Magnetic Information Storage Technology

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

This book is printed on acid-free paper. ♾

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Foreword

This volume in the Academic Press Electromagnetism series presents a modern, comprehensive and self-contained treatment of magnetic information storage technology. This technology evolves at a remarkable pace in the directions of increasing areal density of data storage, increasing rate of data transfer and decreasing cost. The phenomenal and explosive growth and expansion of magnetic storage technology has been achieved as a result of continuous and coordinated progress in such diverse areas as physics and processing of novel magnetic thin film materials and structures, mechanics of positioning and flying with extremely small tolerances and signal coding, detection and processing techniques. Thus, it is becoming increasingly important and challenging to present comprehensive and up-to-date exposition of magnetic storage technology with the emphasis on its interdisciplinary nature and the latest technical achievements. This book responds to this challenge.

Magnetic Information Storage Technology is written by Professor Shan Wang and Dr. Alexander Taratorin who are young, very active and productive researchers in the area of magnetic storage technology with intimate and firsthand knowledge of the latest technological innovations. The authors have managed to put together in one volume an extraordinary amount of technical information. The salient and unique feature of the book is its interdisciplinary nature. It covers with equal depth the topics related to magnetic heads, media, write and read-back processes as well as system aspects of magnetic recording such as coding, signal detection and processing. This book is probably the first attempt to present these diverse topics in the same volume.

I maintain that this book will be a valuable source of ideas, concepts, insights, and facts for students, practicing engineers, material scientists and physicists involved in the fundamental study and development of modern magnetic storage technology.

Isaak Mayergoyz, Series Editor

Preface

Most of us now use magnetic information storage technology, one way or another, on a daily basis. Billions of bytes of digital information storage space can be accessed at a touch of our fingertips, and at a dirt-cheap price! This feat is made possible by the ingenious creativity and hard work of many scientists and engineers who devoted themselves to magnetic information technology over the years. The technology involves many scientific disciplines, and is progressing at a lightning speed. The worldwide economy derived from magnetic and nonmagnetic information storage products is truly global and gigantic. As the new millennium approaches and information revolution deepens, the information storage technology will have unlimited promises and challenges.

There are many excellent books written on this exciting subject, most of which will be listed in the end of Section 1.2. For example, Profs. Hoagland and Monson's classical textbook, *Digital Magnetic Recording*, seems to be more suitable for an undergraduate course nowadays. Drs. Mee and Daniel's *Magnetic Recording Technology* and *Magnetic Storage Handbook* are essential references for practicing engineers, scientists, and specializing students, but somewhat intimidating for beginners. Prof. Bertram's *Theory of Magnetic Recording* is an excellent book for advanced graduate students and researchers, but indeed heavily emphasizes theoretical approaches, as its title suggests. In our humble opinions, there is a need for a textbook on magnetic information storage technology that is reasonably self-contained, emphasizes both experimental and theoretical concepts, and contains the important developments of the 1990s. In addition, the number of books on the subject does not nearly match the size of the information storage industry. Therefore, we invested a great deal of time and energy to write this new book and aimed for the following readers:

1. Graduate and undergraduate students who may or may not be directly involved with the research of magnetic information storage technology, but are interested in the subject at the materials, device, and system levels
2. Professors and instructors who teach courses related to information storage

3. Seasoned researchers who desire an all-around understanding of the fundamentals of the magnetic information storage and a comparison of alternative storage technologies
4. Entry-level engineers at data storage industry who wish to quickly acquire relevant working knowledge
5. Professionals who want to develop new information storage technologies and need to know the competition

We have tried to make the book friendly to beginners, yet at the same time reasonably rigorous and useful to advanced readers. Thus, it is written assuming that the readers have had some basic knowledge of *electromagnetism, Fourier transform, digital circuit,* and *probability and statistics.* Generally speaking, the level of difficulty of this book is between that of Haogland and Monson's and that of Bertram's textbook. However, it contains many materials not covered in either book.

