96

Magnetic and Optical Recording

96.1 Introduction ........................................................................................................... 96-1

96.2 Magnetic Recording .............................................................................................. 96-1

Magnetism and Hysteresis Loop • Magnetic Media • Magnetic Heads • Recording Process • Reproducing Process • Digital versus Analog Recording • Recording Codes • Head/Medium Interface Tribology

Yufeng Li
Samsung Information Systems America

96.3 Optical Recording .................................................................................................. 96-18

CD-ROM • Magneto-optic Recording

References ....................................................................................................................... 96-22

96.1 Introduction

The heart of recording technology is for the process of information storage and retrieval. In addition to its obvious importance in different branches of science and engineering, it has become indispensable to our daily life. When we make a bank transaction, reserve an airplane ticket, use a credit card, watch a movie from a video tape, or listen to music from a CD, we are using the technology of recording. The general requirements for recording are information integrity, fast access, and low cost. Among the different techniques, the most popularly used ones are magnetic and optical recording.

Typical recording equipment consists of a read/write head, a medium, a coding/decoding system, a data access system, and some auxiliary mechanical and electronic components. The head and medium are for data storage and retrieval purposes, and the coding/decoding system is for data error correction. The data access system changes the relative position between the head and the medium, usually with a servo mechanism for data track following and a spinning mechanism for on-track moving. While the data access system and the auxiliary components are important to recording equipment, they are not considered essential in this chapter to the understanding of recording technology, and will not be covered. Interested readers are referred to Ref. [1].

96.2 Magnetic Recording

At present, magnetic recording technology dominates the recording industry. It is used in the forms of hard disk, floppy disk, removable disk, and tape with either digital or analog mode. In its simplest form, it consists of a magnetic head and a magnetic medium, as shown in Figure 96.1. The head is made of a piece of magnetic material in a ring shape (core), with a small gap facing the medium and a coil away from the medium. The head records (writes) and reproduces (reads) information, while the medium stores the information. The recording process is based on the phenomenon that an electric current i generating a magnetic flux \( \phi \) as described by Ampere's law. The flux \( \phi \) leaks out of the head core at the gap,
and magnetizes the magnetic medium which moves from left to right with a velocity \( V \) under the head gap. Depending on the direction of the electric current \( i \), the medium is magnetized with magnetization \( M \) pointing either left or right. The pattern of magnetization is retained in the memory of the medium even after the head moves away.

Two types of head may be used for reproducing. One, termed the *inductive head*, senses magnetic flux change rate, and the other, named the *magneto resistive (M R) head*, senses the magnetic flux. When an inductive head is used, the reproducing process is just the reverse of the recording process. The flux coming out of the magnetized medium surface is picked up by the head core. Because the medium magnetization under the head gap changes its magnitude and direction as the medium moves, an electric voltage is generated in the coil. The process is governed by Faraday’s law. Figure 96.1b schematically shows the digital recording/reproducing process. First, all user data are encoded into a binary format—a serial of 1s and 0s. A write current \( i \) is sent to the coil. The current changes its direction whenever a 1 is being written. Correspondingly, a change of magnetization, termed a *transition*, is recorded in the medium for each 1 in the encoded data. During the reproducing process, the electric voltage induced in the head coil reaches a peak whenever there is a transition in the medium. A pulse detector generates a pulse for each transition. These pulses are decoded to yield the user data.

The minimum distance between two transitions in the medium is the flux change length \( B \), and the distance between two adjacent signal tracks is the track pitch \( W \), which is wider than the signal track width \( w \). The flux change length can be directly converted into bit length with the proper
code information. The reciprocal of the bit length is called linear density, and the reciprocal of the track pitch is termed track density. The information storage areal density in the medium is the product of the linear density and the track density. This areal density roughly determines how much information a user can store in a unit surface area of storage medium, and is a figure of merit for a recording technique. Much effort has been expended to increase the areal density. For example, it has been increased 50 times during the last decade in hard disk drives, and is expected to continue increasing 60% per year in the foreseeable future. At present, state-of-the-art hard disk products feature areal densities of >7 M bits/mm² (B < 0.1 μm and W < 1.5 μm). T gives a total storage capacity of up to 6 Gbytes for a disk of 95 mm diameter.

96.2.1 Magnetism and Hysteresis Loop

Magnetism is the result of uncompensated electron spin motions in an atom. Only transition elements exhibit this property, and nearly all practical interest in magnetism centers on the first transition group of elements (Mn, Cr, Fe, Ni, and Co) and their alloys. The strength of magnetism is represented by magnetization \( M \), and is related to magnetic field \( H \) and magnetic flux density \( B \) by

\[
B = \mu_0(H + M) \tag{96.1}
\]

where

- \( \mu_0 \) is the permeability of vacuum
- Since \( M \) is a property of a magnetic material, it does not exist outside the magnetic material
- \( H \) represents the strength acting on a magnetic material from a magnetic field which is generated either by a magnetic material or by an electric current
- \( B \) is the flux density which determines the induced electric voltage in a coil. The ratio of \( B \) with and without a magnetic material is the relative permeability \( \mu \) of that magnetic material

When a magnetic field \( H \) is applied to a piece of demagnetized magnetic material, the magnetization \( M \) starts increasing with \( H \) from zero. The rate of increase gradually slows down and \( M \) asymptotically approaches a value \( M_s \) at high \( H \). If \( H \) is reduced to zero, then \( M \) is reduced to a lower value \( M_r \). Continuous reduction of \( H \) to a very high negative value will magnetize the material to \( -M_s \). In order to bring the material to demagnetized state, a positive field \( H_e \) is required. Further increase in the \( H \) field will bring the trace of \( M \) to a closed loop. This is the major hysteresis loop, as shown in Figure 96.2.

![FIGURE 96.2 Hysteresis loop of a magnetic material shows the nonlinear relationship between \( M \) and \( H \) that results in magnetic memory.](image-url)
The hysteresis loop shows that a magnetic material has memory. It is this memory that is used in the medium for storing information. $H_C$ is the coercivity, indicating the strength of magnetic field required to erase the memory of a magnetic material. Magnetic materials with high $H_C$ are "hard" magnets, and are suitable for medium applications if they have high $M_s$. On the other hand, magnetic materials with low $H_C$ are "soft" magnets, and are candidates for hard core materials if they have high $M_s$ and high $\mu$. $M_s$ and $M_r$ are the remanent and saturation magnetization, respectively, and their ratio is the remanent squareness. The flux density corresponding to $M_r$ is $B_r$.

