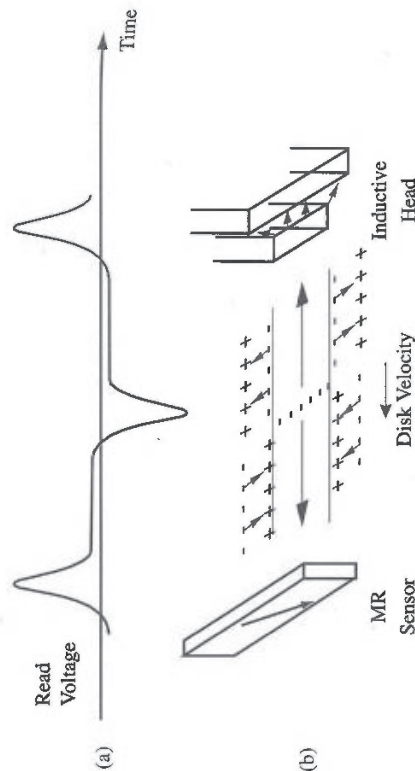


FIGURE 6.17. (a) Baseline shift of MR head readback voltage waveform. (b) Media-induced baseline shift interpretation.

The observed BLS can be interpreted based on the track edge effect during the write process, as shown in Fig. 6.17b. For the untrimmed write head with unequal pole tip widths, the side fringing field will have a transverse component which changes sign alternately as the write gap field is switched. Consequently, magnetic dipoles with alternating directions are written at track edges. These track edge dipoles will contribute no signals to an inductive read head because there is no flux derivative with respect to time, but it will contribute signals to an MR head because the latter is a flux-sensing device. The magnetic dipoles before the transition will increase the readback voltage, while those after the transition will decrease the readback voltage, resulting in a negative baseline shift. At very high recording densities, the magnetic dipoles at the track edges diminish, so the baseline shift also disappears accordingly. Properly trimming the write head pole tips reduces the transverse component of side erase field, thus results in a smaller baseline shift. Using an oriented magnetic disk whose easy axis (EA) is along circumferential direction also helps to reduce the magnetic dipoles at the track edge and thus decreases baseline shift.

Magnetic dipoles at track edges can also be formed when magnetic transitions are written at skew angles, leading to an asymmetrical charge distribution across the data track and a baseline shift in MR readback waveform.²⁴

In addition to the medium-induced baseline shift discussed above, there can also be head-induced baseline shift.²⁵ If the MR element experiences hysteretic behavior, then the MR transfer curve is no longer a single-valued curve. In other words, the quiescent operating point of the MR head will shift slightly, resulting in baseline shift.

6.4.4 Thermal asperity

Like many materials, the resistivity of MR sensor is a function of temperature. The temperature dependence of metallic resistivity is nearly linear, and is often characterized by the temperature coefficient of resistivity (TCR):

$$\alpha = \frac{\rho - \rho_0}{\rho_0 (T - T_0)}, \quad (6.76)$$

where ρ and ρ_0 are the resistivity at temperatures of T and T_0 , respectively. For example, a NiFe sensor has a positive TCR of $\sim 0.24\%/^{\circ}\text{C}$, which means that a temperature fluctuation of about $\pm 10^{\circ}\text{C}$ can completely overwhelm the MR sensor response, because MR ratio of NiFe is only $\sim 2\%$.

Due to Joule heating of the sense current passing through the MR element, the MR sensor generally operates at $20\text{--}50^{\circ}\text{C}$ above the ambient temperature of a hard disk drive. When a MR sensor moves at a high speed relative to a magnetic disk and hits a high spot on the disk such as sputter splash, debris, mechanical scratch, and corrosion spot, its temperature can increase almost instantaneously upon the contact, then drop gradually to its normal operating temperature. Such a heating event is often called a *thermal asperity*. As a result, the MR head read voltage waveform changes accordingly, as shown in Fig. 6.18, where the readback waveform from a square wave recording pattern is greatly distorted by a large broad voltage peak due to a thermal asperity.

The temperature of the MR sensor is kept constant by the balance between Joule heating and cooling mainly through metallic shields. Sometimes MR head-disk contact can cause a modulation of MR element-to-shield spacing, which in turn causes excessive cooling or heating of MR sensor, giving rise to baseline shifts in MR read voltage waveform. This is called "baseline wander."

For MR head to reliably read data at a magnetic spacing as low as possible, thermal noise spikes such as thermal asperity and baseline wander need to be detected and corrected. To this end, electronic counter-

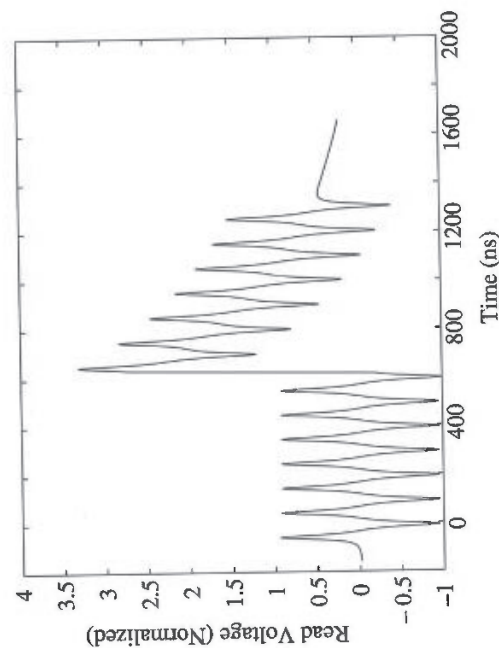


FIGURE 6.18. Simulated read voltage waveform of all 1s data pattern with thermal asperity.

measures have been devised, and an excellent review has recently been given in the literature.²⁶

6.4.5 Electrostatic discharge sensitivity

It has been recognized that MR heads can be easily damaged by electrostatic discharge (ESD) during head fabrication, testing, and assembly.^{27,28} Transient ESD current through MR sensor may cause a permanent increase in MR sensor resistance, and eventually severe melting damages of MR sensors. In addition, dielectric breakdown between MR sensor and shields, and between shields and substrate, can also cause the MR heads to fail.