This book evolved from the lecture notes developed for a two-quarter course on magnetic recording and information storage systems at Stanford University, California. The course is designed for graduate students or upper-level undergraduate students in the departments of materials science and engineering, electrical engineering, mechanical engineering, applied physics, and other related areas. It aims to help students gain an appreciation of the fascinating science and technology of magnetic information storage, and more importantly, to develp an ability to solve problems in magnetic recording using the basic techniques and models introduced in the course. We try to select the models and techniques that are always useful even if the technology changes from generation to generation. In keeping with this spirit, the book emphasizes basic concepts and most fundamental aspects of magnetic information storage. It is relatively self-contained and allows the readers to follow the contents without resorting to technical papers. Technical papers are cited for relatively new and specialized topics and should be studied to enhance the depth and breadth of your understanding. We try to be fair in citing the right papers for original contributions, but sometimes we cite papers for convenience and easy access to students. For the fundamental chapters, we cite fewer papers to force us to make the presentations as readable as possible to beginners and experts alike.

"A picture is worth a thousand words," so we have created many illustrations and figures to demonstrate basic concepts, models and results. We hope to convey to the readers the simplicity and beauty of the fundamental concepts through pictures that will stick in the readers' minds for a long time. Many of the figures and tables are taken or modified from our own research work, published or unpublished. Some of the figures are modified from other books and papers, and their original authors are gratefully acknowledged.

The organization of this book is very straightforward. A brief introduction to digital magnetic information storage and basic magnetics is given in Chapter 1. The latter part is designed for the readers who do not have a good exposure to magnetism, and should be skipped by advanced readers. The two building blocks of magnetic recording—the magnetic recording head and medium—are introduced in Chapter 2, with just enought detail to allow serious discussions of magnetic recording processes. Chapters 3 and 4 deal with write and read processes in magnetic recording, which are the foundation of the whole book. The next three chapters (Chapters 5, 6, and 7) are devoted to the detailed discussions of inductive magnetic heads, magnetic recording media, and magnetoresistive (MR) heads. Device performance, fabrication, and materials issues are covered here. Some sections in these three chapters can be skipped without affecting the reading of later chapters. Chapter 8 covers channel coding and error corrections. This chapter is essential for understanding how digital information storage is actually done, and why. The noise formulation and mechanism in magnetic recording is presented in Chapter 9, with an emphasis of signal-to-noise ratio considerations in magnetic recording. Signal-to-noise ratio is the starting point for understanding magnetic information storage at the system level. Other than noise, magnetic storage is also disturbed by nonlinear distortion and off-track interference, which are discussed in Chapters 10 and 14, respectively. These studies are necessary to make magnetic storage actually work. Chapters 11, 12, and 13 are devoted to three common data detection channels: peak detection, partial-response maximum likelihood (PRML), and decision feedback equalization (DFE). This book is probably the first attempt to cover these signal detection and processing methods in the same context. Chapters 9–13 are intended for advanced readers or students in an advanced course on megnatic information storage, so they can be largely skipped by beginners. Chapter 15 deals with servo and position error signal generation. The coverage does not do justice to the importance of the subject, but it is unintentionally short because of the authors' limited expertise. Similar situations happened in the treatment of other topics such as tribology, and we ask for readers' tolerance. Chapter 16 touches on the fundamental limitations of magnetic recording, including superparamagnetic effects and dynamic effects. These subjects are the focus of intense investigations as we speak. Finally, Chapter 17 is devoted to a brief examination of "alternative," or nonmagnetic information storage technologies, such as optic disk recording (including magneto-optic recording), holographic recording, semiconductor flash memory, and magnetic random access memory (RAM). This chapter is worth studying on its own right, but it also serves to show why magnetic information storage technology, particularly hard disk drive, is called the "once and future king."

Although great efforts have been made to write and edit the book, it is far from being perfect. There are inevitably some errors, typos, and even misconceptions undetected by the authors. If you notice any shortcomings, or simply have a comment, please contact the authors at sxwang@ee.stanford.edu, who will be very grateful.

