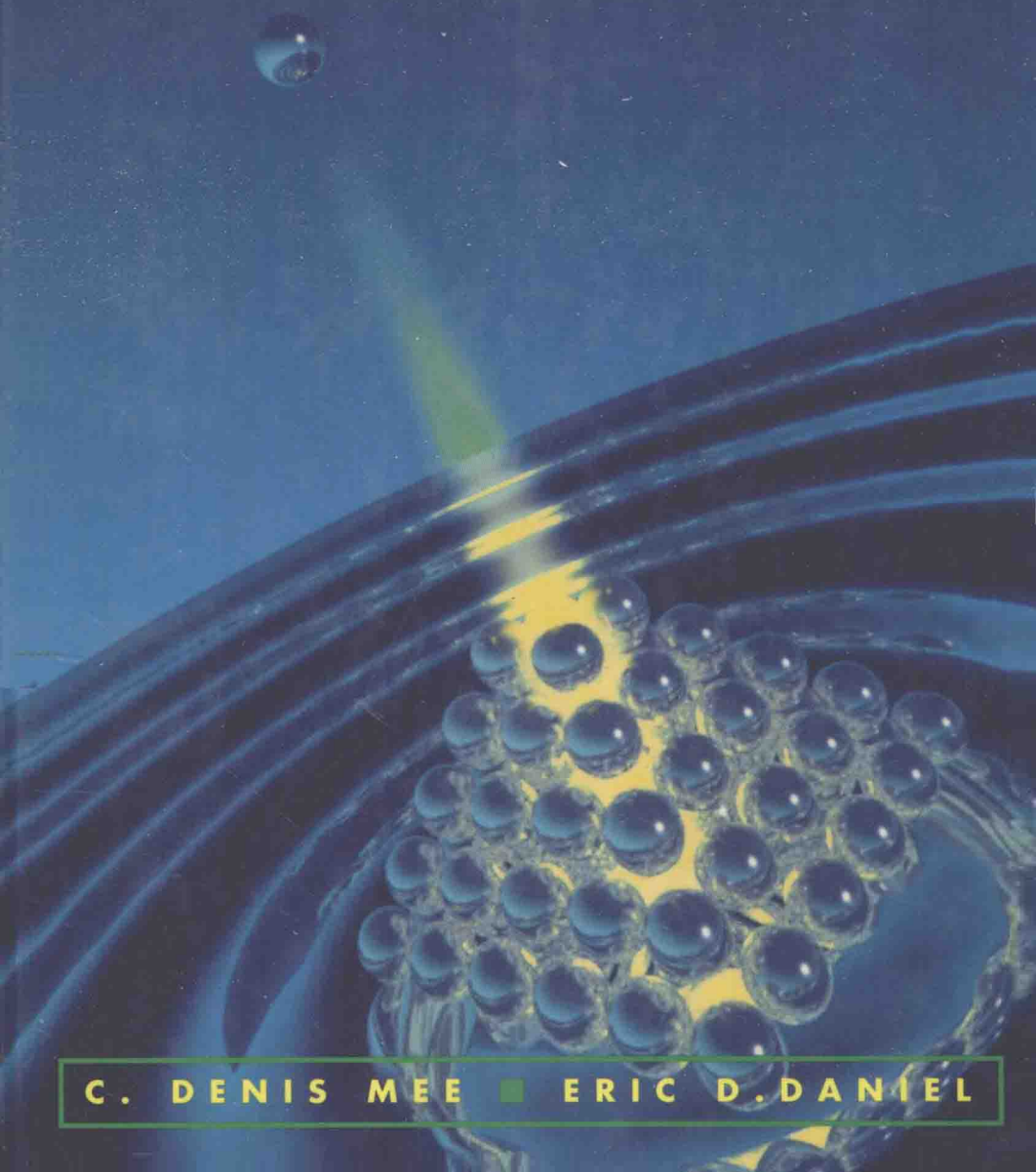


SECOND EDITION

MAGNETIC RECORDING

TECHNOLOGY



C. DENIS MEE ■ ERIC D. DANIEL

MAGNETIC RECORDING TECHNOLOGY

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*To the memory of Eberhard Köster, author of the
chapter on Particulate Media, who died in Au-
gust, 1995.*

C. Denis Mee
Eric D. Daniel
September, 1995

ABOUT THE EDITORS

C. Denis Mee spent nearly three decades with IBM, where he specialized in advanced storage technologies, magneto-optical storage, bubbles, magnetic recording heads, media, and recording technologies for computer rigid disks. He was appointed an IBM Fellow in 1983. He retired from IBM in 1993.

