VIII. MAGNETIC RECORDING

(1) Introduction

(2) magnetic Recording Process

(3) Magnetic Recording Media

(4) Magnetic Random Access Memory (MRAM)

(1) Introduction

▶ The type of information storage with magnetic recording

Analog recording : audio equipment (from 1898, market from 1948)

Digital recording : computers and related devices (from 1950's)

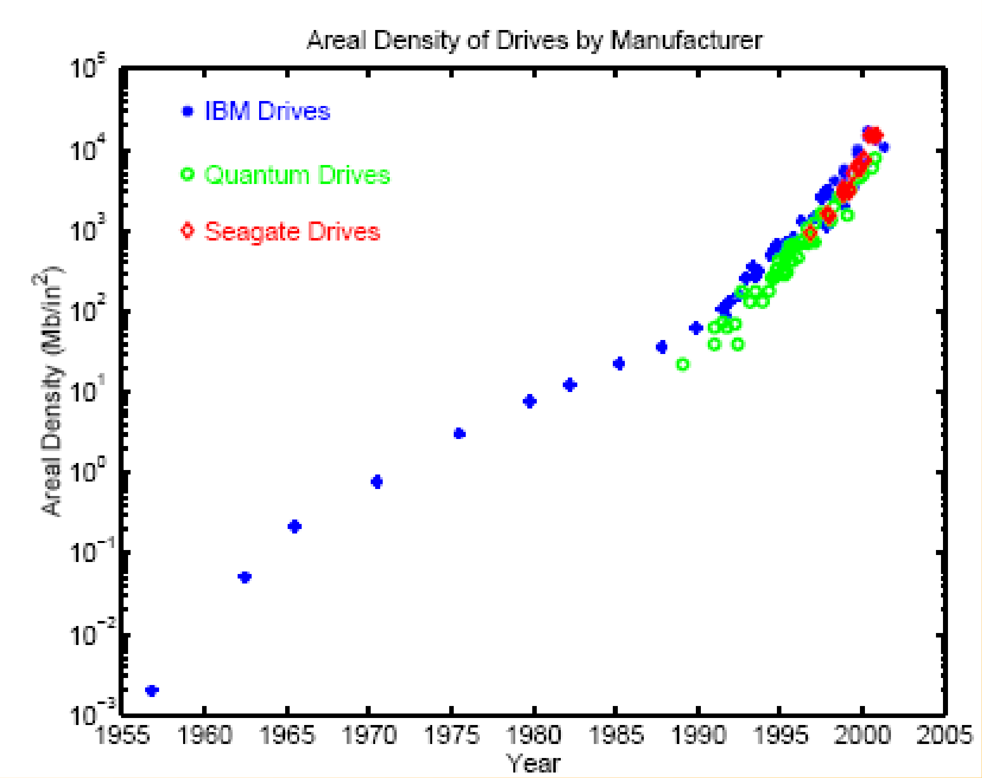
very high information storage density

types: magnetic tapes, floppy disks, hard disks

Video recording : video equipment (from 1956)

▶ Key issues for applications

- Enlargement of the information storage density
- Easy retrieval of the stored information
- Minimization of power requirements
  for recording process

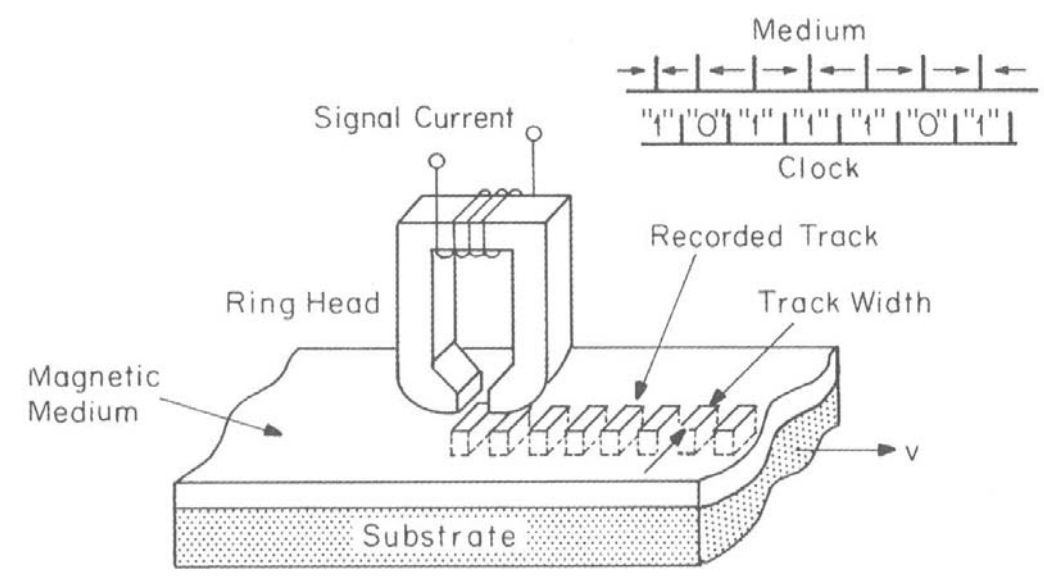


Areal density history of the hard disk drive

(2) Magnetic Recording Process

▶ Recording Process

Electrical impulses conveying information(analog, digital, video)
writing ↓ (writing head)   reading ↑ (reading head)
Magnetic patterns on the storage medium (tapes, disks)



Schematic representation of longitudinal, digital magnetic recording write processes. Insert, upper right, sequence of transitions constitute the bits that are read as binary information.

Writing process :

A magnetic medium is magnetized in one direction or the other by an applied fringe field from the head gap as the drive current changes polarity.

- **analog recording**: the spatial *waveform* written on the recording medium replicates the temporal waveform put into the medium by the write current.
- **digital recording**: the spatial *sequence of the magnetized bits* replicates the temporal sequence of current pulses (see Fig. 17.2 in O‘Handley)

Reading process :

Detecting M_r written on a magnetic medium by a voltage in the pickup windings of the read head. The voltage is amplified and read with an electronic signal processor to make use of the recorded information.

(2) Magnetic Recording Process

▶ Recording Heads

The Write Head : transducers converting electrical signals into a magnetic field

Requirements :

- Large μ at high frequency for its saturation with minimal current
- High M_s to induce high fringe field exceeding the Hc of the recording media (500-3000 Oe)
- low M_r: to prevent writing when a coil current is zero

Key points :

- Field generation : Ampere's law
- For the current I through the N turns enclosing the core of the write head, the magnetic potential (or magnetomotive force), $V_m = NI$

The head efficiency $\eta = 2gH_g/(2gH_g + l_cH_c)$, where the gap length = $2g$, the flux path length in the core = l_c,

In terms of the reluctance and the head parameters

$$\eta = R_g/(R_g + R_c) = 1/[1 + (R_c/R_g)] \approx 1 - l_cA_g/2g\mu A_c$$

If $2g$ is too small and A_c is too large, the head field remains in the gap rather than fringing out toward the medium.

An approximate field about the gap of recording head (see Fig. 17.4)

The Read Head : transducers converting a magnetic field into electrical signals

Requirements :

- Large μ_i to detect a stored information
- Low H_c for reusage
- Low noise to get better signal-to-noise ratio

Key points :

- inductive: Faraday's law: signal depends on reading or scanning speed
- magnetoresistive: independent of reading or scanning speed

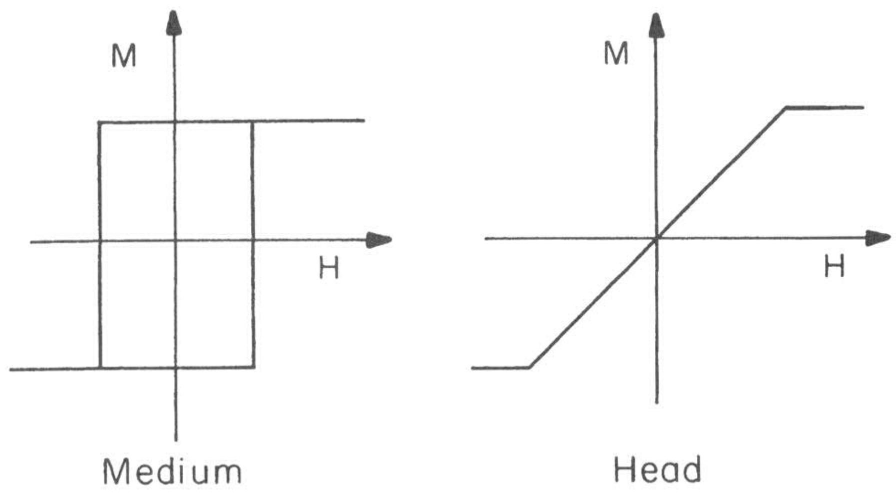
(2) Magnetic Recording Process

▶ Recording Heads

Ideal write head : $\mu \gg 1$, large M_s, $B_r = 0$

Ideal read head : $\mu_i \gg 1$, $H_c = 0$

The gap shears the loop.