Thin-film inductive heads are also susceptible to ESD damages, although not to the extent of MR sensors. Spurious electrostatic discharges between magnetic pole tips and an adjacent conductor will likely damage the pole tips. The insulating layers surrounding write coils may break down due to ESD, causing the failure of the inductive heads.

To prevent ESD damages, we should properly ground operators, table tops and other equipment which may be in contact with heads. In addition, the materials used for storage container and work trays must be carefully

6.5 FABRICATION OF MR HEADS

selected. Bypass paths to ESD away from the sensor or pole tip area can also be implemented.²⁹

6.5 FABRICATION OF MR HEADS

An integrated inductive write, magnetoresistive read head (often simply called MR head) is schematically shown in Fig. 6.19a. The top shield and the bottom pole (P1) of the inductive head are merged to reduce the built-in offset between the MR sensor and inductive write gap due to skew angles in hard disk drive.³⁰ The *merged design* is also helpful to decrease the alignment error between the MR sensor and the inductive head pole tips due to photolithography steps in head manufacturing. In the first-generation IBM MR head "Corsair," the bottom magnetic pole of the inductive writer is separate and placed above the top shield of the MR reader. This is often referred to as *piggyback design*. A real cross-sectional view of a merged inductive write/MR read head is shown in Fig. 6.19b, where the bottom shield is $\sim 2 \mu\text{m}$ thick, and the top shield is $\sim 3 \mu\text{m}$ thick. The actual thickness of the MR sensor is so small compared with the shield thickness that the MR sensor is not visible in Fig. 6.19b, but it can be seen from the magnified photograph shown in Fig. 6.19c.

6.5.1 Magnetoresistive head wafer process

Fabrication of MR heads is similar to inductive thin-film heads in terms of technology, but more complicated in terms of design and fabrication steps. Magnetoresistive heads still use ceramic substrates, and the front-end (substrate preparation) and back-end (lapping, slicing, slider fabrication) processes are almost identical to inductive head technology. During the wafer processing, usually the MR reader is fabricated first, then the inductive writer is processed.

The fabrication steps of the MR reader, with SAL transverse bias and hard longitudinal bias, are shown in Fig. 6.20. The bottom shield is electroplated or sputtered, then the first gap layer (typically alumina) is sputtered. After sputtering SAL/spacer/MR trilayer, photoresist pattern defining MR element is applied. The sidewall of the photoresist pattern must have a reentrant angle or an undercut to facilitate a lift-off process later. The uncovered part of the trilayer is then removed by ion milling (ion beam etching). The angle and exposure of ion beam are controlled such that a slope is formed at the both ends of the MR trilayer. This slope

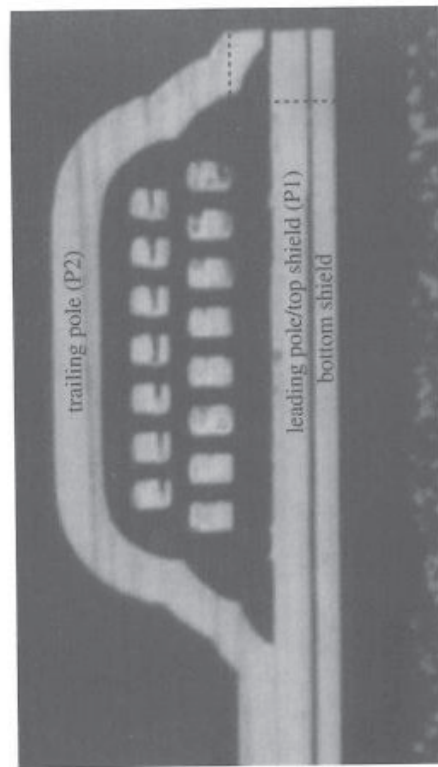
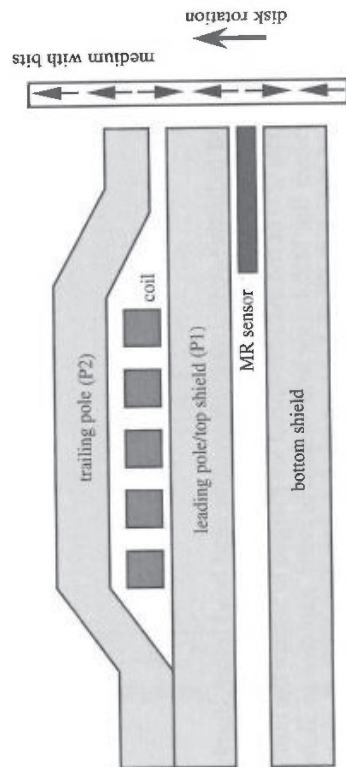


FIGURE 6.19. (a) Top: schematic of MR head cross section (including the writer). (b) Middle: cross-sectional view of a real merged MR head with inductive writer. (c) Bottom: magnified view of the boxed gap region in (b).