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FOREWORD

Magnetic Recording Technology is an updated and substantially expanded version of Part I of the *Magnetic Recording Handbook* published in 1990. A similarly extensive revision of Part II of that work will be published separately under the title *Magnetic Storage Handbook*.

The major additions and revisions that have gone into *Magnetic Recording Technology* are highlighted below:

Film Recording Media. This now rates a separate chapter to reflect the fact that deposited film media have now virtually taken over from particulate media for data recording on hard disks, and have gained significant entry in video and other tape applications.

Micromagnetics of Film Media. This is a completely new chapter included to cover this increasingly important aspect of film media technology.

Magnetoresistive Heads. A new author has contributed a section devoted to this subject in the chapter on *Recording Heads*. This section gives a greatly expanded treatment to reflect the rapidly increasing importance of magnetoresistive heads in high-performance hard-disk drives and other data storage applications.

Tribology of the Head-Medium Interface. This is an entirely new chapter covering the critical interface between the head and the medium, with particular emphasis on tribology.

Recording Limitations. This chapter has been largely rewritten. It includes a more rigorous treatment of noise theory, and a closer examination of the impact of magnetoresistive read heads on recording system limitations.

Magneto-optical Recording. Several sections have been added by a new author, covering advances in the design and analyses of recording media and heads. New multilayer media are described which are capable of direct overwrite and very high resolution recording.

Other chapters of *Magnetic Recording Technology* required less extensive revision. However, where significant technological advances have occurred in recent years, these are covered by the inclusion of the relevant new data, text, and references.

PREFACE

The purpose of this book, *Magnetic Recording Technology*, is to provide a single reference that covers the many scientific and engineering disciplines of magnetic recording. The book is organized in the following way:

This book is concerned with establishing the underlying technologies that are common to all forms of magnetic recording. Separate chapters treat the processes by which recording and reproduction take place; the materials, design, and fabrication of media; the materials, design, and fabrication of heads; the limit on performance due to noise, interference, and distortion; the key magnetic and recording measurement techniques that have evolved; the mechanical interface between the head and medium that is of critical importance in all but optically addressed media; and, finally, reversible optical recording in which the signals are recorded thermomagnetically then reproduced magnetooptically. It is some eight years since the publication of the first of the books that form the basis of the current work. The preface written at that time remarked on the rapid growth of the information-storage industry and the position occupied by magnetic recording as the dominant non-static memory technology. In the intervening years the industry has grown at an accelerated pace, but magnetic recording remains ubiquitous as the technology of choice for reversible, low-cost information storage. The versatility of magnetic recording is still unmatched in providing different storage media formats—tapes, stripes, cards, flexible disks, as well as hard disks—a capability that makes magnetic recording uniquely adaptable to a wide variety of data, video, and audio applications, both at the business and consumer levels.

Optical recording has gained strong acceptance in certain read-only, hard-disk applications where removability (the easy replacement of one disk with another) is the overriding requirement. Major examples are, in the order in which large-scale commercial development occurred, the *Compact Disc* for prerecorded audio, the *CD ROM* for computer applications, and disks for prerecorded digital-video programs are in the offing. Considerable research has been directed toward developing reversible optical recording devices which would expand the applications of optically-addressed storage products. One approach uses media in which recording takes place by optically induced phase changes which, at least to a limited extent, are reversible. The other approach, magneto-optical recording, provides unlimited reversibility by recording thermomagnetically and reading back magneto-optically. Longstanding research has led to commercially viable magneto-optical disk products for computer storage and audio applications. This technology is also capable of sustained improvements in storage density which can be expected to lead to lower-cost products. The combination of inexpensive, large-capacity, rewritable optical disks, which may be removed from the drive, will make this form of storage an increasingly viable contender for future computer and consumer applications. Magneto-optical recording falls within the category “magnetic recording” and is therefore treated extensively in these books.