Schematic *M-H* loops for ideal magnetic recording medium and head materials.

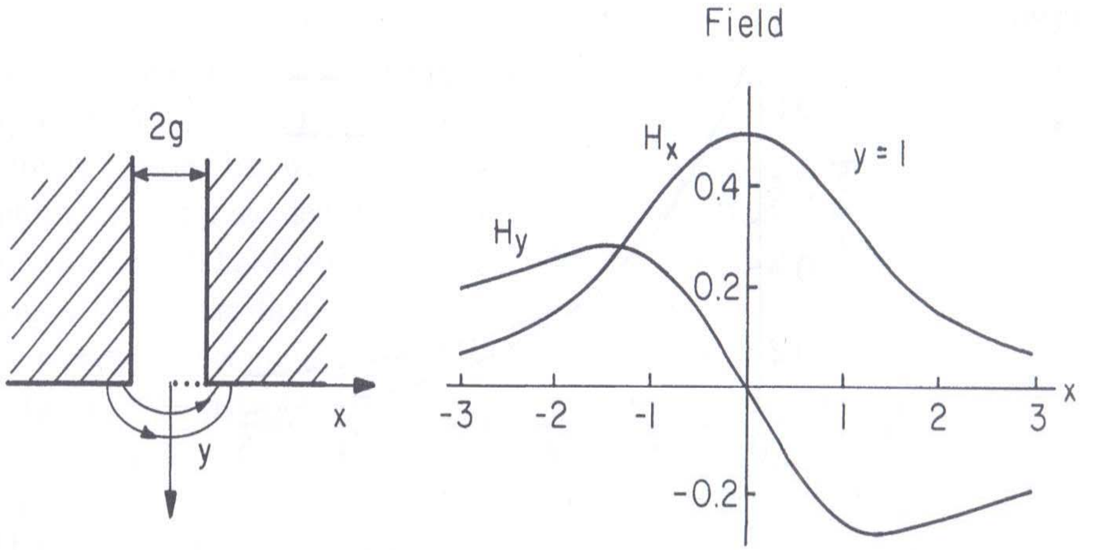


Figure 17.4 Schematic cross section of the gap in a magnetic recording head at left showing coordinate system for calculation of gap fields. The recording medium moves in the x direction at a distance y from the face of the head; x and y are normalized to g. At right, the forms of the Karlkvist field solutions normalized to H_g are shown for $y = 1$.

$$H_y(x, y) = -\frac{H_g}{2\pi}\log\frac{(x+g)^2 + y^2}{(x-g)^2 + y^2}$$

(2) Magnetic Recording Process

▶ Recording Head Materials

Bulk head

Soft magnetic materials: soft ferrites like Mn-Zn ferrite, Al-Fe & Al-Fe-Si alloys, Amorphous Co-Zr

Thin-film head

Write head: Permalloys; $Ni_{81}Fe_{19}$ (M_s ~ 1 T), $Ni_{50}Fe_{50}$, $Fe_{16}N_2$(M_s ~ 3 T)

Read head: Near-zero-magnetostriction permalloy

Recent R&D for Read Head

GMR (giant magnetoresistance)

Large MR values, MR = $(R_H - R_O)/R_H$ = 5 ~ 150%

1st report by M.N. Baibich et al., Physical Review Lett. vol. 61 (1988) 2472

Maximum MR (150%) for Fe-Cr multilayer films at 4.2 K by P.M. Levy, Science 256 (1992) 972

Recently, multilayer structure of alternating ferromagnetic metals : (Fe, Co, Ni) and normal metal (Cu)

CPP (Current-Perpendicular-to-Plane) structure

TMR (tunneling magnetoresistance)
(sometimes called, SDT: spin dependent tunneling)

1st suggestion by M. Julliere, Phys. Lett. 54A (1975) 225 for Fe/Ge/Co

1982 yr: Ni/NiO/Ni, Ni/NiO/Co, Ni/NiO/Fe ; 1987 yr: Ni/NiO/Co.

1995 yr: $Fe/Al_2O_3/Fe$, $Fe\text{-}Co/Al_2O_3/Co$, $Fe/Al_2O_3/Co$

2004 yr: CoFe/MgO/CoFe S.S. Parkins

advantages: faster access time than GMR → higher speed

disadvantages:

- processing difficulty of ultrathin uniform dielectric layer

tunneling current: a few ~ 20% in magnetic fields

tunneling layer: insulting oxides Al_2O_3, MgO

CMR(colossal magnetoresistance)

1st report by R. Von Helmolt et al., Phys. Rev. Lett. 71 (1993) 2331

named, "CMR" by S. Jin et al., Science, 264(1994) 413

Parent compounds: $LaMnO_3$

In general, $T_{1-x}D_xMnO_3$, $x = 0.2 \sim 0.4$ (hole doping)

where, T (trivalent lanthanides) : La, Nd, ...

D (divalent alkaline earths) : Ca, Sr, Ba

advantage: very large MR values (> 100,000%)

disadvantage: large magnetic field (5T) required for obtaining a significant MR values

(2) Magnetic Recording Process

▶ Types of Recording Heads

Inductive Recording Heads

- Ring heads (see Fig. 17.2)
- Single-pole heads (see Fig. 17.11)
- Thin-film heads (see Fig. 17. 15)

  Typically 2~3 μm thickness, ~ 200 nm gap
- Materials (see Table 17.3)