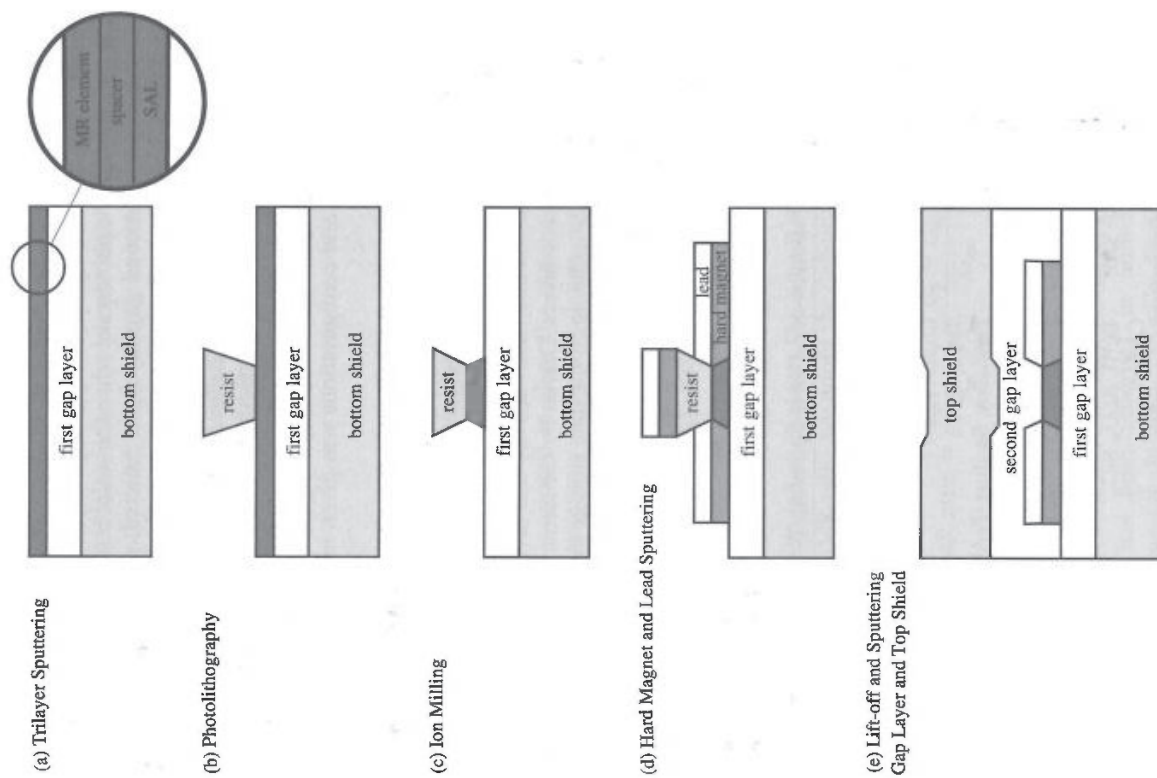


FIGURE 6.20. Fabrication steps of MR reader with SAL and hard bias.

allows a contiguous junction to form reliably when a hard magnet layer and a conductor layer are deposited, as shown in Fig. 6.20d. The hard magnet layer and the conductor layer deposited on the photoresist are lift off along with the photoresist when the wafer is soaked in a photoresist solvent. Then the second gap layer is sputtered, and the top shield is electroplated or sputtered, as shown in Fig. 6.20e. Steps to complete the inductive writer follow.

Actual processing of MR heads involves more subtlety and complexity, and varies from company to company. The important tricks usually remain trade secrets and are unavailable in the literature. A comprehensive review, but with limited details, on the process complexity of MR heads of various designs and configurations was given in the literature.³¹

6.5.2 Materials used in magnetoresistive head fabrication

MR head fabrication consists of many deposition and lithographic steps, and is truly a "materials-intensive" activity that involves numerous magnetic and nonmagnetic layers. Driven by the tremendous growth rate of the magnetic storage technology, the data storage industry seems to have an insatiable appetite for newer and better materials. In fact, new materials are often the enabling factors for the continued gain in head performance. The materials used or proposed for dual-element inductive write/MR read heads are listed in Table 6.2, and the table is growing fast.

TABLE 6.2. Materials Used in MR Heads (Including Writer and Reader)^a

Layers	Materials
Undercoat/overcoat/gap	Alumina (Al ₂ O ₃)
Magnetic poles	Permalloy (Ni ₈₁ Fe ₁₉ , Ni ₈₀ Fe ₂₀), Ni ₄₅ Fe ₅₅ , CoNiFe, CoXZr, FeXN
Coils	Ti/Cu, Cr/Cu
Shields	Permalloy, Sendust (FeAlSi)
MR sensor	Permalloy, spin valves
Soft adjacent layer (SAL)	NiFeRh, CoZrMo, NiFeMo, NiFeCo
Hard bias	CoPt, CoCr, CoCrPt
Exchange bias	FeMn, NiMn, IrMn, PtMn, TbCo, NiO
Spacer between MR & SAL	Ta, Ti, Al ₂ O ₃ , SiO ₂
Protective coating	Carbon

^aRef. 32.

6.6 GIANT MAGNETORESISTIVE (GMR) HEADS

The signal output of MR heads is directly proportional to the MR ratio of the sensor material. No wonder that people have been searching for the materials that display much larger changes in resistivity than permalloy for a long time. It turns out that the match made in heaven for the MR head technology is the so-called giant magnetoresistive (GMR) material first discovered in 1988. It took less than a decade to transform this scientific breakthrough into commercial products, both of which will be examined here.

6.6.1 Giant magnetoresistance effect

In 1988 Baibich et al. reported their seminal work on giant magnetoresistance (GMR) effect in Fe/Cr multilayers.³³ In this type of "magnetic/nonmagnetic metal" multilayers, the magnetic layers are antiferromagnetically coupled (or antiparallel) in the absence of external field. When a field strong enough is applied to align the magnetizations of adjacent magnetic layers, the resistivity of the multilayers drop significantly (up to a factor of 2) as shown in Fig. 6.21. The ferromagnetic state, i.e., the saturated state, has a much lower resistivity than that of the antiferromagnetic state, because the former state allows electrons of one spin have a lower average resistance, leading to a so-called "short-circuit" effect. The origin of GMR effect is the spin-dependent scattering either at the interfaces of magnetic/nonmagnetic metals or inside the ferromagnetic metal layers.