### 96.2.2 Magnetic Flux Media

Magnetic media are used to store information in a magnetic recording system. In order to increase the areal density, we need to reduce the flux change length $B$ and track width $w$. Since $B$ is limited by the term $M_r\delta/H_C$, where $\delta$ is the magnetic layer thickness, we can reduce $B$ by either decreasing $M_r\delta$ or increasing $H_C$. However, the amplitude of the magnetic signal available for reproducing head is proportional to the term $M_r\delta w$. If we reduce track width $w$ to increase areal density, we must increase $M_r\delta$ to avoid signal deterioration. In addition, if the magnetic layer is so thin that it causes thickness nonuniformity, more noise will appear in the reproducing process. Therefore, the major requirements for magnetic layer are high $H_C$, high $M_r$, and ease of making a uniform thin layer. Additional requirements include good magnetic and mechanical stability.

There are two groups of magnetic media. The first group is called particulate media because the magnetic materials are in the form of particles. This group includes iron oxide ($\gamma$-Fe$_2$O$_3$), cobalt-modified iron oxide ($\gamma$-Fe$_2$O$_3$+Co), chromium dioxide ($\text{CrO}_2$), metal particles, and barium ferrite (BaFe$_{12}$O$_{19}$). Some of these have been used in the magnetic recording for several decades. More recently, another group of media has been developed largely due to the ever-increasing demand for higher storage capacity in the computer industry. This group of media is the thin-film media, where the magnetic layer can be made as a continuous thin film. Most materials in this group are cobalt-based metal alloys. Compared with particulate media, the thin-film media usually have a higher coercivity $H_C$, a higher remanence $M_r$, and can be deposited in a very thin continuous film. Table 96.1 lists $H_C$ and $M_r$ for some of the most popularly used particulate and thin-film media. Note that magnetic properties are affected by the fabrication process and film structure. Therefore, their values can be out of the ranges of Table 96.1 if different processes are used.

Magnetic media can be classified into three general forms of applications. Tape is the oldest form and remains an important medium today. It is central to most audio, video, and instrumentation recording, although it is also used in the computer industry for archival storage. Tape is economical and can hold a large capacity, but suffers slow access time. Hard disk is primarily used as the storage inside a computer, providing fast data access for the user, but having poor transportability. Flexible disk is designed for easy data transportation, but is limited in capacity. Besides these three general forms of applications, a hybrid of

| TABLE 96.1 Remanence ($M_r$) and Coercivity ($H_C$) Values of Some Commonly Used Magnetic Media |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Particulate | Particulate | Particulate | Particulate |
| Material | Material | Material | Material |
| $\gamma$-Fe$_2$O$_3$ | $\gamma$-Fe$_2$O$_3$+Co | Cr$_2$O$_3$ | BaFe$_{12}$O$_{19}$ |
| $M_r$ (kA/m) | $M_r$ (kA/m) | $H_C$ (kA/m) | $H_C$ (kA/m) |
| 56-140 | 60-140 | 110-140 | 56 |
| 23-32 | 44-74 | 38-58 | 58 |
| Floppy disk, audio, video, and instrumentation tapes | Floppy disk, audio, video, and instrumentation tapes | Floppy disk, audio, video, and instrumentation tapes | Floppy disk |
| T in f lm | T in f lm | T in f lm | T in f lm |
| Co-Ni | Co-Fe | Co-P | Co-Ni-Pt |
| $H_C$ (kA/m) | $H_C$ (kA/m) | $H_C$ (kA/m) | $H_C$ (kA/m) |
| 600-1100 | 1100-1500 | 600-1000 | 600-1100 |
| 30-85 | 60-150 | 36-120 | 60-175 |
| Hard disk | Hard disk | Hard disk | Hard disk |
| Co-Cr-Ta | Co-Cr-Fe | Co-Cr-Pt | Co-Cr-Pt |
| $M_r$ (kA/m) | $M_r$ (kA/m) | $M_r$ (kA/m) | $M_r$ (kA/m) |
| 350-900 | 300-750 | | |
| 55-190 | 56-200 | | |
| Hard disk | Hard disk | | |

96.2.3 Magnetic Heads

Magnetic heads have three functions: recording, reproducing, and erasing. Usually for stationary head applications such as tape drives, multiple heads are used to perform these functions. For moving head applications such as disk drives, a single head is employed because of the requirements of simple connections and small head mass for fast data access. Most of these heads are the inductive type, where the fundamental design is an inductive coil and a magnetic core. The general requirements for the core materials are high relative permeability $\mu$, high saturation flux density $B_s$, low coercivity $H_c$, high electric...
resistivity $\rho$, and low magnetostriction coefficient $\lambda$. Some of the properties for the commonly used core materials are listed in Table 96.2.

The evolution of the magnetic head follows the selection of core materials, as shown in Figure 96.4. Early heads used laminated molybdenum Permalloy (Ni-Fe-Mo, 79-17-4 wt%). These heads are inexpensive to make, and have low $H_c$ and high $\mu$ and $B_s$. The primary drawbacks are frequency limitation, gap dimension inaccuracy, and mechanical softness. Frequency limitation is caused by the difficulty of making the

<table>
<thead>
<tr>
<th>Material</th>
<th>$\mu$</th>
<th>$B_s$ (T)</th>
<th>$H_c$ (A/m)</th>
<th>$\rho$ ($\mu\Omega$ cm)</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni-Fe-Mo</td>
<td>11,000</td>
<td>0.8</td>
<td>2.0</td>
<td>100</td>
<td>Audio tape</td>
</tr>
<tr>
<td>Ni-Zn</td>
<td>300-1,500</td>
<td>0.4-0.46</td>
<td>11.8-27.6</td>
<td>$10^{11}$</td>
<td>Floppy and hard disk drives, video and instrumentation tapes</td>
</tr>
<tr>
<td>Mn-Zn</td>
<td>3,000-10,000</td>
<td>0.4-0.6</td>
<td>11.8-5.8</td>
<td>$10^6$</td>
<td>Floppy and hard disk drives, video and instrumentation tapes</td>
</tr>
<tr>
<td>Fe-Si-Al</td>
<td>8,000</td>
<td>1.0</td>
<td>2.0</td>
<td>85</td>
<td>Floppy and hard disk drives, video and instrumentation tapes</td>
</tr>
<tr>
<td>Ni-Fe</td>
<td>2,000-4,000</td>
<td>1.0</td>
<td>&lt;10</td>
<td>20</td>
<td>Hard disk drives</td>
</tr>
</tbody>
</table>