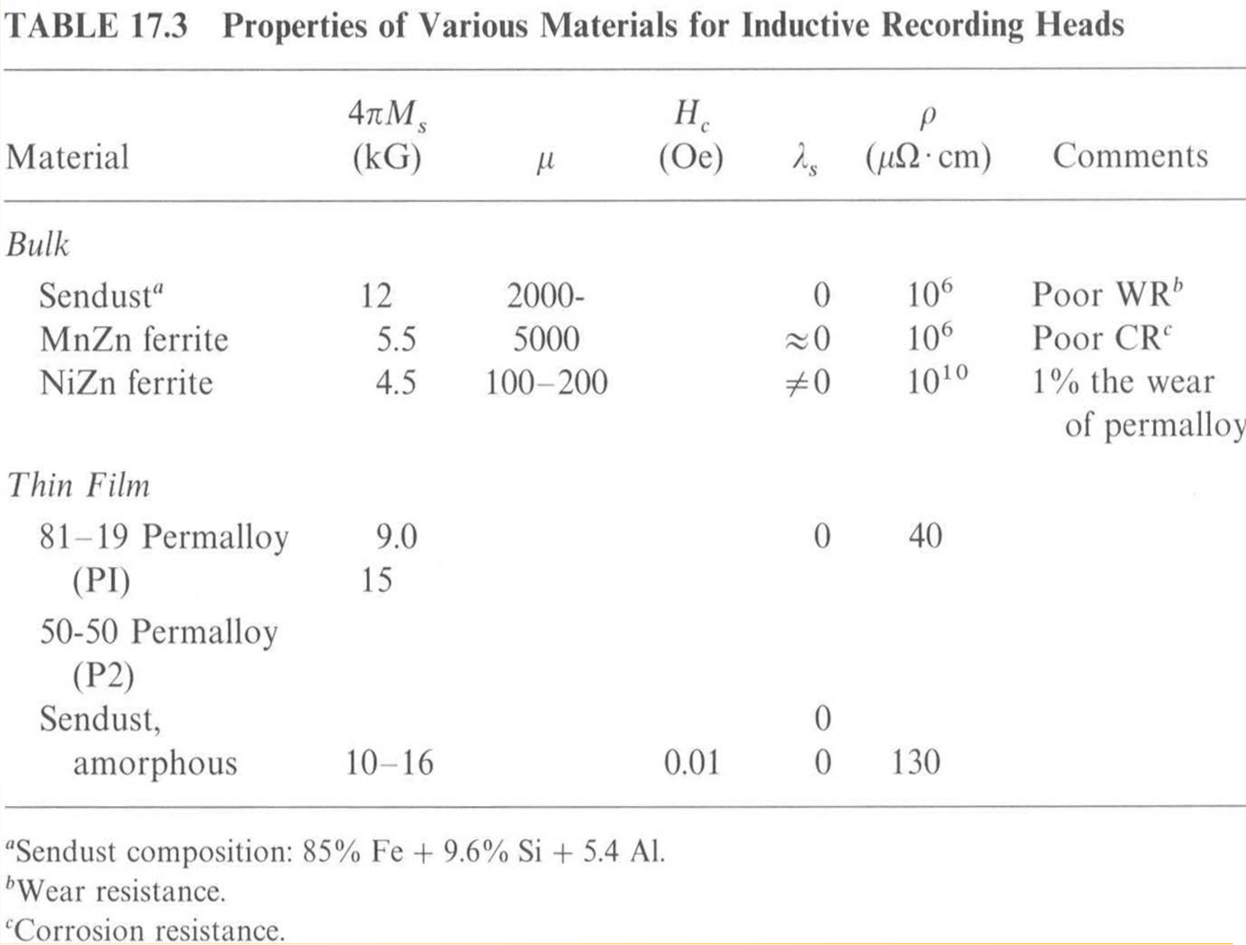


TABLE 17.3 Properties of Various Materials for Inductive Recording Heads

Material	$4\pi M_s$ (kG)	μ	H_c (Oe)	λ_s	ρ ($\mu\Omega \cdot$cm)	Comments
Bulk						
Sendust[a]	12	2000-		0	10^6	Poor WR[b]
MnZn ferrite	5.5	5000		≈ 0	10^6	Poor CR[c]
NiZn ferrite	4.5	100–200		$\neq 0$	10^{10}	1% the wear of permalloy
Thin Film						
81–19 Permalloy (PI)	9.0 15			0	40	
50-50 Permalloy (P2)						
Sendust, amorphous	10–16		0.01	0 0	130	

[a] Sendust composition: 85% Fe + 9.6% Si + 5.4 Al.
[b] Wear resistance.
[c] Corrosion resistance.

(2) Magnetic Recording Process

▶ Types of Recording Heads (continued)

Magnetoresistive Heads

AMR effect

$$\frac{\Delta\rho(H)}{\rho_{av}} = \frac{\Delta\rho}{\rho_{av}}(\cos^2\theta - \frac{1}{3})$$

In the case of transverse anisotropy

and y-direction field,

$M_y/M_s = H_y/H_a = \sin\theta$

Thus, below saturation

$\Delta\rho/\rho = (\Delta\rho/\rho)_{\max}[2/3 - (H_y/H_a)^2]$

Sensitivity ≈ $H_a/\rho H_a$,

where H_a (field change over which H_a occurs)

$= H_u + H_d$

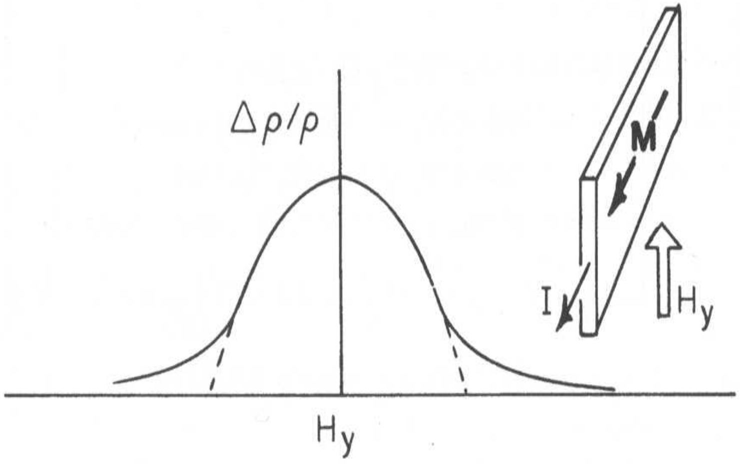


Figure 17.17 Field dependence of magnetoresistance (solid line) for uniform response to a uniform field H_y. Dotted line shows idealistic, quadratic MR response.

(2) Magnetic Recording Process

▶ Types of Recording Heads (continued)

Magnetoresistive Heads (continued)

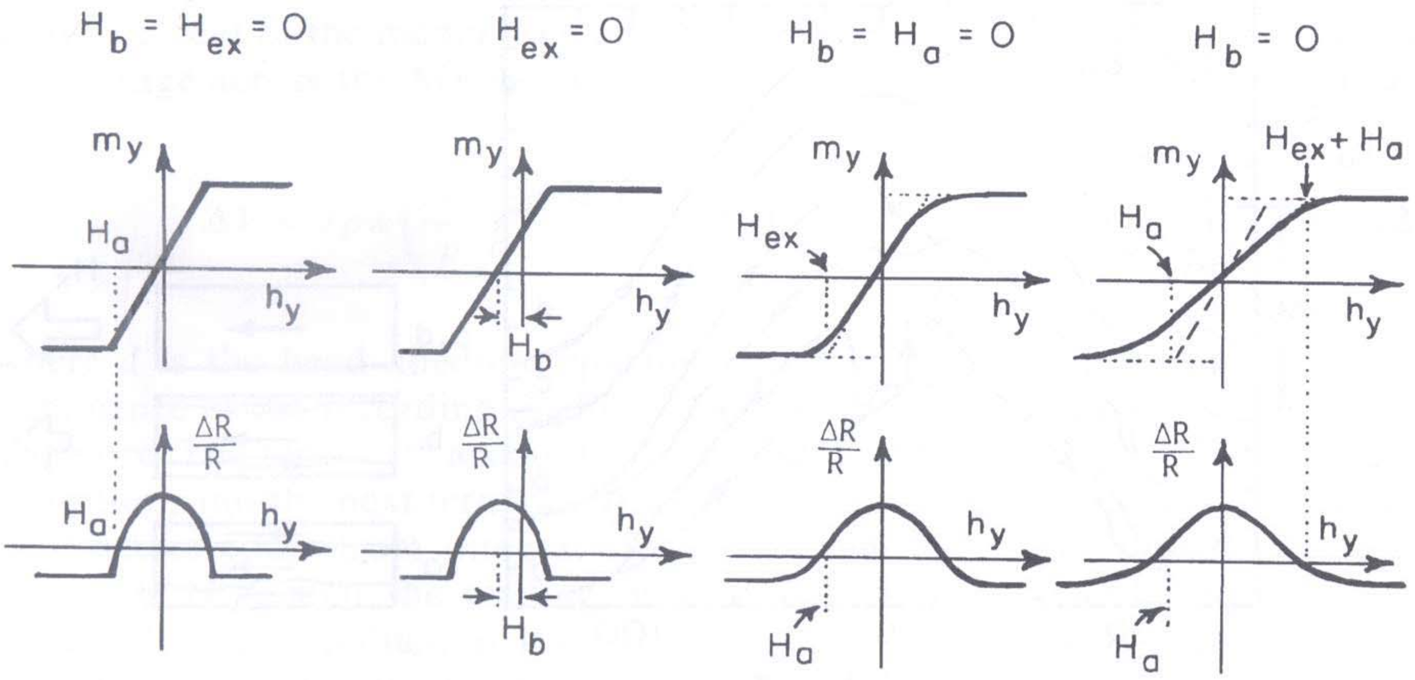


Figure 17.20 Schematic reduced magnetization versus external field h_y, showing the different effects of anisotropy field, bias field, exchange field, and exchange plus anisotropy. Lower part shows the transfer functions $\Delta R/R$ corresponding to each magnetic effect above.