The definition of GMR ratio varies somewhat in the literature. To be consistent with the AMR ratio, we adopt the definition of GMR ratio as the ratio of the maximum difference in resistance over the minimum resistance:

$$\text{GMR ratio} \equiv \frac{R_{ap} - R_p}{R_p} = \frac{G_p - G_{ap}}{G_{ap}}, \quad (6.77)$$

where R_p (or G_p) is the resistance (or conductance) when the magnetizations are parallel, and R_{ap} (or G_{ap}) is the resistance (or conductance) when the magnetizations are antiparallel. This definition gives a GMR ratio of ~85% at 4.2 K for the (Fe 3 nm/Cr 0.9 nm)₆₀ multilayers. Since the discovery of GMR effect, it has been observed in numerous ferromagnetic metal/nonmagnetic metal multilayers.³⁴ In a Co₉₅Fe₅/Cu multilayer, GMR ratios of ~220% at 4.2 K and ~110% at 295 K have been reported.³⁵

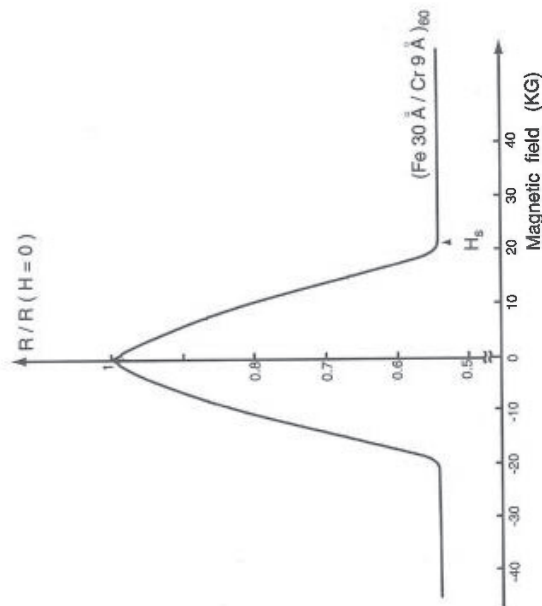


FIGURE 6.21. Giant magnetoresistance of Fe/Cr superlattice at 4.2 K. The current and applied field are along the [110] axis in the plane of the layers. When the temperature increases to room temperature, the saturation magnetoresistance ratio is reduced by a factor of ~ 2 , and the saturation magnetic field H_s is reduced by about 30%.

The GMR multilayers typically require a rather large saturation field to overcome the antiferromagnetic coupling of magnetic layers to display the large GMR ratios. It was found that the strength of the antiferromagnetic coupling is a periodic function of the nonmagnetic spacer.³⁶ It was later recognized that the antiferromagnetic (AF) coupling and GMR effect in multilayers are due to entirely different physical mechanisms although the two phenomena often occur at the same time. The origin of oscillatory antiferromagnetic coupling has been explained by the RKKY (Ruderman-Kittel-Kasuya-Yosida) theory³⁷ and by quantum well models.³⁸

The field sensitivity of GMR multilayers is actually lower than the AMR ratio of NiFe because of the large saturation fields in the multilayers. In addition, CoFe/Cu multilayers are difficult to implement in a device like a recording head. These considerations motivated the invention of an alternative GMR structure that consists of NiFe/Cu/NiFe/FeMn, where the FeMn layer pins the magnetization of the top NiFe layer through exchange anisotropy.³⁹ Between the ferromagnetic NiFe layers, the ferro-

magnetic (or antiferromagnetic) interaction are much weaker than that in the GMR multilayer such that the bottom NiFe magnetization can switch under a field as small as ~ 6 Oe. Therefore, these GMR sandwiches are referred as "spin valves."

Initial NiFe-based spin valves displayed GMR ratio of $\sim 4\%$, many variations of spin valve structures with higher GMR ratios have since been proposed. An example is shown in Fig. 6.22a. The Si/Ta/NiFe(5 nm)/Co(2 nm)/Cu(2 nm)/Co(2 nm)/NiFe(3 nm)/FeMn(15 nm) spin valve displays a GMR ratio of $\sim 9\%$, where Co is inserted to enhance interfacial spin-dependent scattering, and Ta seed layer is used to promote desirable film texture and morphology. Spin valves with top FM layer pinned are often called *top spin valves*. On the other hand, in a *bottom spin valve* shown in Fig. 6.22b, the bottom FM is pinned while the top FM is free. The Si/NiO(75 nm)/NiFe(3 nm)/Co(2 nm)/Cu(2 nm)/NiFe(5 nm) spin valve displays a GMR ratio of $\sim 12\%$.⁴⁰ There are reports that higher GMR ratios can be attained in spin valves by achieving specular electron reflection at outer surfaces. For example, by introducing a tiny amount of oxygen ($\sim 5 \times 10^{-9}$ Torr) into an ultrahigh vacuum (UHV) deposition chamber during spin valve growth, GMR ratios of 19% and 25% have been obtained in a bottom pin valve structure of Si/NiO(50 nm)/Co(2.5 nm)/Cu(1.9 nm)/Co(3 nm) and a *symmetrical spin valve* structure of Si/NiO(50 nm)/Co(2.5 nm)/Cu(1.9 nm)/Co(4 nm)/Cu(1.9 nm)/Co(2.5 nm)/NiO(50 nm), respectively.⁴¹ In the symmetric spin valve, the central