Figure 96.4 Schematic illustrations of (a) a laminated head, (b) cross section of a MIG head, (c) cross section of a thin-film head, and (d) an MRF sensor with leads.
lamination layer thinner than 25 μm. Eddy current loss, which is proportional to layer thickness and square root of frequency, reduces the effective permeability. As a result, laminated heads are seldom used for applications exceeding 10 MHz. Gap dimension inaccuracy is associated with the head fabrication process, and makes it unsuitable for high areal density applications. Lack of mechanical hardness reduces its usable life.

One way to reduce eddy current loss is to increase core material electric resistivity. Two types of ferromagnetic materials have high resistivity (four to nine orders higher than Permalloy) and reasonable magnetic properties: Ni–Zn and Mn–Zn. These materials are also very hard, elongating head life during head/medium contacts. The major deficiency of ferrite materials is their low $B_s$ values. In order to record in high $H_r$ media, high flux density $B$ is needed in the head core. When the flux density in the core material reaches its saturation $B_s$, it will not increase despite the increase of recording current or coil turns. $T$ is saturation starts from the corners of the gap due to its geometry. To remedy this deficiency, a layer of metallic alloy material with much higher $B_s$ is deposited on the gap faces. $T$ is type of head is called the metal-in-gap (MIG) head. Sendust (Fe–Si–Al, 85–9.6–5.4 wt%) is one of the materials used for the deposition. MIG heads are capable of recording up to 100 MHz frequency and 180 kA/m medium coercivity. Thin-film heads capitalize on semiconductor-like processing technology to reduce the customized fabrication steps for individual heads. The core, coil, gap, and insulator layers are all fabricated by electroplating, sputtering, or evaporation. Due to the nature of the semiconductor process, the fabrication is accurate for small dimensions. Small gap dimensions are suitable for high linear and track density, and small core dimensions allow the use of high $B_s$. Permalloy material (Ni–Fe, 80–20 wt%) as core with low inductance for high data rate applications. Thin-film heads are used for high medium $H_r$, high areal density applications. The high cost of the semiconductor-like process is of set by high throughput: a 150 × 150 mm wafer can produce 16,000 nanoslider heads. One disadvantage is the limited-band recording capability because the small pole length limits low-frequency response and introduces under-shoots. A second disadvantage, the Barkhausen noise, is caused by the relatively small number of magnetic domains in the core. At present, thin-film heads are used up to frequencies of 80 MHz and medium coercivity of 200 kA/m. MIG thin-film heads are also being used for high-coercivity applications.

An inductive head is often used for both recording and reproducing. The optimal performance cannot be achieved because recording and reproducing have contradictory requirements for head design. To solve this problem, the MR head has been developed. The MR head is for reproducing only, and an inductive head is used for recording. As schematically shown in Figure 96.4, an MR head has a magnetoresistive element (MRE) and two electric leads. The MRE is a Permalloy stripe (Ni–Fe, 80–20 wt%), with thickness $t$, width $w$, and height $h$. An electric current, with density $J$, passes through the MRE through the leads. The electric resistivity of the MRE is a function of the angle $\theta$ between $J$ and MRE magnetization $M$:

$$\rho_\theta = \rho \left(1 + \frac{\Delta \rho}{\rho} \cos^2 \theta \right)$$  \hspace{1cm} (96.2)

where

- $\rho_\theta$ is the resistivity at $\theta$
- $\rho$ is the resistivity at $\theta = 90^\circ$
- $\Delta \rho$ is the resistivity difference between $\theta = 0^\circ$ and $\theta = 90^\circ$
- $\Delta \rho/\rho$ is the anisotropic M R ratio (AMR) of the MRE

Usually, a transverse magnetic field is applied to the MRE so that $\theta = \theta_0$ when the head is not reading a magnetic signal. Assume that a magnetic signal from the medium rotates $M$ from $\theta_0$ to $\theta$, then an electric voltage change $v$ will be detected across the MRE as the output signal:

$$v = J \omega \frac{\Delta \rho}{\rho} (\sin^2 \theta_0 - \sin^2 \theta)$$  \hspace{1cm} (96.3)
where $\theta_b$ is the bias angle and is set to 45° for good linearity. In practice, a longitudinal bias is also used along the M RE width direction to stabilize the magnetic domain and reduce large Barkhausen noise. To compare the output between an M R head and an inductive head, we write the inductive head output using Faraday’s equation:

$$
\nu = -nV \frac{d\phi}{dx}
$$

where

- $n$ is the number of the coil turns
- $V$ is the medium velocity
- $\phi$ is the magnetic flux
- $x$ is the coordinate axis fixed on the medium surface

Equations 96.3 and 96.4 tell us that while inductive head output is proportional to medium velocity and not suitable for low-velocity applications, the M R head can be used for either high- or low-velocity applications.

### 96.2.4 Recording Process

We can imagine the recording process in two steps. First, the magnetic flux flowing in the head core generates a fringe magnetic field around the gap. Then the magnetic field magnetizes the magnetic medium and leaves a magnetization transition in it. Partly due to the nonlinear nature of the hysteresis loop, the recording process is so complex that there has been no rigorous explanation. However, we can still obtain significant insights into the recording process by using simple models if we keep in mind the limitations.