(2) Magnetic Recording Process

▶ Types of Recording Heads (continued)

Magnetoresistive Heads (continued)

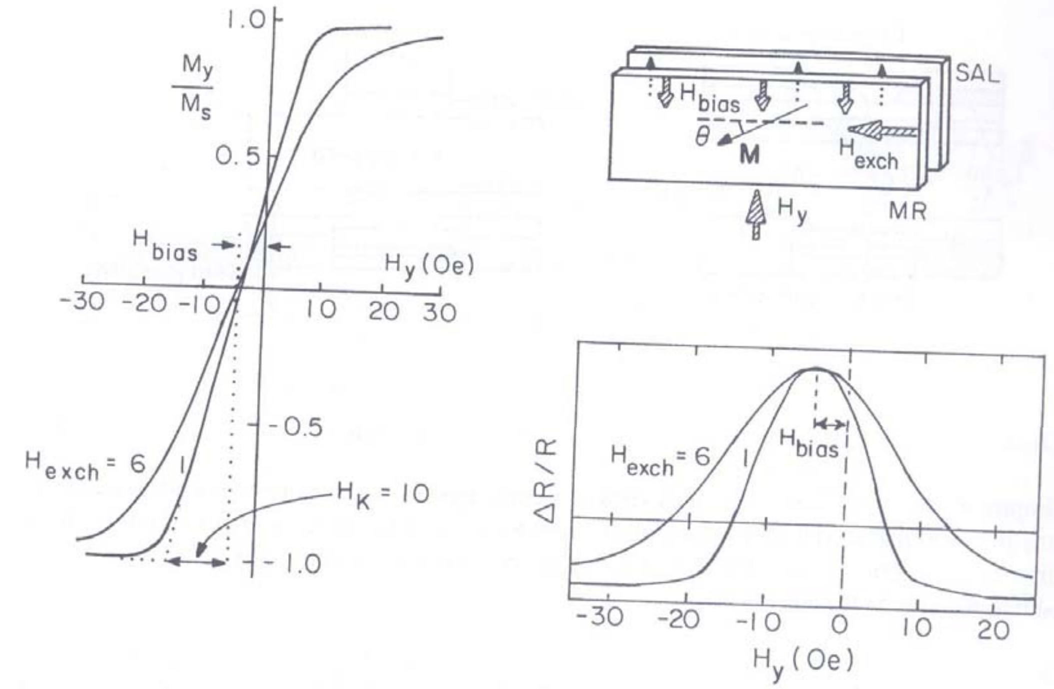


Figure 17.21 Upper right, geometry of MR head and various fields acting on its magnetization. Left, $M-H$ loop calculated from simple theory in text using exchange fields of 6 and 1 Oe, respectively, $H_a = 10$ and a 4 Oe bias. Lower right, MR transfer functions calculated from same model for the parameters used in $M-H$.

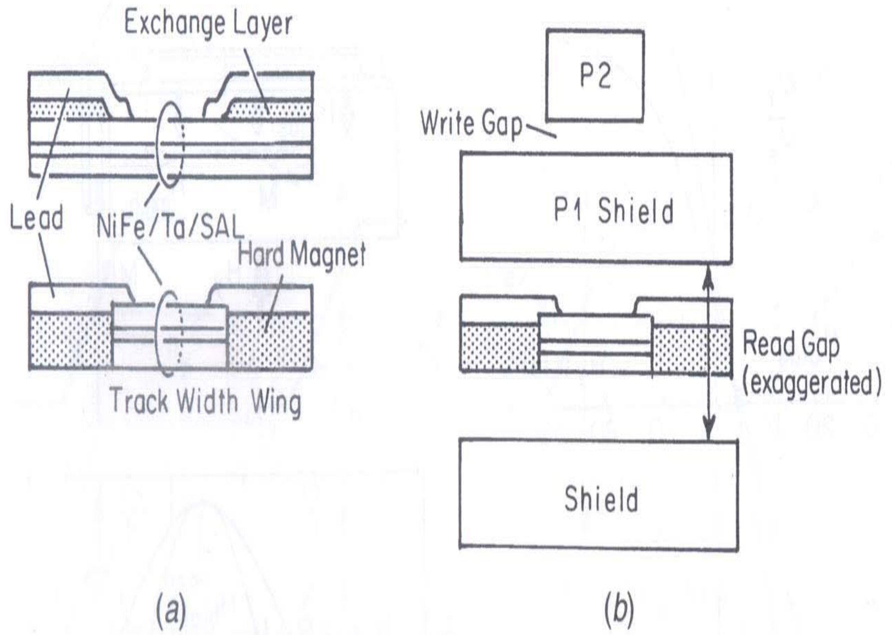


Figure 17.22 (*a*) Cross-sectional views of exchange-stabilized (above) and permanent-magnet-stabilized MR elements (Ishiwata et al. (1995); (*b*) Arrangement of components in a dual-function head. The P1 element of the inductive write head also serves as one shield for the MR element.

(2) Magnetic Recording Process

▶ Types of Recording Heads (continued)

Spin-Valve Read Heads

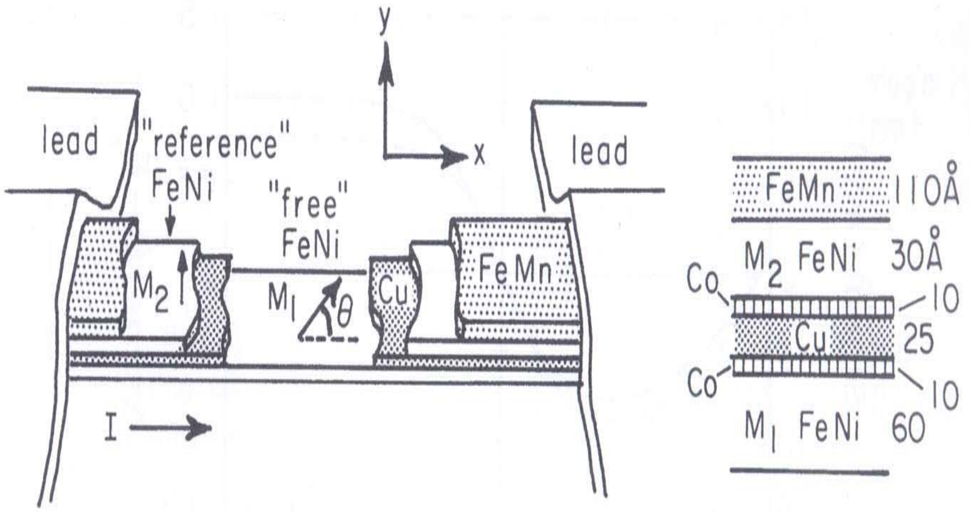


Figure 17.23 Structure of a simple spin valve. Note that free layer is deposited first, reference layer is magnetized in positive y direction, and sense current is in positive x direction; the device dimensions are approximately $h = 2$ to $6\ \mu m$ and $w = 10\ \mu m$ (Heim et al. 1994).

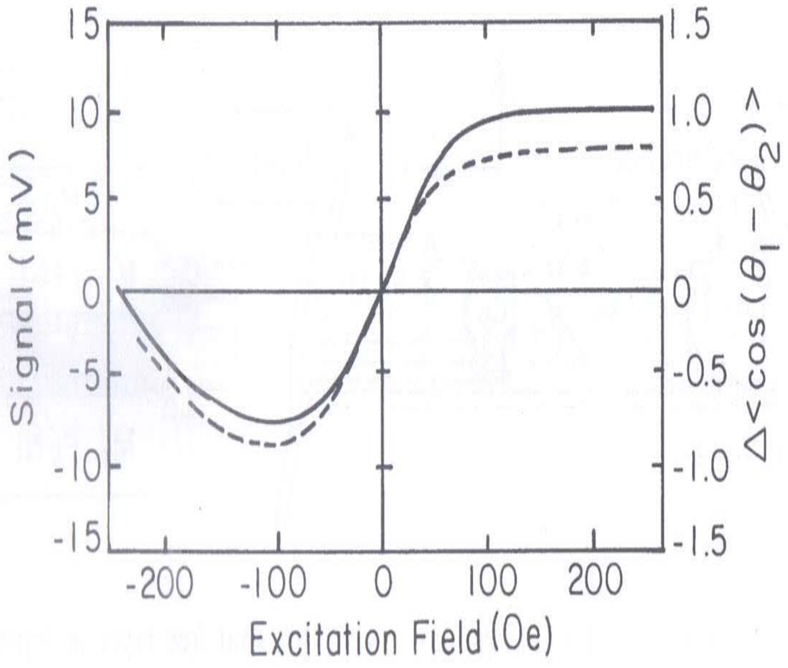


Figure 17.24 Experimental transfer curve for a 2-μm high-spin valve sensor for +5 mA (solid) and −5 mA (dashed) sense current. Computed transfer curves follow the data within experimental error. [Adapted from Heim et al. 1994).]

(2) Magnetic Recording Process

▶ Types of Recording Heads (continued)

Spin-Valve Read Heads

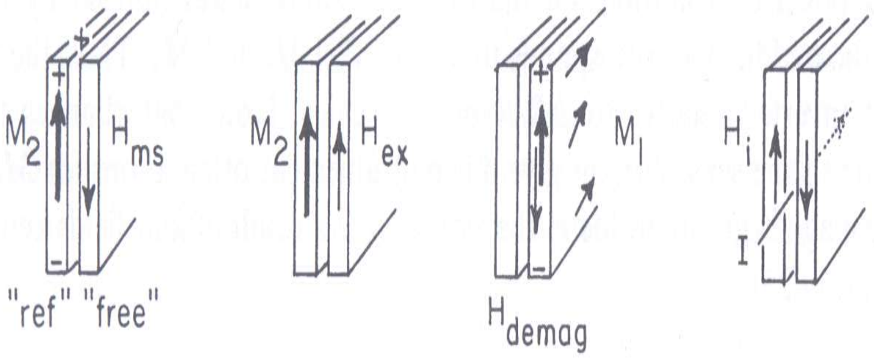


Figure 17.25 Representation of four contributors to the field (fine arrows) acting on M_1 of the spin valve in Figure 17.23 to establish its quiescent orientation. Bold arrows give orientation of M_2 or M_1.