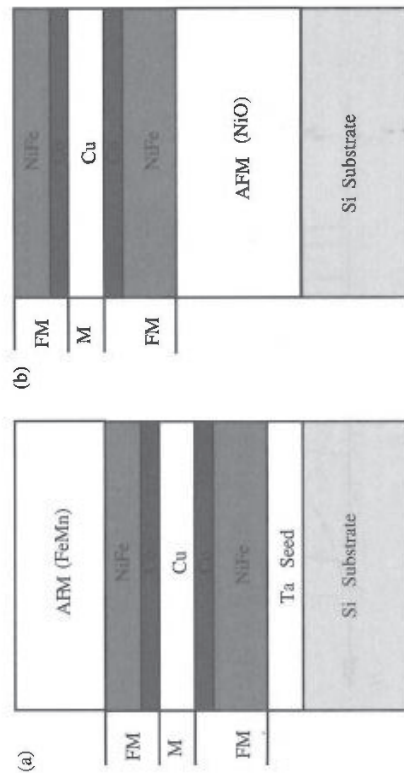


FIGURE 6.22. Schematic cross sections of (a) top spin valve, and (b) bottom spin valve. (FM = ferromagnet; M = noble metal; AFM = antiferromagnet)

Co (4 nm) layer is free, while the other two Co layers are pinned. It has a higher GMR ratio than the bottom spin valve because it contains more Co/Cu spin-dependent scattering interfaces.

The commonly used pinning methods in spin valves include: (1) Antiferromagnetic or ferrimagnetic exchange bias layer, including NiO, NiMn, IrMn, PtMn, TbCo, etc. (2) Permanent magnetic thin film layer such as CoCrPt. (3) Synthetic ferrimagnets such as Co/Ru/Co where the two Co layers are antiferromagnetically coupled as in GMR multilayers.

The magnetic hysteresis loop and MR transfer curve of spin valves are shown in Fig. 6.23. In this case, both the free layer and the pinned layer have the same EA and the hysteresis loop shown is along the EA. The hysteresis loop near the origin is associated with the magnetic switching of the free layer, while the other loop is associated with the magnetic switching of the pinned layer. The free-layer hysteresis loop is slightly shifted

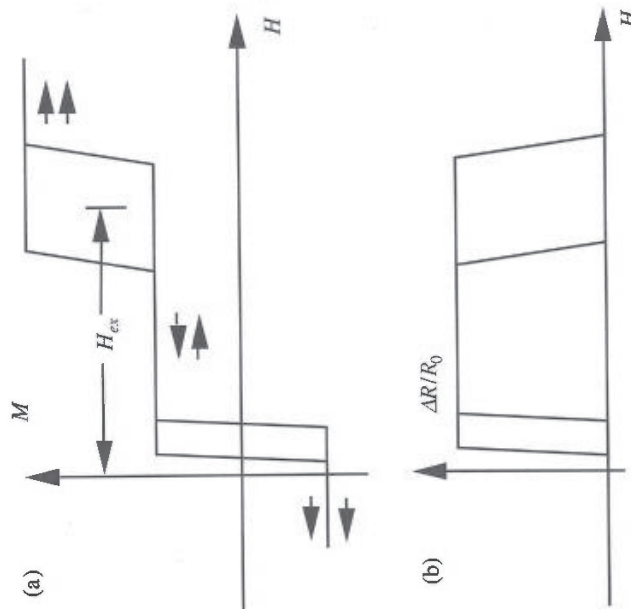


FIGURE 6.23. (a) The magnetic hysteresis loop, and (b) the MR transfer curves of spin valve along the easy axis. The arrows represent the magnetizations of free and pinned FM layers.

to the right because of a weak ferromagnetic coupling from the pinned layer. The resistance of the spin valve is maximum when bottom and top FM layers are antiparallel, and minimum when parallel. The corresponding MR transfer curve along the EA is shown in Fig. 6.23b.

The GMR ratio of a spin valve can be expressed as

$$\frac{\Delta R}{R_0} = \frac{\Delta R_{\max}}{R_0} \left[\frac{1 - \cos(\theta_2 - \theta_1)}{2} \right], \quad (6.78)$$

where θ_1 and θ_2 are the orientation angles of the magnetizations of the pinned and free FM layers in the spin valve, respectively. In contrast, the AMR ratio is expressed as

$$\frac{\Delta \rho}{\rho_0} = \frac{\Delta \rho_{\max}}{\rho_0} \cos^2 \theta, \quad (6.1)$$

where θ is the angle between the current and the magnetization. Both GMR and AMR effects are shown in Fig. 6.24. As a comparison, the AMR transfer curve is most linear at $\theta = 45^\circ$ or 135° , while the GMR transfer curve is most linear at $\theta_2 - \theta_1 = 90^\circ$. Also note that the spin valve requires magnetization rotation of 180° instead of 90° to realize its maximum variation of resistance.

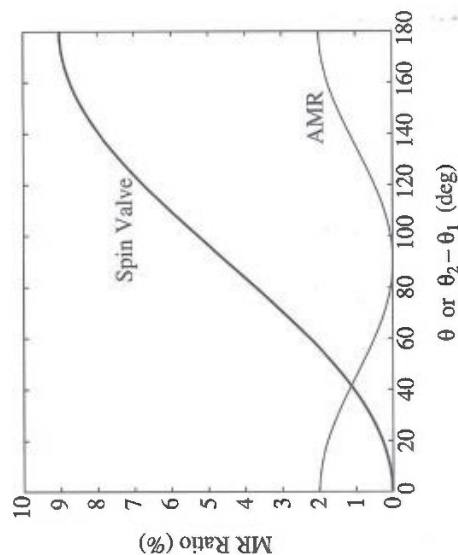


FIGURE 6.24. MR ratios of spin valve and NiFe vs. magnetization orientation. The maximum ratios are 9% and 2%, respectively.

6.6.2 GMR read heads

GMR read heads that are capable of reading areal densities ≥ 5 Gb/in.² and are based on spin valve structures have been reported by a number of companies.⁴²⁻⁴⁴ GMR head technology is not a simple extension of AMR technology because of many new requirements, including much stricter control of film thickness and interfaces, better exchange bias materials, good thermal stability of spin valves, etc.