If we set the origin of a coordinate system at the center of the gap with $x$ axis on the head surface and $y$ axis pointing away from the head, then the longitudinal magnetic field $H_x$ and perpendicular magnetic field $H_y$ of this head can be expressed by the Karlqvist approximation [2]:

$$
H_x = \frac{ni}{\pi(g + lA_g/\mu A_c)} \tan^{-1} \left[ \frac{yg}{x^2 + y^2 - (g^2/4)} \right]
$$

$$
H_y = \frac{ni}{2\pi(g + lA_g/\mu A_c)} \ln \left[ \frac{(x - g/2)^2 + y^2}{(x + g/2)^2 + y^2} \right]
$$

where

- $n$ is the number of coil turns
- $i$ is the current in the coil
- $g$ is the gap length
- $l$ is the core length
- $A_g$ is the core cross-sectional area
- $\mu$ is the relative permeability of core material
- $A_c$ is the gap cross-sectional area

Both Equations 96.5 and 96.6 give accurate results for points 0.25g away from gap corners. Since longitudinal recording mode dominates the magnetic recording industry, we will focus on the field $H_x$. Equation 96.5 shows that the contours of constant $H_x$ field are circles nesting on the two gap corners, as shown in Figure 96.5. The greater the diameter of the circle is the weaker the magnetic field. Assume a magnetic medium, moving from left to right with a distance $d$ above the head, has a thickness $\delta$ and a magnetization $M$ pointing to right. At some instant, the recording current turns on and generates
FIGURE 96.5 The constant horizontal fields of the Karlqvist approximation are circles resting on the gap corners of a head, and the change of magnetization in the medium is gradual.

The magnetic field $H_x$ above the gap as depicted in Figure 96.6. On the circumference of $H_x = H_c$, half of medium material has its magnetization reversed and half remains the same, resulting in a zero total magnetization. Since $H_x$ has a gradient, the medium closer to the gap (inside a smaller circle) gets its magnetization reversed more completely than the medium farther away from the gap (outside a bigger circle). Therefore, magnetic transition is gradual in the medium even if the change of recording current follows a step function. Assume the original magnetization is $M_i$ and the completely reversed magnetization is $-M_i$, this gradual change of magnetization for an isolated transition can be modeled by [3]:

$$M = \frac{2}{\pi} M_i \tan^{-1} \frac{x}{a}$$  \hspace{1cm} (96.7)

where

$x$ is the distance from the center of transition
$a$ is a parameter characterizing the sharpness of the transition as shown in Figure 96.6

FIGURE 96.6 An isolated arctangent magnetization transition from negative $M_i$ to positive $M_i$. 

© 2014 by Taylor & Francis Group, LLC
Assuming a thin-film medium and using the Karlqvist approximation for the head field, \( a \) is found to be [4–6]

\[
a = \frac{(1 - S^*)(d + \delta/2)}{\pi Q} + \sqrt{\frac{(1 - S^*)(d + \delta/2)}{\pi Q}} + \frac{M_\delta(d + \delta/2)}{\pi QH_c} \tag{96.8}
\]

where

\( S^* \) is the medium loop squareness

\( Q \) is the head field gradient factor

For a reasonably well-designed head, \( Q \approx 0.8 \). It is obvious that we want to make parameter \( a \) as small as possible so that we can record more transitions for a unit medium length. If the head gap length \( g \) and medium thickness \( \delta \) are small compared with head/medium separation \( d \), and the medium has a squareness of 1, then the minimum possible value of \( a \) is [7]

\[
a_m = \begin{cases} 
\frac{M_\delta}{2\pi H_c} & \frac{M_\delta}{4\pi H_c d} \geq 1 \\
\sqrt{\frac{M_\delta d}{\pi H_c}} & \frac{M_\delta}{4\pi H_c d} < 1 
\end{cases} \tag{96.9}
\]

In order to decrease the value of \( a \) and therefore increase areal density, we need to reduce medium remanence \( M_r \), thickness \( \delta \), head/medium separation \( d \), and to increase coercivity \( H_c \).

### 96.2.5 Reproducing Process

In contrast to the recording process, the reproducing process is well understood. The flux density induced in the head core is on the order of a few millitesla, yielding a linear process for easier mathematical treatment. The head fringe field is the Karlqvist approximation (Equation 96.5) and the foundation is the reciprocity theorem. For an isolated transition (Figure 96.6) with a thin magnetic layer \( \delta \ll d \), the induced electric voltage \( v \) for an inductive head is [7]

\[
v(x) = \frac{-2\mu_0 V w M_\delta n}{\pi (g + l A_{e}/\mu A_c)} \left[ \tan^{-1} \left( \frac{g/2 + x}{a + d} \right) + \tan^{-1} \left( \frac{g/2 - x}{a + d} \right) \right] \tag{96.10}
\]

where

\( \mu_0 \) is the permeability of vacuum

\( \mu \) is the relative permeability of the core

\( V \) is the medium velocity

\( w \) is the track width

\( n \) is the number of coil turns

\( g \) is the head gap length

\( d \) is the head/medium separation

\( x \) is the distance between the center of the medium transition and the center of the head gap

The term \( l A_{e}/\mu A_c \) is closely related to \( g \) for head efficiency. When a transition passes under the head, its voltage starts with a very low value, reaches a peak, then falls off again, as shown in Figure 96.7, where the following typical values for a hard disk drive are used: \( V = 20 \text{ m/s} \), \( w = 3.5 \mu \text{m} \), \( M_r = 450 \text{ kA/m} \), \( \delta = 50 \text{ nm} \), \( n = 50 \), \( l A_{e}/\mu A_c = 0.1g \). The effects of \( g \) and \( a + d \) are shown in Figure 96.7. Since a greater peak voltage and a narrower spatial response are desired for the reproducing process, smaller \( g \) and \( a + d \) values are helpful.
When an MR head is used for reproducing, the MRE is usually sandwiched between two magnetic shields to increase its spatial resolution to medium signals, as shown in Figure 96.8. Since the MR head is flux-sensitive, the incident flux $\phi_i$, on the bottom surface of the MRE, should be derived as a function of the distance ($x$) between the center of MRE and the center of the transition [7,8]:

$$\phi_i(x) = \frac{2\mu_0 w M_c \delta (a + d)}{\pi g} \left[ f \left( \frac{x + (g + t)/2}{a + d} \right) - f \left( \frac{x + t/2}{a + d} \right) \right]$$

$$+ f \left( \frac{x - (g - t)/2}{a + d} \right) - f \left( \frac{x - t/2}{a + d} \right)$$

(96.11)

where

- $g$ is the distance between the MRE and the shield
- $t$ is the MRE thickness

$$f(\beta) = \beta \tan^{-1} \beta - \ln(\sqrt{1 + \beta^2})$$

(96.12)

FIGURE 96.7 The reproducing voltage of an inductive head over an isolated arctangent transition shows the effects of gap length $g$, parameter $a$, and head/medium separation $d$.