With the exception of magneto-optical recording, all magnetic recording products employ the same basic inductive-recording technology which has been developed over the last 40 to 60 years. The technology has improved immensely as understanding has been gained of the underlying physics of the recording and

reproducing processes. Advances in recording materials and processes for fabricating components have also contributed in a major way to extending the performance of magnetic recording technology into different industries. Costs have continued to go down as means have been developed to pack more information reliably into a given storage space or to replace existing devices with ones smaller and less expensive to fabricate. A useful measure of such advances is the annual increase in areal storage density—the quantity of information that can be stored in a given area of the surface of a recording medium. For example, in the case of rigid disks, the areal storage density over the last eight years has risen by a factor of 25, equivalent to an astonishing average annual increase of approximately 50 percent, with no sign of peaking out in the immediate future.

The bulk of the research and development that has made this rate of progress possible has been carried out in the magnetic recording industry. During the past eight years, however, a surge in research activities in magnetic recording and related fields has occurred in the U.S.A. through the formation of nine research centers at universities throughout the country. Not only have these university centers accelerated the progress in materials, components, and systems for information storage, they have also provided a steady stream of trained graduates who have carried this progress to industry.

The purpose of this book, *Magnetic Recording Technology*, and the companion volume, *Magnetic Storage Handbook*, to be published later, is to provide definitive, comprehensive, up-to-date reference material for use by anyone engaged in the research, development, or manufacturing of information storage products based on magnetic recording.

Magnetic Recording Technology. This book covers the underlying technologies that are common to the various forms of magnetic recording, from the physics of the recording and reproducing processes to the tribology of the head-medium interface. The book should be of particular value to the students and staff at the University Storage Research Centers and to their counterparts engaged in research and advanced development within industry.

Magnetic Storage Handbook. This book covers the more practical aspects of magnetic recording, including the major applications and products used for storing computer data, and video and audio signals in analog and digital form. It will be useful to the student as a reference book, but its main purpose is to provide the scientists and engineers in industry with a single source of information on the major applications of magnetic recording, and the related storage products.

SI (Système International D'Unités) units are used throughout. Where other units (such as cgs) are widely used, values expressed in these units are listed in parentheses.

A comprehensive treatise on magnetic recording is possible only by combining the knowledge of many talented people. We greatly appreciate the dedicated efforts of the authors who have contributed their reviews of each branch of the subject and have cooperated in producing an in-depth coverage of this multi-disciplined field. We are also grateful to a number of external reviewers who assisted in our attempt to produce a uniform and up-to-date coverage of the subject matter.

C. Denis Mee
Eric D. Daniel

LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

AFM	atomic force microscope
APD	avalanche photo diode
CNR	carrier-to-noise ratio
DRAW	direct read after write
EPR-4	extended partial response, Class 4
FM	frequency modulation
HPF	hot pressed ferrite
LSB	least significant bit
ME	metal evaporated
MFM	magnetic force microscope
MP	metal particle
MSB	most significant bit
NEP	noise-equivalent power
NOP	non-contact optical profiler
NPR	noise-power ratio
PBS	polarizing beam splitter
PET	polyethylene terephthalate
PMMA	polymethyl methacrylate
SCF	single crystal ferrite
SFD	switching field distribution
SNR	signal-to-noise ratio
STM	scanning tunneling micro- scope
TEM	transmission electron micro- scope