To linearize a spin valve GMR read head, we can design the spin-valve head as shown in Fig. 6.25 such that $\theta_1 = 0^\circ$, $\theta_2 = 90^\circ$, $\theta_2 - \theta_1 = 90^\circ$ in the quiescent state. In this design of spin valve heads, $\theta_2 = 90^\circ$ is fixed, but θ_1 is influenced by the flux signal. In principle the spin valve head is very similar to AMR head shown in Fig. 6.7. However, the free layer magnetization in the former rotates from -90° to $+90^\circ$ (maximum dynamic range), while the magnetization in the latter rotate from 0° to 90° (if biased at $\sim 45^\circ$).

The readback voltage from a spin valve GMR read head is

$$\begin{aligned} V_{GMR}(\bar{x}) &= I \Delta R_{\text{max}} \frac{\langle -\cos(90^\circ - \theta_1) + \cos(90^\circ - \theta_{1,0}) \rangle}{2} \\ &= -\frac{1}{2} I \Delta R_{\text{max}} \langle \sin \theta_1 - \sin \theta_{1,0} \rangle \\ &= -\frac{1}{2} I \Delta R_{\text{max}} [\langle \sin \theta_1 \rangle - \langle \sin \theta_{1,0} \rangle], \end{aligned} \quad (6.79)$$

where I is the sense current through the spin valve, and $\theta_{1,0}$ is the quiescent magnetization orientation of the free layer. Note that the resistivity and current density in spin valve is not uniform, so we no longer use current

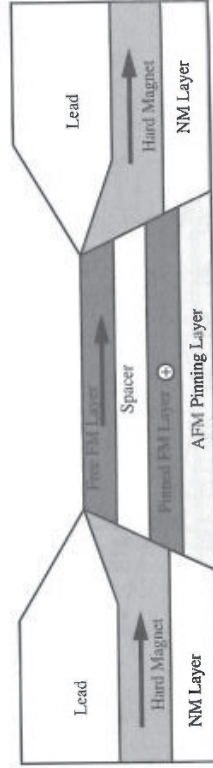


FIGURE 6.25. Schematic cross section of a spin-valve GMR read head with exchange-pinned layer and longitudinal hard bias. The nonmagnetic (NM) layer under the hard magnet is for controlling the coercivity and thickness of the hard magnet.

density and resistivity to express readback voltage. The magnetization orientation of the free layer is determined by minimizing total energy of the free layer (intrinsic induced anisotropy H_k of the free layer is neglected). This leads to the following relation:

$$-H_i \cos \theta_1 + H_i \sin \theta_1 + \frac{1}{2} N_{dy}^f M_s^f \sin(2\theta_1) = 0,$$

where H_i is the transverse field (bias plus signal); H_i is the longitudinal bias field, and $N_{dy}^f M_s^f$ is the transverse demagnetizing field of the free layer. To make sure that the free-layer magnetization is oriented at $\theta_1 \sim 0^\circ$, the required transverse bias field is

$$H_{i,bias} = 0.$$

This means that there is no transverse bias field required to linearize the spin valve head. However, ferromagnetic coupling field from the pinned layer must be canceled by the sense current field. If biased at $\theta_{1,0} = 0^\circ$, the small field sensitivity of the free layer can be found as follows:

$$\begin{aligned} -\cos \theta_{1,0} + H_{i,bias} \sin \theta_{1,0} \frac{\partial \theta_1}{\partial H_{sig}} + H_i \cos \theta_{1,0} \frac{\partial \theta_1}{\partial H_{sig}} \\ + N_{dy}^f M_s^f \cos(2\theta_{1,0}) \frac{\partial \theta_1}{\partial H_{sig}} = 0, \\ \frac{\partial \theta_1}{\partial H_{sig}} = \frac{H_{i,bias} \sin \theta_{1,0} + H_i \cos \theta_{1,0} + N_{dy}^f M_s^f \cos(2\theta_{1,0})}{\cos \theta_{1,0}} \\ = \frac{1}{H_i + N_{dy}^f M_s^f}. \end{aligned} \quad (6.80)$$

For both spin valve head and AMR head, the longitudinal bias field must not be excessive so that the field sensitivity can be maintained.

The spin valve GMR head readback voltage can be related to the flux signal $\phi(\bar{x}, y')$ based on the following relation:

$$\sin \theta_1 = \frac{M_y^f}{M_s^f} = \frac{\phi(\bar{x}, y')}{\mu_0 t W M_s^f}. \quad (6.81)$$

where y' is the vertical coordinate of the free layer, t is its thickness, and W is the read trackwidth. Therefore, if $\langle \sin \theta_{1,0} \rangle = 0$, Equation (6.79) becomes

$$V_{GMR}(\bar{x}) = -\frac{I \Delta R_{\text{max}}}{2 \mu_0 D t W M_s^f} \int_0^D \phi_{sig}(\bar{x}, y') dy'. \quad (6.82)$$

According to the transmission line model, the signal flux $\Phi_{sig}(\bar{x}, y')$ in the free layer decays from the ABS ($y' = 0$) to the top of free layer ($y' = D$) due to flux leakage to the shields. Similar to the case of the AMR head, the efficiency of the spin valve GMR head can be defined as

$$E_{GMR} \equiv \frac{\langle \Phi_{sig}(\bar{x}, y') \rangle}{\Phi_{sig}(\bar{x}, y' = 0)} = \frac{\int_0^D \Phi_{sig}(\bar{x}, y') dy'}{\Phi_{sig}(\bar{x})} \quad (6.39)$$

where $\Phi_{sig}(\bar{x}) \equiv \Phi_{sig}(\bar{x}, y' = 0)$ is the signal flux injected into the free layer at the ABS. The spin valve GMR head efficiency can be evaluated by a transmission line model as described earlier. Therefore, Equation (6.82) can be simplified as

$$V_{GMR}(\bar{x}) = -\frac{I \Delta R_{max}^s E_{GMR} \Phi_{sig}(\bar{x})}{2\mu_0 t W M_s^s} \quad (6.83)$$

where $\Phi_{sig}(\bar{x}) \equiv \Phi_{sig}(\bar{x}, y' = 0)$ can be found by the reciprocity principle (Section 6.3). When the free-layer-to-shield gaps are small and symmetrical, Equation (6.52) holds, and the GMR head readback voltage from an arctangent transition is approximately

$$V_{GMR}(\bar{x}) = -\frac{E_{GMR} I \Delta R_{max}^s M_s^s g + t}{\pi t M_s^s} \left(\tan^{-1} \frac{\bar{x} + g/2}{a + d} - \tan^{-1} \frac{\bar{x} - g/2}{a + d} \right), \quad (6.84)$$

where t is the thickness of the free layer, and g is the free-layer-to-shield gap length.