FIGURE 96.8 Schematic diagram of a shielded MR head with a shield to MRE distance $g$. 
The angle between magnetization and current varies along the MRE height \( h \). To find out the variation, we need to calculate the signal flux decay as a function of \( y \) by

\[
\phi_s(y) = \phi_i \sin h((h - y)/l_c) \\
\sin h(h/l_c) \tag{96.13}
\]

where

\[
l_c = \sqrt{\frac{\mu g t}{2}} \tag{96.14}
\]

Then the bias angle \( \theta_b \) and signal angle \( \theta \) can be calculated by

\[
\sin \theta_b(y) = \frac{\phi_b(y)}{M_s} \tag{96.15}
\]

and

\[
\sin \theta(y) = \frac{\phi_s(y) + \phi_b(y)}{M_s} \tag{96.16}
\]

where
- \( \phi_b \) is the biasing flux in the MRE
- \( M_s \) is the saturation magnetization of the MRE

Application of Equations 96.15 and 96.16 to Equation 96.3 and integration over height \( h \) lead to

\[
v = \frac{J w}{\rho} \frac{A \rho}{h} \left[ \int_0^h \sin^2 \theta_b(y) dy - \int_0^h \sin^2 \theta(y) dy \right] \tag{96.17}
\]

For an M R head with a 45° bias at the center and small height \( h \ll l_c \), the peak voltage is [6]

\[
v_p \approx \frac{9J w M_s \delta_s (g + t)}{8\sqrt{2} \mu g M_s} \tan^{-1} \left[ \frac{g}{2(a + d)} \right] \tag{96.18}
\]

The general shape of the reproducing voltage from an M R head is similar to that in Figure 96.7.

The study of an isolated transition reveals many intrinsic features of the reproducing process. However, transitions are usually recorded closely in a magnetic medium to achieve high linear density. In this case, the magnetization variation in the medium approaches a sinusoidal wave. That is,

\[
M(x) = M_s \sin \frac{2\pi x}{\lambda} \tag{96.19}
\]

where \( \lambda \) is the wavelength. The reproducing voltage in an inductive head becomes [9,10]

\[
v(x) = -\frac{\mu_o V w M_s A_g (e^{-2\pi d/\lambda})(1 - e^{-2\pi d/\lambda})}{g + I A_k/\mu A_c} \left( \frac{\sin(\pi g/\lambda)}{\pi g/\lambda} \right) \cos \frac{2\pi x}{\lambda} \tag{96.20}
\]

This equation presents all the important features of the high linear density-reproducing process. The term \( e^{-2\pi d/\lambda} \) is the spacing loss. It shows that the reproducing voltage falls exponentially.
with the ratio of head/medium spacing to wavelength. The second term $1 - \exp(-2\pi\delta/\lambda)$ is the thickness loss. The name of this term is misleading because its value increases with a greater medium thickness. However, the rate of increase diminishes for thicker medium. In fact, 80% of the maximum possible value is achieved by a medium thickness of 0.25\(\lambda\). The last term $\sin(\pi g/\lambda)/(\pi g/\lambda)$ is the gap loss. This term is based on the Karlovqvist approximation. If a more accurate head fringe field is used, this term is modified to $\sin(\pi g/\lambda)\sin(1.25g^2 - \lambda^2)/(g^2 - \lambda^2)$ [11]. It shows a gap null at $\lambda = 1.12g$, and limits the shortest wavelength producible. These three terms are plotted in Figure 96.9. The most significant loss comes from the spacing loss term, which is 54.6 dB for $d = \lambda$.

Therefore, one of the biggest efforts spent on magnetic recording is to reduce the head/medium spacing as much as possible without causing mechanical reliability issues. For an MR head, the reproducing voltage is [11]

$$v \propto \frac{4M_i\Delta p A\lambda}{ht} \left(e^{-2\pi\delta/\lambda}\left(1 - e^{-2\pi\delta/\lambda}\right)\frac{\sin(\pi g/\lambda)}{\pi g/\lambda}\right) \frac{\pi(g + t)}{\lambda} \cos \frac{2\pi x}{\lambda}$$  \hspace{1cm} (96.21)

**96.2.6 Digital versus Analog Recording**

Due to the nonlinearity of the hysteresis loop, magnetic recording is intrinsically suitable for digital recording, where only two states (1 and 0) are to be recognized. Many physical quantities, however, are received in analog form before they can be recorded, such as in consumer audio and instrumentation recording. In order to perform such recording, we need to either digitize the information or use the analog recording technique. In the case of digitization, we use an analog-to-digital converter to change a continuous signal into binary numbers. The process can be explained by using the example shown in Figure 96.10.

An electric signal $V$, normalized to the range between 0 and 1, is to be digitized into 3 bits. The signal is sampled at time $t = 1, 2, \ldots, 6$. At each sampling point, the first bit is assigned a 1 if the value of the continuous signal is in the top half ($>0.5$), otherwise assigned a 0. The second bit is assigned a 1 if the value of the continuous signal is in the top half of each half ($0.25 \leq V < 0.5$, or $>0.75$), otherwise assigned a 0. The third bit is assigned similarly. If the first bit is the most significant bit (MSB), and the last bit is the least significant bit.
The converted binary numbers are listed below each sampling point in Figure 96.10. The process of digitization is termed quantization. In general, the final quantization interval is

\[ \Delta V = \frac{V}{2^N} \]  \hspace{1cm} (96.22)

where

- \( V \) is the total voltage range
- \( N \) is the number of bits

Because we use a finite number of bits, statistically there is a difference between the continuous signal and the quantized signal at the sampling points. This is the quantization error. It leads to a signal-to-quantization-noise ratio [12]:

\[ \text{SNR} = \frac{12P_s}{\Delta V^2} \]  \hspace{1cm} (96.23)

where \( P_s \) is the mean square average signal power. For a signal with uniform distribution over its full range, this yields

\[ \text{SNR} = 2^{2N} \]  \hspace{1cm} (96.24)

For a sinusoidal signal, it changes to

\[ \text{SNR} = 1.5 \times 2^{2N} \]  \hspace{1cm} (96.25)

The SNR can be improved by using more bits. Improvement, however, is limited by the SNR of the incoming continuous signal. The quantized signal is then pulse code modulated (PCM) for recording.