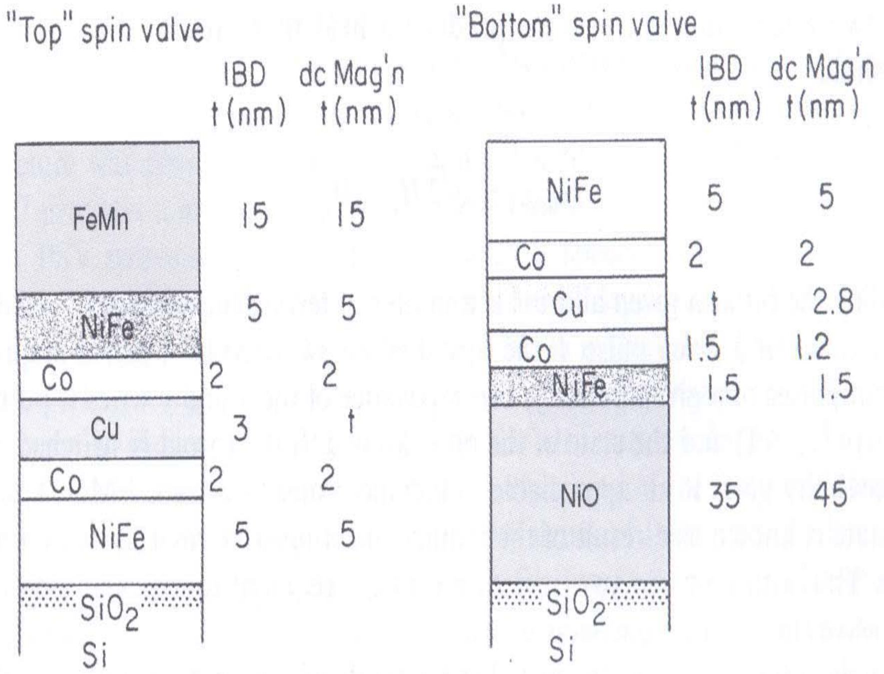


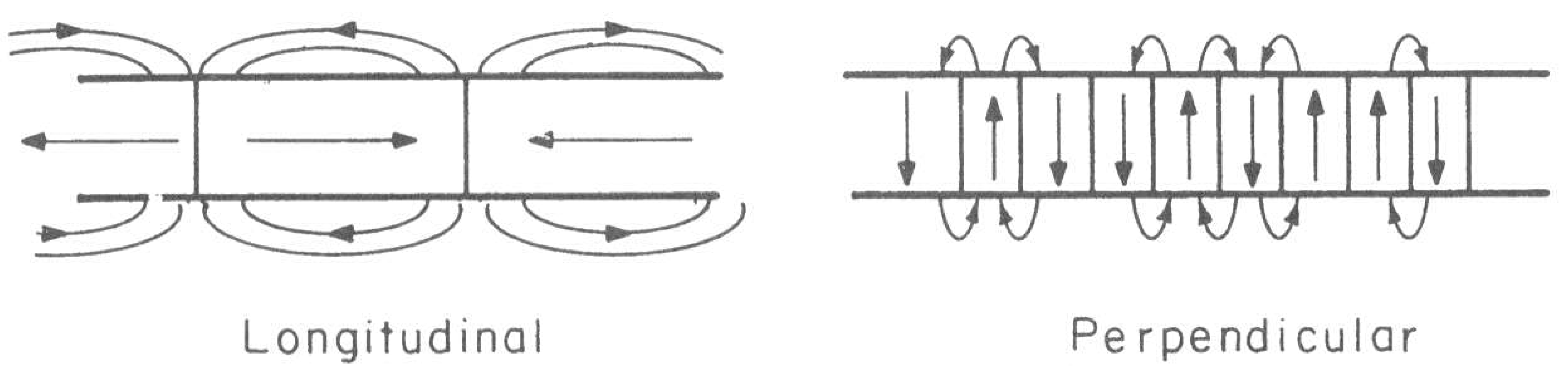
Figure 17.26 Structure of spin valves made by Wang *et al.* (1997) to compare effects of ion-beam versus dc magnetron sputter deposition and the relative merits of NiO versus FeMn exchange biasing layers.

(3) Magnetic Recording Media

▶ General Requirements

- **High M_s (typically, 500 - 1000 G)** : to obtain large M_r during the reading process
- **Appropriate H_c** : Not too low (to prevent erasure due to adjacent bits, stray fields and ambient temperature fluctuations) but not too high (to respond to the field of the write head, typical H_c values : 500 - 3000 Oe)
- **Sharp domain walls (not a sawtooth wall)**: to obtain a sharp transition to a read head for high-frequency analog or digital recording. Ideally, a regular array of isolated single-domain magnetic elements. Since this is not practical, approximately 10^3 particles should constitute a bit in order to insure a sharp transition.

▶ Recording types



(3) Magnetic Recording Media

Longitudinal media :

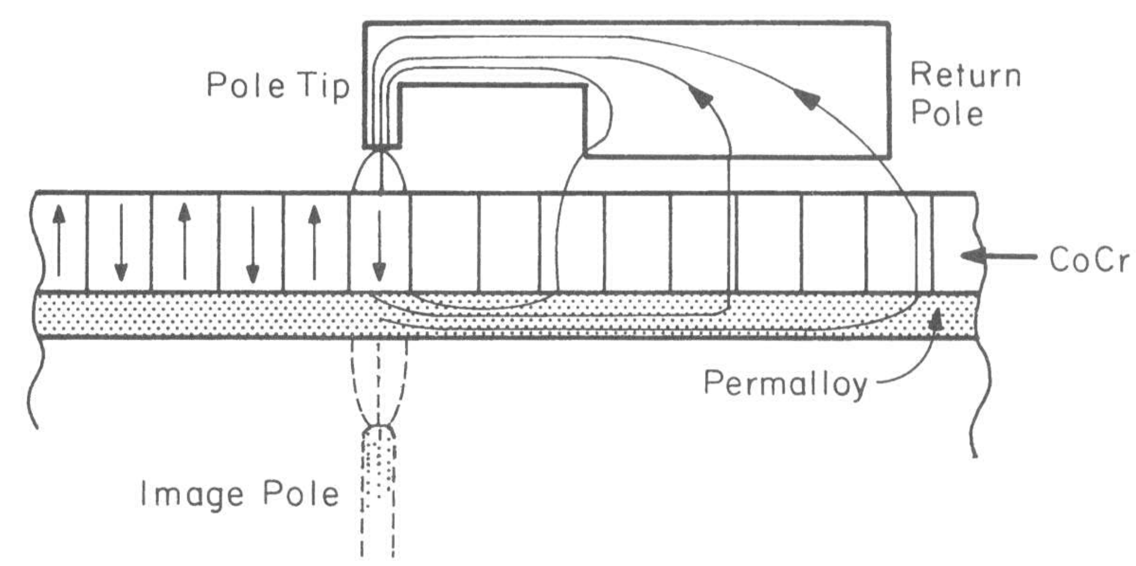
- The easy axis of magnetization lies in the plane of the recording layer
- Since demagnetization factor $\propto M_r t/\lambda$, where t is thickness and λ is the length, the demagnetization of the recording bits become unfavorable with increasing recording density
- advantageous for tape media where information is recorded linearly
- disadvantageous for floppy disk where the tracks are circumferential
- usual linear bit densities ~ 10^5 bits per inch (bpi) or $\lambda = 0.5$ μm)

Perpendicular media :

- The easy axis of magnetization is perpendicular to the recording layer
- Advantageous for higher information density since demagnetization effect (demagnetization factor $\propto M_r \lambda/t$) becomes greatly reduced: 100,000 - 500,000 bpi
- Replaced by magneto-optic media

Isotropic media :

- an optimal response to both longitudinal and perpendicular field component known as vector magnetic recording (under investigation)