If the flux signal at the ABS and head efficiency are fixed, then the ratio of the readback amplitude of the spin valve (SV) GMR head over that of the AMR head is

$$\frac{V_{0-peak}^{SV}}{V_{0-peak}^{AMR}} = \frac{1}{2\sqrt{2}} \frac{t_{MR} M_s^{MR}}{t M_s^s} \frac{(I \Delta R_{max}^s)^{SV}}{(I W \Delta \rho_{max})^{AMR}}, \quad (6.85)$$

where t_{MR} and M_s^{MR} are the AMR element thickness and magnetization, respectively. For example, a Si/Ta/NiFe(5 nm)/Co(2)/Cu(2)/Co(2)/NiFe(3)/FeMn(15) spin valve displays a GMR ratio of ~9% and a square resistance of $R_{sq} \approx 12 \Omega$. If the spin valve total thickness is $t_{sv} \approx 26$ nm, then

$$(I \Delta R_{max}^s)^{SV} \approx I t_{sv} D \cdot \frac{\Delta R_{max}^s R_{sq}}{R_0} W = J W R_{sq} t_{sv} \cdot \frac{\Delta R_{max}^s}{R_0},$$

where D is the sensor height, and J is the average current density through the spin valve. If $t_{MR} = 10$ nm, $\Delta \rho_{max} = 0.34 \mu\Omega \cdot \text{cm}$, and the sense current density and read trackwidth are the same for the AMR head, then

$$\frac{V_{0-peak}^{SV}}{V_{0-peak}^{AMR}} = \frac{1}{2\sqrt{2}} \frac{10 \times 10 \times 26 \Omega \cdot \text{nm} \times 9\%}{0.34 \times 10 \Omega \cdot \text{nm}} \approx 4.$$

The GMR head output is a factor of 4 bigger, which is a significant gain. Note that the ratio above is the ratio of readback voltages under the same flux signal. This ratio is slightly different from the ratio of the maximum readback voltages that can be attained with each head if different flux signals can be applied. In the latter case, if the sense current density and trackwidth are still the same for the SV GMR head and AMR head, then the ratio of the maximum readback voltages is

$$\frac{V_{0-peak}^{SV}}{V_{0-peak}^{AMR}} = \frac{(I \Delta R_{max}^s)^{SV} / 2}{(J W \Delta \rho)_{max}^{AMR} / 2} = \frac{12 \times 26 \Omega \cdot \text{nm} \times 9\%}{0.34 \times 10 \Omega \cdot \text{nm}} \approx 8. \quad (6.86)$$

This is a boost of eight times! In short, when properly designed, spin valve GMR heads could generate significantly greater readback voltages than conventional AMR heads. With the help of GMR materials, we can further reduce the trackwidth W while maintaining adequate readback signal. Without the discovery and improvement of GMR materials, magnetic recording at a density of >10 Gb/in.² would be unthinkable.

6.6.3 Tunneling magnetoresistive effect

What is next after GMR? This is anyone's guess. The recent development in room temperature spin-dependent tunneling (SDT) junctions,⁴⁵ also called magnetic tunneling junctions, is very exciting and worth our attention. These devices are made of ferromagnetic metal/insulating barrier/ferromagnetic metal sandwiches, as shown in Fig. 6.26. If the barrier is very thin (<2 nm), electrons can tunnel through the barrier from one ferromagnetic electrode to another, or vice versa. Since the electrons in the ferromagnetic electrodes are at least partially spin polarized, the tunneling current through the barrier is larger when the magnetization in the two electrodes is parallel than when they are aligned antiparallel, resulting in a so-called tunneling magnetoresistance (TMR) effect. TMR ratios more than 25% at room temperature have been reported, making it very attractive for applications in magnetic read heads and magnetic random access memory (MRAM, see Chap. 17).⁴⁶

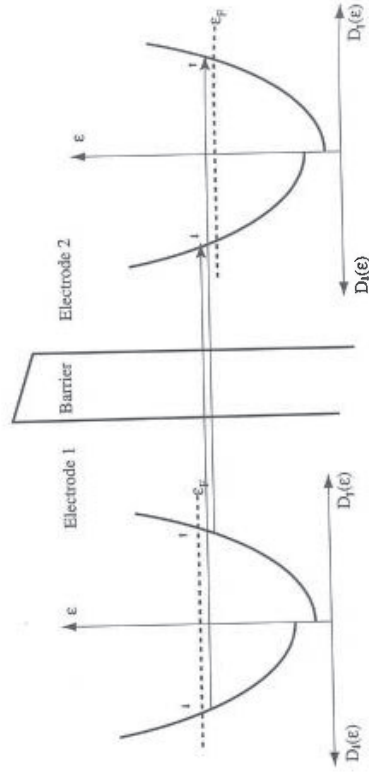


FIGURE 6.26. Spin-dependent (spin polarized) tunneling in ferromagnet/barrier/ferromagnet junctions. The energy bands shown are for free-electron-like tunneling carriers, where $D(\epsilon)$ is the density of states and dashed lines represent the Fermi levels. The spin-up band is split from the spin-down band due to exchange interaction. It is assumed there is no spin flipping.