For analog recording, a linear relationship between the medium magnetization and the recording signal is required. This is achieved through the anhysteretic magnetization process. If we apply an alternating magnetic field and a unidirectional magnetic field to a previously demagnetized medium, and then reduce the amplitude of the alternating field to zero before we remove the unidirectional field, the remanent magnetization shows a pseudo-linear relationship with the unidirectional field strength \( H_u \) up to some level. Figure 96.11 shows such an anhysteretic curve. The linearity deteriorates as \( H_u \) gets greater. In applications, the recording signal current is biased with an ac current of greater amplitude.
and higher frequency. Therefore, it is also termed ac-biased recording. Analog recording is easy to implement, at the price of a lowered SNR because remanent magnetization is limited to about 30% of the maximum possible $M_r$ to achieve good linearity.

### 96.2.7 Recording Codes

PCM is a scheme of modifying input binary data to make them more suitable for a recording and reproducing channel. These schemes are intended to achieve some of the following goals: (1) reducing the dc component, (2) increasing linear density, (3) providing self-clocking, (4) limiting error propagation, and (5) achieving error-free detection. There is numerous code schemes, only three of the ones developed early are shown in Figure 96.12. The earliest and most straightforward one is the return-to-zero (RZ) code. In this scheme, a positive and negative pulse is used to represent each 1 and 0, respectively, of the data. The main drawback is that direct recording over old data is not possible due to the existence of zero recording current between two data. It also generates two transitions for each bit, therefore reducing the linear density. In addition, it only uses half of the available recording current range for a transition. The non-return-to-zero-invert (NRZI) method was developed to alleviate some of these problems. It changes the recording current from one direction to the other for each 1 of the data, while making no changes for all 0s. However, it has a strong dc component and may lose reproducing synchronization if

![Graph showing remanent magnetization](image)

**FIGURE 96.11** An anhysteretic remanent magnetization shows a pseudo-linear relationship with the applied unidirectional magnetic field to some $H_u$ level.

![Comparison of codes](image)

**FIGURE 96.12** Comparison of some early developed codes.
there is a long string of 0s in the input data. In addition, reproducing circuits are usually not designed for dc signal processing. In frequency modulation (FM) code, there is always a transition at the bit-cell boundary which acts as a clock. There is also an additional transition at the bit-cell center for each 1 and no transition for 0s. It reduces the dc component significantly. The primary deficiency is the reduction of linear density since there are two transitions for each 1 in the data.

The most popularly used codes for magnetic recording are the run length–limited (RLL) codes. They have the general form of \( m/n(d, k) \). In these schemes, data are encoded in groups. Each input group has \( m \) bits. After encoding, each group contains \( n \) bits. In some schemes, multiple groups are coded together. \( d \) and \( k \) are the minimum and maximum 0s, respectively, between two consecutive 1s in the encoded sequence. While \( d \) is used to limit the highest transition density and intersymbol interference, \( k \) is employed to ensure adequate transition frequency for reproducing clock synchronization. The encoding is carried out by using a lookup table, such as Table 96.3 for a \( \frac{1}{2}(2, 7) \) code [13].

### 96.2.8 Head/Medium Interface Tribology

As expressed in Equation 96.20, the most effective way to increase signal amplitude, therefore areal density, is to reduce head/medium spacing \( d \). However, wear occurs when a moving surface is in close proximity to another surface. The amount of wear is described by Archard’s equation:

\[
V = k \frac{WS}{H}
\]

(96.26)

where

- \( V \) is the volume worn away
- \( W \) is the normal load
- \( S \) is the sliding distance
- \( H \) is the hardness of the surface being worn away
- \( k \) is a wear coefficient

In order to increase medium hardness \( H \), hard Al\(_2\)O\(_3\) particles are dispersed in particulate media and a thin layer of hard carbon (=10 nm) with either hydrogenation or natrogeneation is coated on thin-film media of hard disks. A layer of liquid lubricant, typically polyurea with various end groups and additives, is applied on top of the carbon film to reduce the wear coefficient \( k \). Load is minimized to reduce wear while keeping adequate head/medium dynamic stability. For applications where the sliding distance \( s \) is modest over the lifetime of the products such as floppy disk drives and consumer tapes drives, the head physically contacts the medium during operations. In the case of hard disk application, heads are separated nominally from the media by a layer of air cushion. The head is carried on a slider, and the slider uses air-bearing surfaces (ABS) to create air film based on hydrodynamic lubrication theory. Figure 96.13 shows two commonly used ABS. Tapers are used to help the slider takeoff
and maintain flying stability. ABS generates higher-than-ambient pressure to lift the slider above the medium surface during operations. The tripad slider is for pseudo-contact applications while the sub-ambient pressure (SAP) slider is for flying (such as MR head) applications. Because the relative linear velocity between the slider and the medium changes when the head moves to different radii, a cavity region is used in the SAP slider to generate suction force to reduce flying height variation. The ABS is designed based on the modified Reynolds equation:

$$\frac{\partial}{\partial X} \left( PH^3 Q \frac{\partial P}{\partial X} \right) + \frac{\partial}{\partial Y} \left( PH^3 Q \frac{\partial P}{\partial Y} \right) = \Lambda_x \frac{\partial (PH)}{\partial X} + \Lambda_y \frac{\partial (PH)}{\partial Y} + \sigma \frac{\partial (PH)}{\partial T}$$  (96.27)

where

- $X$ and $Y$ are coordinates in the slider longitudinal and transverse directions normalized by the slider length and width, respectively
- $P$ is the hydrodynamic pressure normalized by the ambient pressure
- $H$ is the distance between the ABS and medium surface normalized by the minimum flying height
- $Q$ is the molecular slip factor
- $T$ is time normalized by the characteristic squeeze period
- $\Lambda_x$ and $\Lambda_y$ are the bearing numbers in the $x$ and $y$ directions, respectively
- $\sigma$ is the squeeze number

A full derivation and explanation of the Reynolds equation can be found in Ref. [14]. At present, high end hard disk drives feature a flying height on the order of 20–50 nm.