THD	third harmonic distortion
VSM	vibrating sample magne- tometer

Symbols

A	area; exchange energy con- stant; exchange stiffness
a	acceleration; arctangent transition parameter; lattice constant
A_c	cross-sectional area of head core
A_g	cross-sectional area of head gap
a_l	transition parameter for lon- gitudinal magnetization
a_t	transition parameter for per- pendicular magnetization
B	half-amplitude (0-peak) of zig-zag pattern; magnetic in- duction (flux density)
b	base-film thickness; bit length; radius of particle; space between mag- netoresistive head shields; width of guard band

B_g	air-gap flux density	E	energy; Young's modulus
B_m	maximum induction (flux density)	e	charge of electron; head output voltage
b_p	critical particle radius for superparamagnetic behavior	E_a	anisotropy energy
B_r	remanent induction (flux density)	e_h	back emf
B_s	saturation induction (flux density)	E_d	demagnetizing energy
b_0	particle radius for single-domain behavior	E_e	exchange energy
C	capacitance; capacity (bytes)	E_f	Fermi energy
c	average length per turn in magnet coil; damping constant	E_h	external magnetic field energy
C_i	specific heat per unit volume of layer i	E_k	magnetocrystalline energy
C_r	crosstalk	E_{ms}	magnetoelastic energy
D	data rate; delay factor; recording density; width of domain wall	e_n	noise output voltage
d	head-to-medium spacing	e_o	signal output voltage
D_a	areal density (b/mm ²)	E_t	total energy
D_c	recording density for maximum resolution	e_x	output from longitudinal magnetization
d_{eff}	effective head-to-medium spacing	e_y	output from perpendicular magnetization
D_l	linear (bit) density (b/mm)	F	force
d_l	lens diameter	f	focal length; frequency
D_r	recording density (fr/mm)	f_c	carrier frequency
D_t	track density (t/mm)	f_{max}	maximum recorded frequency
d_0	minimum stable domain diameter spacing corresponding to nominal "in-contact" conditions	f_s	signal frequency
D_{50}	linear density at which the output falls 50%	f_0	Larmor frequency
$D_{(i)}$	thermal diffusivity of magneto-optical film ($\{i\} = f$) and dielectric ($\{i\} = d$)	$F(\theta)$	particle orientation factor
		G	gain; Green's function
		g	gap length
		g_{eff}	effective gap length
		H	magnetic field
		h	reduced magnetic field; stripe height of magnetoresistive head
		H_a	total anisotropy field
		H_{appl}	applied field (e.g., of magnetometer)
		H_b	bias field
		H_c	coercivity
		h_c	reduced coercivity (H_c/H_a)
		H_d	demagnetizing field
		H_g	deep gap field
		H_k	magnetocrystalline anisotropy field
		H_m	shape anisotropy field; maximum (applied) field
		$H_{\text{max}}, H_{\text{mrx}}$	sensitivity-function fields for a magnetoresistive head
		H_r	remanence coercivity