Recording head for perpendicular magnetic recording

(3) Magnetic Recording Media

▶ Types of Recording Media

Particulate Media

- Single-domain particles
- H_c reaches maximum between the single-domain and superparamagnetic limits
- The volume of a single-domain particle can be increased if the particle is elongated since E_{ms} can be reduced.
- Acicular particles are more often used because of their strong shape anisotropy

Structure

- Particles are suspended in a polymer matrix
- Unidirectional texturing in magnetic tape
- Need loop squareness
- Enhanced spatial sharpness (acuity) of the transition
- Typically 20-50% particle loading
  → low magnetization density

Materials

- Gamma Fe_2O_3
- Co^{2+} γ-Fe_2O_3
- CrO_2
- Metal particles: Fe
- Barium Ferrite

Loop Squareness

- A quantitative measure of loop squareness : $S = M_r/M_s = m_r$
  An indicator mainly of the strength of the read signal
  (No information about stability related to H_c)
- Another measure of squareness : $S^* = 1 - M_r/\chi_0 H_c$
  where $\chi_0 = [\partial M/\partial H_c]_{Hc}$ at $M = 0$
  If $S^* = 1$: most square and $S^* = 0$: not square
- Switching field distribution (SFD) : $\mathrm{SFD} = \Delta H/H_c$
  where, ΔH = the full width half max. of χ near H_c
  A measure of the transition fluctuations

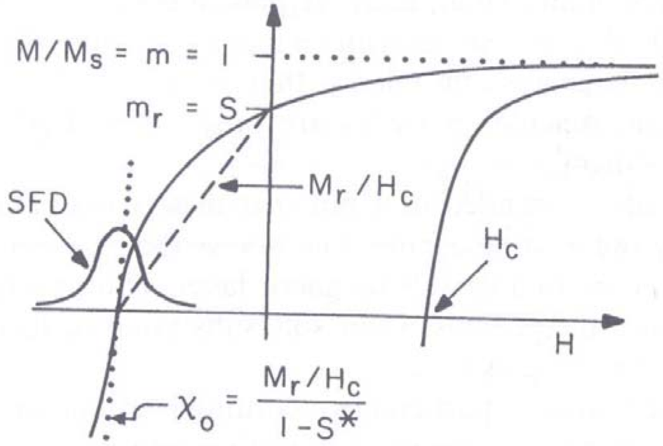


Figure 17.12 Part of M–H loop showing various measures of loop squareness.

(3) Magnetic Recording Media

▶ **Types of Recording Media**

Particulate Media (continued)

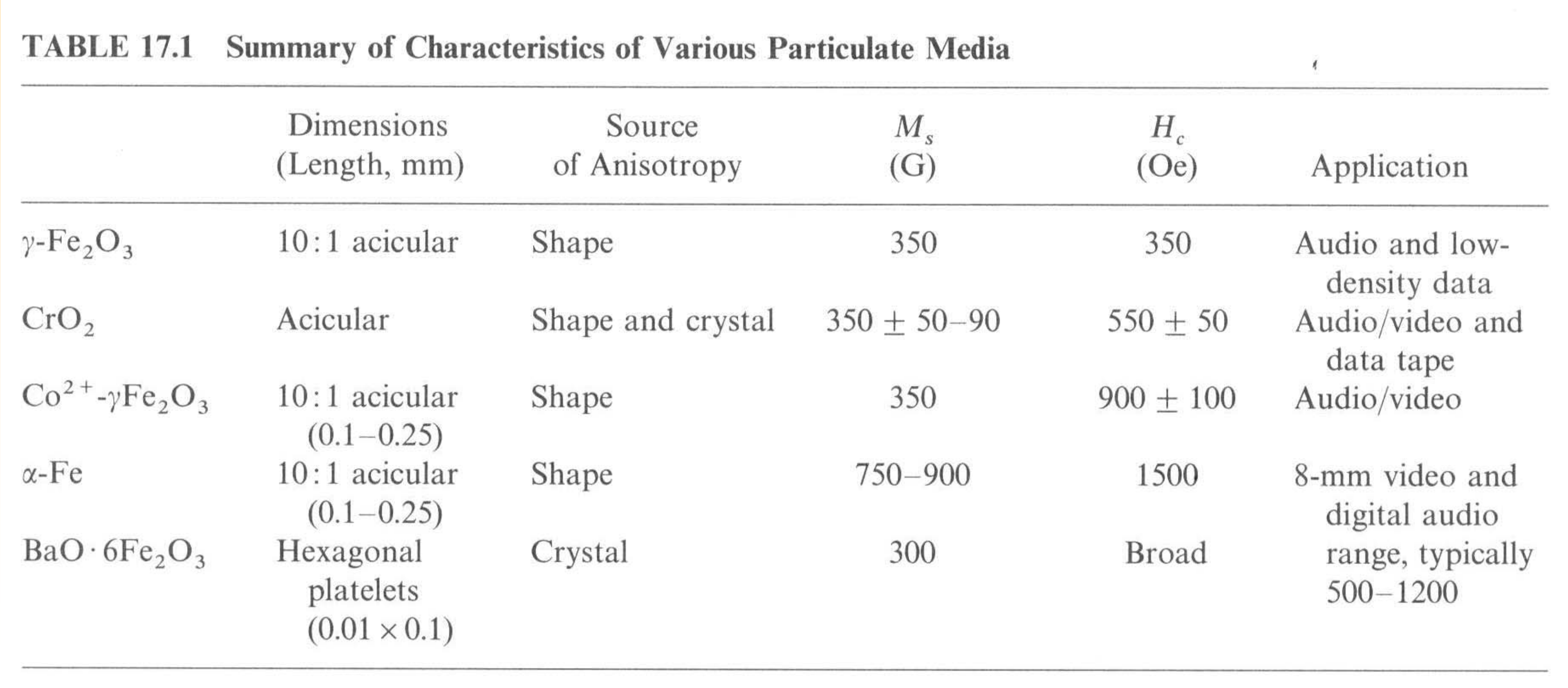


TABLE 17.1 Summary of Characteristics of Various Particulate Media

	Dimensions (Length, mm)	Source of Anisotropy	M_s (G)	H_c (Oe)	Application
γ-Fe_2O_3	10:1 acicular	Shape	350	350	Audio and low-density data
CrO_2	Acicular	Shape and crystal	350 ± 50–90	550 ± 50	Audio/video and data tape
Co^{2+}-γFe_2O_3	10:1 acicular (0.1–0.25)	Shape	350	900 ± 100	Audio/video
α-Fe	10:1 acicular (0.1–0.25)	Shape	750–900	1500	8-mm video and digital audio
$BaO \cdot 6Fe_2O_3$	Hexagonal platelets (0.01 × 0.1)	Crystal	300	Broad range, typically 500–1200	

(3) Magnetic Recording Media

- **Types of Recording Media**

Particulate Media (continued)