When power is turned off, the slider in the popularly used Winchester-type drives rests on the medium surface. Although the ABS and medium surface look flat and smooth, they really consist of microscopic peaks and valleys. If we model an ABS/medium contact by a flat surface and a sphere tip, the liquid lubricant on the medium surface causes a meniscus force $F_m$ as depicted in Figure 96.14 [15]:

$$F_m = \frac{4\pi R \gamma \cos \theta}{1 + \gamma/(h - y)}$$  (96.28)

where

- $R$ is the radius of the sphere
- $\gamma$ is the surface tension of the lubricant
- $\theta$ is the contact angle between the lubricant and the surfaces
- $y$ is the sphere to flat surface distance
- $h$ is the lubricant thickness
FIGURE 96.14 Formation of meniscus between a sphere tip and a flat at surface.

Detailed analysis [16] shows that the static friction $F$ at a head/medium interface is a function of several parameters:

$$F = f(h, R, A, \eta, \gamma, \theta, E', \phi, \sigma, s)$$  \hspace{1cm} (96.29)

where

- $A$ is the ABS area
- $\eta$ is the peak density
- $E'$ is the effective modulus of elasticity
- $\phi$ is the peak height distribution
- $\sigma$ is the rms peak roughness
- $s$ is the solid-to-solid shear strength

If friction $F$ is too large, either the drive cannot be started or the head/medium interface is damaged. While friction can be reduced practically by reducing $A, \gamma,$ and increasing $\theta,$ the most effective ways are to control $h, \sigma, \eta,$ and $\phi.$ Too thin a lubricant layer will cause wear, and too thick will induce high friction. $T$ limits $h$ to the range of 1-3 nm, $\sigma$ is controlled by surface texture. Historically, texture is created by mechanical techniques using either free or fixed abrasives. $T$ is leaves a surface with a random feature and is unsuitable for controlling $\eta$ and $\phi.$ Recently, people started to use lasers [17]. $T$ is technique generates a surface texture with well-defined $\eta$ and $\phi$ to improve wear and friction performance. Figure 96.15 shows AFM images of a mechanical and a laser texture.

### 96.3 Optical Recording

The major obstacle to achieving higher areal density in magnetic recording is the spacing loss term. It is a great engineering challenge to keep heads and media in close proximity while maintaining the head/medium interface reliable and durable. Care must also be taken in handling magnetic media since even minute contamination or scratches can destroy the recorded information. In addition, the servo technique of using magnetic patterns limits the track density to about one order lower than the linear density. Optical recording, on the other hand, promises to address all these concerns.

Optical recording can be categorized into three groups. In the first group, information is stored in the media during manufacturing. Users can reproduce the information, but cannot change or record new information. CD-ROM (compact disk-read only memory) belongs to this group. The second group is WORM (write once read many times). Instead of recording information during manufacturing, it leaves this step to the user. This is usually achieved by creating physical holes or blisters in the media during
the recording process. Once it is recorded, however, the medium behaves like the first group: no further recording is possible. The third group is similar to magnetic recording. Recording can be performed infinitely on the media by changing phase or magnetization of the media. The most noticeable example in this group is the magneto-optic (MO) technique [18]. Only CD-ROM and the MO recording are described in the following sections.

96.3.1 CD-ROM

Figure 96.16 shows the CD-ROM reproducing principle. Data are pressed as physical pits and lands on one surface of a plastic substrate, usually polycarbonate. A layer of aluminum is deposited on this surface to yield it reflective. Lacquer is then coated to protect the aluminum layer. During the reproducing process, an optical lens is used to focus a laser beam on the reflective pit and land surface. The diameter of the lens is \( D \), the distance between the lens and the substrate is \( h_3 \), and the substrate thickness is \( h_2 \). The diameter of the laser beam is \( d_2 \) when entering the substrate, and becomes \( d_1 \) when focused on the reflective surface. The width of the pits is designed smaller than \( d_1 \). The reflected light consists of two
FIGURE 96.16  Schematic representation of the CD-ROM reproducing principle.

portions: \( I_1 \) from the land and \( I_2 \) from the pit. According to the theory of interference, the intensity of the reflected light is

\[
I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \frac{4\pi h_1}{\lambda}
\]  

(96.30)

where

- \( \lambda \) is the wavelength of the laser
- \( h_1 = \lambda/4 \) is the pit height

\( T \) is leads to

\[
I = \begin{cases} 
I_1 + I_2 - 2\sqrt{I_1 I_2} & \text{if there is a pit (} h_1 = \lambda/4 \text{)} \\
I_1 + I_2 + 2\sqrt{I_1 I_2} & \text{if there is no pit (} h_1 = 0 \text{)}
\end{cases}
\]

(96.31)

\( T \) is change of light intensity is detected and decoded to yield the recorded data. The reflected light is also used for focusing and track following.

The fundamental limit on optical recording density is the focused beam diameter \( d_2 \). For a Gaussian (TEM\(_{00}\)) laser, this is the diffraction-limited diameter at which the light intensity is reduced to 1/\( e^2 \) of the peak intensity:

\[
d_2 \approx \frac{2\lambda}{\pi\theta}
\]

(96.32)

where \( \theta \) is the aperture angle. The following values are typical for a CD-ROM system: \( \lambda \) (gallium arsenide laser) = 780 nm, \( \theta = 27^\circ \), \( h_2 = 1.2 \) mm, \( D = 5 \) mm, \( h_3 = 4.2 \) mm. \( T \) is yields \( d_3 \approx 1.0 \mu\text{m} \) and \( d_2 \approx 0.7 \) mm, and sets the areal density limit of optical (including MO) recording to about 1 M bit/mm\(^2\). For most CD-ROM applications, the areal density is smaller than this limit, and a disk with 120 mm diameter holds about 600 M byte information. In order to increase areal density, we can either reduce light wavelength or increase numerical aperture. Much of the effort has been to adopt a new light source with short wavelength such as a bluel laser. Increasing numerical aperture is more difficult because increasing lens diameter is cost prohibitive and reducing \( h_2 \) or \( h_3 \) is reliability limited. Note that although the beam...
size on the focus plane is on the order of 1 μm \((d_z)\), it is two to three orders greater at the air/substrate interface \((d_y)\). The means that optical recording can tolerate disk surface contamination and scratches much better than magnetic recording. However, the performance of optical recording does not match magnetic recording in general. The data transfer rate of CD-ROM drives is expressed as multiple \((\times)\) of 150 kB/s. Even for a 12× CD-ROM drive, the data access time and data transfer rate are still on the order of 100 ms and 1.8 M B/s, respectively, while for a high-performance rigid disk drive these values are less than 10 ms and greater than 30 M B/s, respectively.