h_r	reduced remanence coercivity (H_r/H_0)	K_{eff}	effective uniaxial anisotropy constant
H_{rx}, H_{ry}	fields from a ring head (Karlqvist equations)	K_p	figure of merit including laser power tolerance
H_t	total field ($H_{\text{appl}} + H_d$)	K_r	figure of merit for rotating power
H_u	effective field seen by spin-up electrons due to spin-orbit effect	K_u	uniaxial anisotropy constant
H_0	particle switching (nucleation) field	k_i	position gain constant
h_0	reduced nucleation field (H_0/H_u)	K_{01}, K_1, K_2	crystalline anisotropy constants
$H_{0.25}$	reverse field required to switch 25% of particles after saturation [$M_r(H_{0.25})/M_r(\infty) = 0.5$]	k_1, k_2, k_3	spring constants
$H_{0.5}$	dc field in ideal anhysteresis required to obtain one-half saturation [$M_{ar}(H_{0.5})/M_{ar}(\infty) = 0.5$]	K_{\perp}	perpendicular anisotropy constant
$H_{0.75}$	reverse field required to switch 75% of particles after saturation [$M_r(H_{0.75})/M_r(\infty) = -0.5$]	$K(H_1, H_2)$	Preisach distribution function
H_1	positive field axis of the Preisach diagram	L	inductance; inductance of voice coil; length of dipole; length of head poles; orbital angular momentum quantum number
H_2	negative field axis of the Preisach diagram	l	length of head magnetic circuit; length of particle
I	intensity of electron beam; Laplace transform of current	l_i	length of head core
i	current	L_d	spacing loss
i_n	total noise current	$L_{\text{diff}}(t)$	approximate thickness of dielectric layer heated in time t
i_{nc}	electronic noise current	L_g	gap loss
i_{nt}	thermal noise current	L_{δ}	thickness loss
$I(r)$	light intensity at radius r	$L_{\{i\}}$	thickness of magnetic layer ($\{i\} = f$), overlayer ($\{i\} = o$), and intermediate layer ($\{i\} = i$)
$I_{(i)}$	intensity of magneto-optical radiation from semi-infinite ($\{i\} = s$) or quadrilayer ($\{i\} = q$) sample	M	magnetization; mass
J	exchange integral; moment of inertia; total angular momentum quantum number	m	dipole magnetic moment; mass; mass of electron; particle magnetic moment; reduced magnetization [$M(H)/M(\infty)$]
j	$\sqrt{-1}$	m_{ar}	reduced anhysteretic magnetization, $M_{ar}(H)/M_{ar}(\infty)$
J_{ij}	exchange integral between nearest neighbor atoms i and j	m_B	Bohr magneton
K	magnetic anisotropy constant	M_d	dc demagnetizing remanent magnetization
k	Boltzmann constant; wave number ($2\pi/\lambda$)	M_r	remanent magnetization (remanence)
		m_r	reduced remanent magnetization [$M_r(H)/M_r(\infty)$]
		M_s	saturation magnetization
		M_{sb}	saturation magnetization of bulk material

M_0	peak value of sine-wave magnetization; value of magnetization in between transitions	p_a	ambient (atmospheric) pressure
$M(H)$	magnetization in a field H	P, P_c	power dissipated
$M(H_m)$	magnetization in a field of maximum value H_m	P_i	laser power incident on medium
$M_r(H)$	remanent magnetization after applying a field H	P_s	optical signal power on each detector
$M_r(H_m)$	remnant magnetization after applying a field of maximum value H_m	P_{shot}	optical shot noise power on each detector
$M_r(\infty)$	saturation remanent magnetization (retentivity)	p_{25}	pulse width at 25% amplitude
N	demagnetization factor; number of atoms per unit volume; number of particles per unit volume	p_{50}	pulse width at 50% amplitude
n	index of number of tracks; number of turns; refractive index	Q	head parameter in calculating transition length
N_A	numerical aperture	R	data rate; reflectivity; reluctance; resolution; resistance
N_a	demagnetization factor along a axis of an ellipsoid	r	radial coordinate; radius
N_b	demagnetization factor along b axis of an ellipsoid	r_h	e^{-1} intensity radius of laser beam
N_c	demagnetization factor along c axis of an ellipsoid	R_c	reluctance of core
N_{eff}	effective demagnetization factor used for deskewing hysteresis loop	R_e	resolution
N_h	number of turns on head	R_g	reluctance of gap
N_i	number of turns on coil	r_{ij}	distance between nearest neighbor atoms i and j
$N_d(E)$	density of spin-down states at energy E	r_v	ordinary (unconverted) reflected amplitude for linear polarization x
$N_u(E)$	density of spin-up states at energy E	r_v	magneto-optical (converted) reflected amplitude for linear polarization y for incident polarization x
\mathbf{n}^+	complex refractive index for right circularly polarized light	R_0	base resistance of magnetoresistive head
\mathbf{n}^-	complex refractive index for left circularly polarized light	r_+	reflected amplitude for right circularly polarized light
$n_{[i]}$	refractive index of overlayer ($\{i\} = o$), or intermediate layer ($\{i\} = i$)	r_-	reflected amplitude for left circularly polarized light
P	average laser power on each detector; normalized pressure (p/p_a); power; print-to-signal ratio	$r_{[i]}$	complex Fresnel coefficient ($\{i\} = x, y, +$ or $-$)
p	pole-tip length; volumetric packing density	S	element of surface; remanence squareness [$M_r(H)/M_s$]; signal normalized to zero-peak signal from saturated region; spin angular momentum quantum number; synchronization pattern
		s	distance between head and permeable layer
		S_{sat}	zero-to-peak signal from a saturated region