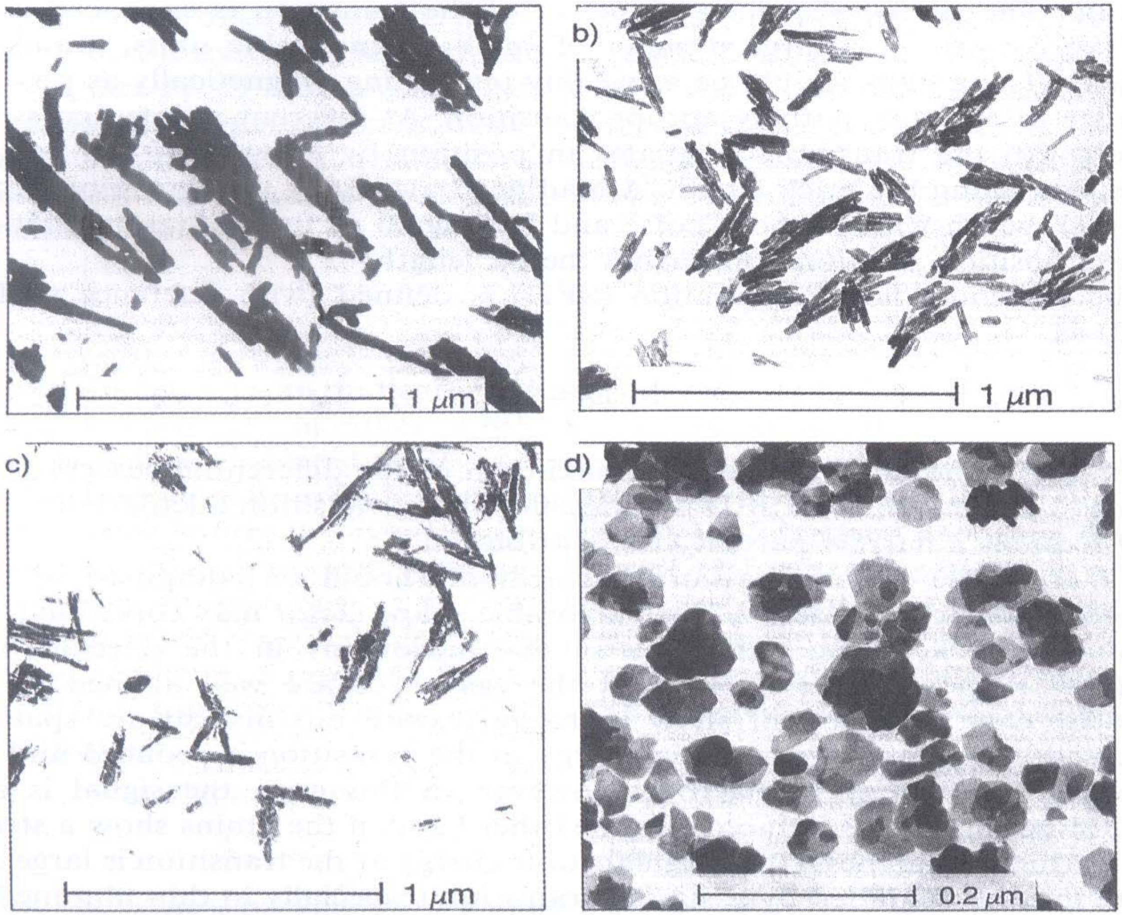


Figure 17.13 Magnetic particles used in recording: (*a*) iron oxide particles with surface-deposited cobalt of coercivity 700–750 Oe; (*b*) iron oxide with Co-treated surface having coercivity of order 900 Oe; (*c*) iron metal particles with coercivity of 1500 Oe; (*d*) barium ferrite particles (note different scale) (Sharrock 1990).

(3) Magnetic Recording Media

▶ Types of Recording Media

Thin-Film Media

- Decreased grain size for increased SNR without loss of H_c
- Improved grain isolation for low noise and higher H_c
- Higher H_c in smaller, single-domain (particle) grains

▶ Materials

Magnetic tapes

- A coating of fine particles on a flexible, non-magnetic, plastic substrate (thickness ~25 μm) by a tape-casting process
- Tape heads operate in contact with a protective layer over the magnetic recording tape medium
- Applications: audio, video, and sometimes computer data storage

Materials for magnetic tapes:

γ-Fe_2O_3 : H_c = 20 –30 kA/m (250 – 375 Oe), M_s = 370 kA/m, T_c = 600℃
particle size : 0.25 – 0.75 μm length × 0.05 – 0.15 μm diameter
(length : dia = 10:1 ~ 3:1)

Co-doped γ-Fe_2O_3 : used for most video tapes
~ 30 Å depth doping from the surface
H_c = 480 kA/m due to higher magnetic anisotropy
disadvantages: low T_c (→ temperature sensitive)

CrO_2 : H_c = 40 – 80 kA/m, M_s = 500 kA/m, T_c = 128℃
particle size : 0.4 μm length × 0.05 μm diameter
(length : dia = 10:1 ~ 3:1)
disadvantages: low T_c (temperature sensitive), expensive

Hexagonal ferrites : used for credit cards
M_s = 300 G
Much higher H_c

Ferromagnetic powders

Fe powder : reduction of iron oxides to Fe at 300℃ in a hydrogen atmosphere, and usually coating of Sn to prevent a particle coalescence during sintering : H_c ~ 120 kA/m, M_s ~ 1700 kA/m, T_c ~ 750℃

(3) Magnetic Recording Media

▶ Types of Recording Media

Thin-Film Media (continued)

Magnetic disks: floppy disks & hard disks

Advantages compared with tapes

- shorter access time
- in the case of hard disks, no direct contact between disks and heads, called,"flying head" (about 40 nm air gap)

Materials for magnetic tapes:

Thin metallic films: Co–Ni–P or Co–Cr–Cr or Co–Cr–Ta on the Ni–P substrate

H_c = 60 – 100 kA/m

M_s = 1000 kA/m

Perpendicular recording media: Co–Cr (Cr > 18%) or Oriented Ba–ferrite films

1st by Iwasaki, 1987

for higher recording density

Problems: a very small flying height of the head is necessary (noise problems)

Magnetic bubbles: Bubble domain devices, 1970's

- cylinder-shaped domains, whose magnetic moment is perpendicular to a film surface
- Advantage: large storage capacity
- Disadvantage: relatively slow access time

Materials for magnetic bubbles:

Garnets and their derivatives: $(Eu,Y)_3(Ga,Fe)_5O_{12}$

- high bubble mobility but large bubble size

Hexagonal ferrites

- small bubble size but low bubble mobility

(3) Magnetic Recording Media

▶ Types of Recording Media

Thin-Film Media (continued)

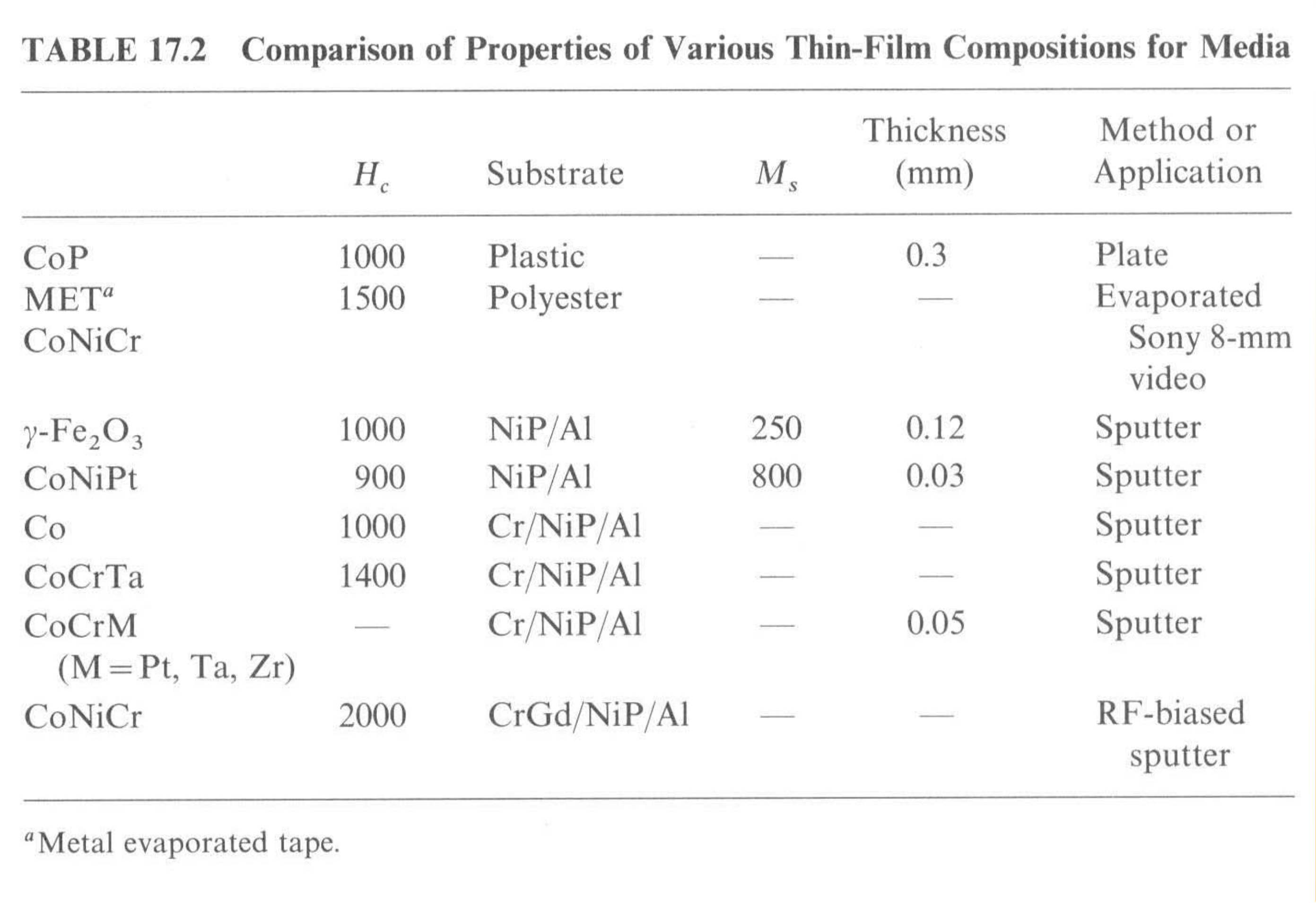


TABLE 17.2 Comparison of Properties of Various Thin-Film Compositions for Media

	H_c	Substrate	M_s	Thickness (mm)	Method or Application
CoP	1000	Plastic	—	0.3	Plate
MET[a]	1500	Polyester	—	—	Evaporated
CoNiCr					Sony 8-mm video
γ-Fe_2O_3	1000	NiP/Al	250	0.12	Sputter
CoNiPt	900	NiP/Al	800	0.03	Sputter
Co	1000	Cr/NiP/Al	—	—	Sputter
CoCrTa	1400	Cr/NiP/Al	—	—	Sputter
CoCrM (M = Pt, Ta, Zr)	—	Cr/NiP/Al	—	0.05	Sputter
CoNiCr	2000	CrGd/NiP/Al	—	—	RF-biased sputter

[a] Metal evaporated tape.