The *spin polarization* of a ferromagnetic material is defined as

$$p = a_{\uparrow} - a_{\downarrow} = 2a_{\uparrow} - 1, \quad (6.87)$$

where $a_{\uparrow}$ and $a_{\downarrow} (= 1 - a_{\uparrow})$ are the fractions of spin-up electrons and spin-down electrons, respectively. Related to tunneling phenomena under a small bias voltage, only the electrons near the Fermi energy should be counted because they are the tunneling carriers. A simple model was proposed by Julliere to explain spin-dependent tunneling. It was Julliere who first discovered the effect at low temperatures in Fe/Ge/Co junctions.⁴⁷ One can assume that the electrons tunnel through the barrier without spin flipping, i.e., spin-up (or spin-down) electrons tunnel to empty spin-up (or spin-down) electron states only. Therefore, the tunneling current when the magnetizations of the two electrodes are parallel is

$$\begin{aligned} I_p &\propto a_{\uparrow 1} a_{\uparrow 2} + a_{\downarrow 1} a_{\downarrow 2} \\ &= (1 + p_1)(1 + p_2)/4 + (1 - p_1)(1 - p_2)/4 \\ &= (1 + p_1 p_2)/2, \end{aligned} \quad (6.88)$$

where p_1 and p_2 are the spin polarizations of the two electrodes. When the magnetizations are antiparallel, the spins of one electrode are turned upside down, so the tunneling current becomes

$$\begin{aligned} I_{ap} &\propto a_{\uparrow 1} a_{\downarrow 2} + a_{\downarrow 1} a_{\uparrow 2} \\ &= (1 + p_1)(1 - p_2)/4 + (1 - p_1)(1 + p_2)/4 \\ &= (1 - p_1 p_2)/2. \end{aligned} \quad (6.89)$$

The TMR ratio is then

$$\frac{R_{ap} - R_p}{R_p} = \frac{G_p - G_{ap}}{G_{ap}} = \frac{I_p - I_{ap}}{I_{ap}} = \frac{2p_1 p_2}{1 - p_1 p_2}. \quad (6.90)$$

The Julliere model is widely used to predict the TMR ratios attainable in a SDT junction, and ferromagnetic electrodes with larger spin polarizations are sought to achieve higher TMR ratios. For example, for a $\text{Co}_{50}\text{Fe}_{50}/\text{Al}_2\text{O}_3/\text{Co}$ junction, $p_1 \sim 47\%$, $p_2 \sim 34\%$, and a TMR ratio of $\sim 38\%$ can be predicted, which is close to experimentally observed values.

Consider the band structure shown in Fig. 6.26. Near the Fermi level,

$$\begin{aligned} a_{\uparrow} &\propto D_{\uparrow}(\epsilon_F) \propto k_{\uparrow F}, \\ a_{\downarrow} &\propto D_{\downarrow}(\epsilon_F) \propto k_{\downarrow F}, \end{aligned} \quad (6.91)$$

where k_F is the Fermi wavevector. Therefore, the spin polarization of an electrode near the Fermi level can be expressed as

$$p = \frac{k_{\uparrow F} - k_{\downarrow F}}{k_{\uparrow F} + k_{\downarrow F}}, \quad (6.92)$$

which is a good approximation if the tunneling electron band is parabolic and the barrier height is much higher than the Fermi level.⁴⁸ It has been accepted for a long time that the spin polarization of transition metal ferromagnets is roughly proportional to its saturation magnetization.⁴⁹ However, more recent studies indicate that tunneling spin polarization is strongly dependent upon the nature of electrode/barrier bonding at the interfaces, and may vary widely from the traditional accepted values.^{50,51}

The major challenge to use SDT junctions in magnetic read heads is that we must lower their junction resistance. The smallest junction resistance-area product reported to date is about $0.24 \text{ K}\Omega \cdot \mu\text{m}^2$, which is getting close to the required values for MR read head applications.⁵² The research of SDT devices is a rapidly developing research field, and more exciting results are anticipated in the future.

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Magnetic Recording Media

After analyzing magnetic inductive and MR heads, it is natural to revisit the magnetic recording media introduced briefly in Chapter 2. Magnetic recording media contain all the recorded information, with which most users are concerned. No wonder many refer to a magnetic disk drive simply as a "magnetic disk" although it requires a lot of other components to function at all. A magnetic recording layer is composed of either closely packed magnetic particles or continuous magnetic thin films deposited on a substrate. Therefore, magnetic disks are often called *particulate* or *thin-film* disks, respectively.

Magnetic disks are also classified as *flexible* (or floppy) disks and *rigid* (or hard) disks based on the substrates used. Flexible disks commonly use polyester substrates, which are very suitable for removable disk storage such as the 1.4-MB floppy disk and the Iomega zip™ disk. Rigid disks usually use aluminum-magnesium (Al-Mg) alloy, glass, or ceramic substrates. Their rigidity permits higher rotation speeds, lower magnetic spacing, and smaller data track misregistration (see Chapters 14 and 15). Therefore, rigid disks can generally accommodate higher linear data densities and track densities, but they are permanently enclosed in a box and thus remain irremovable. Removable hard disk drives have been designed and commercialized by companies like Iomega and SyQuest, but with somewhat inferior performance compared with irremovable hard disk drives.

Finally, magnetic disks can be classified according to their *form factors* as specified by their physical diameters, as shown in Table 7.1. The first rigid disk drive (IBM 350) commercialized in 1957 employed 24-in.-diameter

TABLE 7.1. Magnetic Disk Form Factors

Form factor (in.)	24	14	8	5.25	3.5	2.5	1.8	1.3
Diameter (mm)	606	355	210	130	95	65	48	33