S_{trans}	normalized zero-to-peak signal from an isolated transition	α_u	coefficient of thermal expansion of arm
S^*	coercivity squareness factor	β	angle; bandwidth; direction cosine
$S(H)$	remanence squareness in an applied field H	γ	angle; direction cosine
$S(H_m)$	remanence squareness in an applied field of maximum value H_m	Δh_i	switching field distribution
T	data period; temperature; tension; thickness of pole in a single-pole head; torque	ΔT	change in temperature
t	magnetoresistive sensor thickness; time; total thickness of medium including substrate; track spacing	Δw	side fringe width
T_c	Curie temperature	δ	depth of focus; eddy current penetration depth; stripe width in transmission line theory; thickness of a domain wall; thickness of a magnetic medium
T_{comp}	compensation temperature	δ_i	thickness of base film
t_{min}	minimum track spacing	δ_a	domain wall width parameter; side fringe width of read head
U	magnetostatic potential	δw_w	side fringe width of write head
U_0	magnetostatic potential between pole tips	$\epsilon(\omega)$	complex dielectric tensor (at frequency ω)
V	head-to-medium velocity; output voltage	ζ	fraction of heat residing in magnetic film
v	particle volume; volume	η	efficiency; quantum efficiency
v_p	critical volume for superparamagnetic behavior	η_k	polar Kerr ellipticity
W	full-width-at-half-maximum of Gaussian read beam; work	θ	angular coordinate
w	head width; track width; written mark width	θ_c	Curie temperature
w_{eff}	effective track width	θ_h	half-angle of lens
w_h	width of head	θ_k	polar Kerr rotation
W_i	strength of single ion anisotropy of atom of type i	θ_r	maximum Kerr rotation in system
w_r	read track width	κ	thermal conductivity
w_t	tape width	λ	characteristic length in transmission line theory; magnetostriiction coefficient; wavelength
w_w	write track width	λ_c	critical wavelength for maximum resolution
X	normalized coordinate (x/B)	λ_{min}	minimum recordable wavelength
X_i	atomic fraction of atom of type i	λ_s	magnetostriiction coefficient
Y	normalized coordinate (y/L)	μ	coefficient of friction; relative magnetic permeability
Z	atomic number; impedance	μ_r	relative permeability
Z_{ij}	number of j atoms that are nearest neighbors of atom i	μ'	real permeability
α	absorption coefficient; angle of polarizer; coefficient of thermal expansion; direction cosine	μ''	imaginary permeability
		μ_0	magnetic permeability of vacuum
		ν	frequency; Poisson's ratio

ξ	polarizing beam splitter efficiency	τ_d	penetration diffusion time
ρ	base resistivity of magnetoresistive head; density; resistivity	τ_e	electrical time constant
ρ_m	magnetic pole volume density	τ_{eq}	time constant to reach uniform film temperature
σ	standard deviation; stress	τ_{lat}	lateral diffusion time
σ_m	magnetic pole surface density	τ_m	time constant of magnet
σ_r, σ_s	stresses along polar coordinates	Φ	magnetic flux
σ_s	specific magnetic moment (saturation moment per unit mass)	ϕ	angular coordinate; magnetic flux; physical rotation of polarizing beam splitter
$\sigma(\omega)$	complex conductivity tensor (at angular frequency ω)	χ	constant relating fluctuations in anisotropy to average anisotropy; magnetic susceptibility
τ	time constant	χ_{ar}	anhysteretic susceptibility
		χ_0	initial reversible susceptibility
		ω	angular frequency ($2\pi f$)