(4) Magnetic Random Access Memories

MRAM

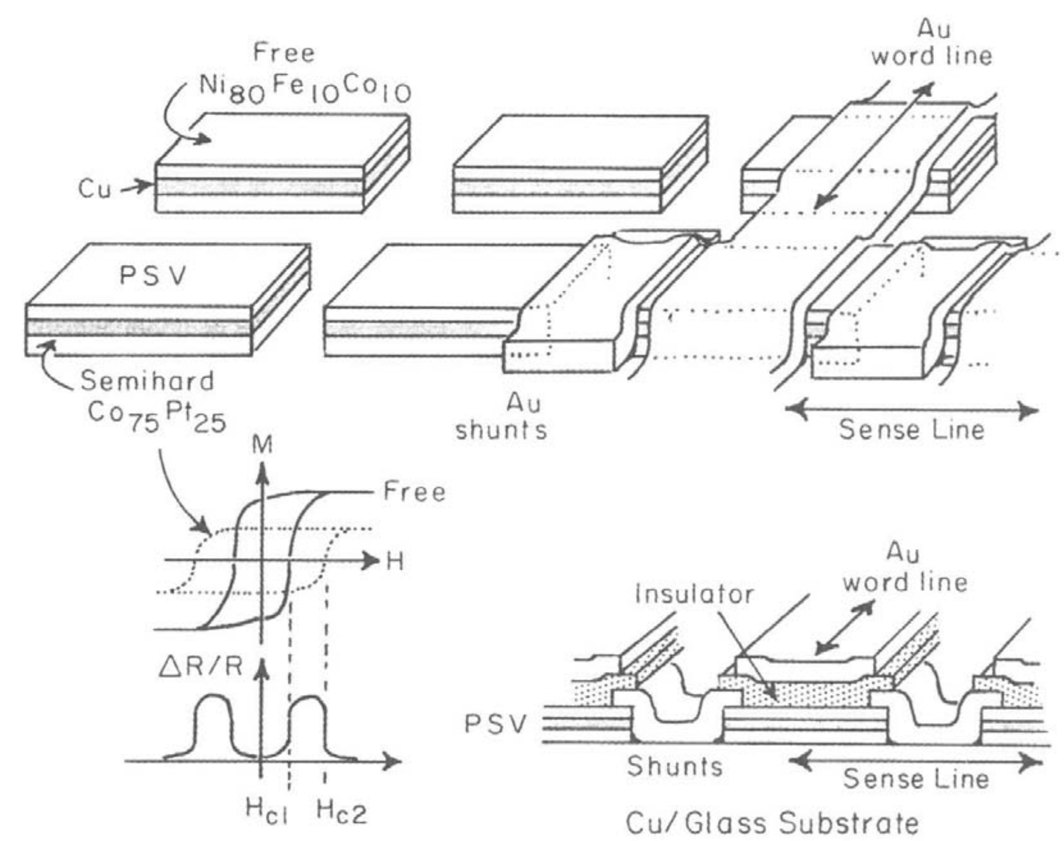
- Use GMR or TMR as memory units
- Non-volatile information storage devices
- Thin-film, high-density MRAM: To achieve higher storage density (1Gbit/in^2), nano technology must be developed: a nano scale patterned media by high resolution lithography

Advantages

- No moving parts
- No heads
- The ability to access information in arbitrary sequence of addresses (random access) as opposed to sequential access as in tape and disk storage.

Structure and Operation

- MRAM composed of pseudo-spin-valve (PSV) structure elements



(4) Magnetic Random Access Memories

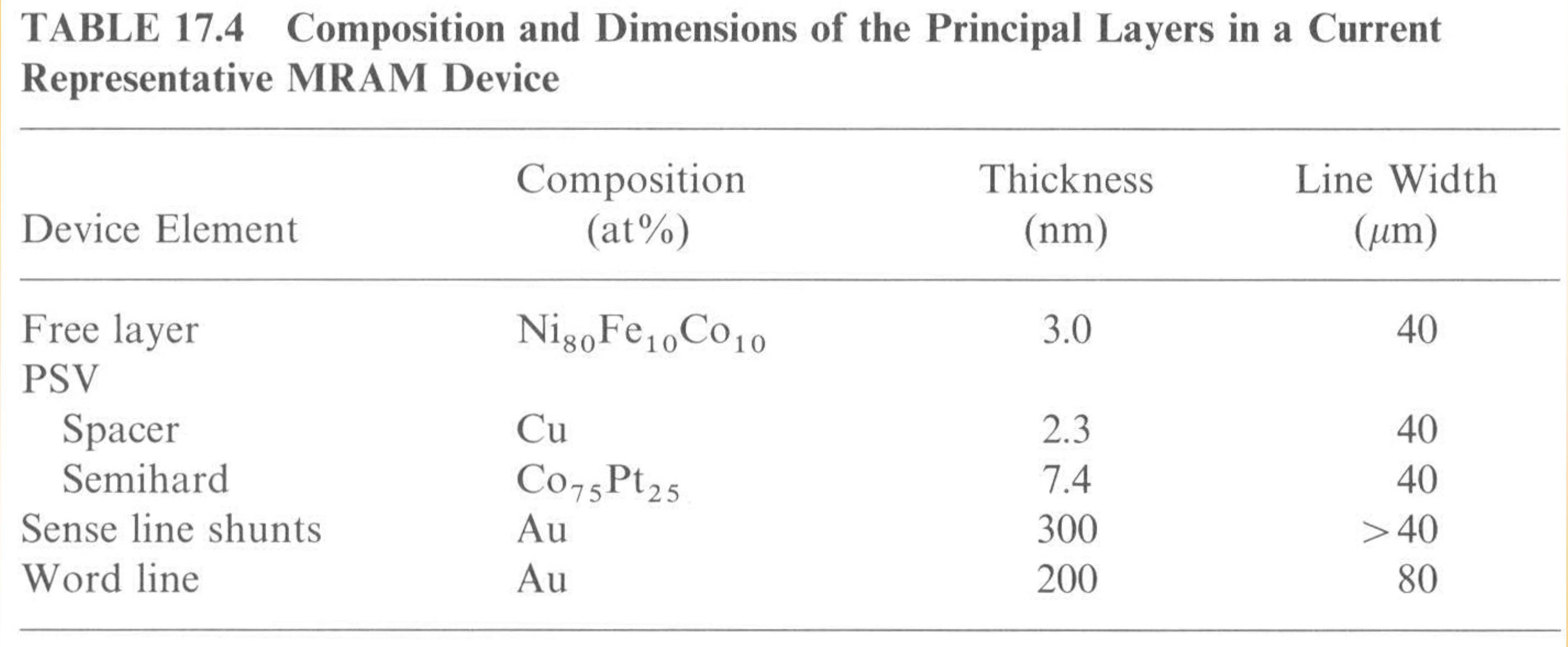


TABLE 17.4 Composition and Dimensions of the Principal Layers in a Current Representative MRAM Device

Device Element	Composition (at%)	Thickness (nm)	Line Width (μm)
Free layer	$Ni_{80}Fe_{10}Co_{10}$	3.0	40
PSV			
Spacer	Cu	2.3	40
Semihard	$Co_{75}Pt_{25}$	7.4	40
Sense line shunts	Au	300	>40
Word line	Au	200	80

(4) Magnetic Random Access Memories

Operation

- Read process
- Write process

Fundamental Limits

-Min. particle or grain size which is magnetically stable against ambient thermal demagnetization > superparamagnetic limit

-Incerased areal density puts a lower limit on medium anisotropy without so high medium coercivity

- Higher operating frequencies : resonance freq. & eddy current damping