### 96.3.2 Magneto-optic Recording

The primary drawback of a CD-ROM to an end user is its inability to record. The deficiency is remedied by MO recording technology, as depicted in Figure 96.17. A linearly polarized laser beam is focused on a layer of magnetic material, and a coil provides a dc magnetic field on the other side of the medium. The dc magnetic field is too weak to affect the medium magnetization at normal temperature. The recording process utilizes the thermomagnetic property of the medium, and the reproducing process is achieved by using the Kerr effect. During recording, the medium is initialized magnetized vertically in one direction, and the dc magnetic field is in the opposite direction. The laser heats up the medium to its Curie temperature, at which the coercivity becomes zero. During the cooling process, the dc magnetic field aligns the medium magnetization of the heated region to the magnetic field direction. In the process of reproducing, the same laser is used with a smaller intensity. The medium is heated up to its compensation temperature, at which the coercivity becomes extremely high. Depending on the direction of the magnetization, the polarization of the reflected light is rotated either clockwise or counterclockwise (Kerr rotation). The rotation of polarization is detected and decoded to get the data. The main disadvantage of MO recording is that a separate erasing process is needed to magnetize the medium in one direction before recording. Recently, some technologies have been developed to eliminate this separate erasing process at the cost of complexity.

The medium used in MO recording must have a reasonable low Curie temperature \((<300^\circ\text{C})\). The materials having this property are rare earth transition metal alloys, such as \(\text{Tb}_{27}\text{Fe}_{77}\) and \(\text{Tb}_{21}\text{Co}_{29}\). Unfortunately, the properties of these materials deteriorate in an oxygen and moisture environment. To protect them from air and humidity, they are sandwiched between an overlayer and an underlayer, such as \(\text{SiO}, \text{Al}_{2}\text{O}_{3}, \text{SiN},\) and \(\text{TiO}_{2}\). Another issue with the rare earth transition metal alloys is their small Kerr rotation, about 0.3°. To increase this Kerr rotation, multiple layers are used. In the so-called quadrilayer structure (Figure 96.17b), the overlayer is about a half-wavelength thick and the underlayer is about a quarter-wavelength thick [18]. The MO layer is very thin \((\approx 3 \text{ nm})\). Light reflected from the reflector is out of phase with the light reflected from the surface of the MO layer, and is in-phase with the light reflected from the inside of the MO layer. As a result, the effective Kerr rotation is increased several times.

**FIGURE 96.17** Schematic illustrations of (a) MO recording/reproducing and (b) quadrilayer medium cross section.
TABLE 96.4 Digital Magnetic and Optical Storage Devices

<table>
<thead>
<tr>
<th>Description</th>
<th>Manufacturers</th>
<th>Approximate Price, $</th>
</tr>
</thead>
<tbody>
<tr>
<td>T in-film head for hard disk drive</td>
<td>AMC, Read-Rite, SA E</td>
<td>6.00–9.00</td>
</tr>
<tr>
<td>M R head for hard disk drive</td>
<td>AMC, Read-Rite, SA E, Seagate</td>
<td>8.00–12.00</td>
</tr>
<tr>
<td>T in-film hard disk</td>
<td>Akashic, HMT, Komag, M CC, Stormmedia</td>
<td>7.00–10.00</td>
</tr>
<tr>
<td>Hard disk drive</td>
<td>IBM, Maxtor, Quantum, Samsung, Seagate, WD</td>
<td>0.02–0.20/M bytes</td>
</tr>
<tr>
<td>Floppy drive</td>
<td>Panasonic, Sony</td>
<td>20.00–40.00</td>
</tr>
<tr>
<td>Floppy disk</td>
<td>3M, Fuji, Memorex, Sony</td>
<td>0.15–0.50</td>
</tr>
<tr>
<td>Removable rigid disk drive</td>
<td>Iomega, Syquest</td>
<td>100.00–400.00</td>
</tr>
<tr>
<td>Removable rigid disk</td>
<td>Iomega, Maxell, Sony</td>
<td>5.00–20.00/100 M bytes</td>
</tr>
<tr>
<td>Tape drive</td>
<td>Exabyte, H P, Seagate</td>
<td>100.00–400.00</td>
</tr>
<tr>
<td>Backup tape</td>
<td>3M, Sony, Verbatim</td>
<td>4.00–25.00/G bytes</td>
</tr>
<tr>
<td>8 x CD-ROM drive</td>
<td>Goldstar, Panasonic</td>
<td>100.00–200.00</td>
</tr>
<tr>
<td>Recordable optical drive</td>
<td>JVC, Philips</td>
<td>300.00–500.00</td>
</tr>
<tr>
<td>Recordable optical disk</td>
<td>3M, Maxell, Memorex</td>
<td>3.00–15.00/650 M bytes</td>
</tr>
</tbody>
</table>

Compared with magnetic recording, optical recording has the intrinsic advantages of superior reliability and portability. However, its performance is inferior due to slower data access time and transfer rate. Another advantage of optical recording, higher areal density, has been disappearing or even reverting to magnetic recording. Both magnetic and optical recording will be continuously improved in the near future, probably toward different applications. Currently, there are some emerging techniques that try to combine the magnetic and optical recording techniques [19], such as amorphous rare earth materials. Table 96.4 is a short list of representative magnetic and optical devices for digital recording.

References