This book is probably suitable as a textbook for a one-semester or two-quarter course on magnetic information storage technology. It has worked quite well at Stanford. Obviously, an instructor may choose to use some chapters and add his or her own supplemental materials. The authors do have a limited number of problem sets that can be shared on an informal basis. It is very important to do *homework.* To paraphrase a cliché, you forget after hearing, you remember after seeing, but you remember and understand only after doing.

The writing of this book is a substantial endeavor, which will not be possible without the help and support of many individuals. S. X. W. wishes to thank his colleagues at Stanford University, who have created an atmosphere conducive to productive work. In particular, Professors Robert White and Bruce Clemens have provided vital intellectual support over the years. The students at Stanford have also been very helpful and stimulating. A. T. wishes to thank his former colleagues at Guzik Technical Enterprises for their essential technical expertise and engineering support, and his fellow researchers and the management at IBM for providing an excellent work environment and for allowing him to take on this endeavor. Both authors wish to thank Professor Isaak Mayergoyz for his encouragement, and Zvi Ruder, Diane Grossman, and Michael Granger for their professionalism during the production of this book. Finally, we wish to thank our families, to whom this book is dedicated, for their loving support and sacrifices.

List of Acronyms

2D	two-dimensional
3D	three-dimensional
a.u.	arbitrary unit
ABS	air-bearing surface
AC	alternating current
ADC	analog-to-digital converter
AF	antiferromagnetic
AFM	antiferromagnet
AGC	automatic gain circuit
Al	aluminum
Al-Mg	aluminum magnesium
AMR	anisotropic magnetoresistive
Ar	Argon
AWGN	additive white Gaussian noise
BER	bit error rate
BLS	baseline shift
CCD	charge-coupled device
CD	compact disk
CD-ROM	compact disk read-only memory
CGS	centimeter, gram, and second (unit system)
CMOS	complementary metal oxide semiconductor
CNR	carrier-to-noise ratio
CTF	continuos time filter
Cu	copper
DASD	direct access storage devices
DC	direct current
DFE	decision feedback equalization
DRAM	dynamic random access memory
DVD	digital video disk or digital versatile disk
DVD-RAM	digital versatile disk random access memory (rewritable)
DVD-ROM	digital versatile disk read-only memory
E/H	easy/hard (transitions)
E^2PROM	electrically erasable programmable read-only memory
EA	easy axis
ECC	error-correction code
EFM	eight-to-fourteen modulation (code)
emu	electromagnetic unit
EPR4	class 4 extended partial response (channel)

EPROM	erasable programmable read-only memory
ESD	electrostatic discharge
esu	electrostatic unit
ETOM	electron trapping optical memory
FCI	flux change per inch
FDTS/DF	fixed-depth tree search with decision feedback
FE	ferroelectric
FFT	fast Fourier transform
FIR	finite impulse response
FM	frequency modulation
FM	ferromagnet
FT	Fourier transform
GB	gigabyte
Gb	gigabit
GMR	giant magnetoresistance
H/E	hard/easy (transitions)
HA	hard axis
HGA	head-gimbal assembly
HREM	high-resolution (transmission) electron microscopy
HTS	hard transition shift
IC	integrated circuit
IF	intermediate frequency
ISI	intersymbol interference
KB	kilobyte
Kb	kilobit
KBPI	1000 bit per millimeter
KFCI	1000 flux change per inch
LAN	local area network
MB	megabyte
Mb	megabit
MDFE	multilevel decision feedback equalization (channel)
MFM	magnetic force microscope
MFM	modified frequency modulation (code)
M-H	M (magnetization) versus H (magnetic field)
MIG	metal-in-gap (recording head)
MKSA	meter, kilogram, second, and ampere (unit system)
ML	maximum likelihood
M-O or MO	magneto-optic
MOKE	magneto-optical Kerr effect
MPEG	Moving Pictures Experts Group
MR	magnetoresistive or magnetoresistance
MRAM	magnetic random access memory
MSD	mean squared distance
MSE	mean squared error
NEP	noise equivalent (optical) power
Ni	nickel
NLTS	nonlinear transition shift
NM	nonmagnetic metal

NRZ	non-return-to-zero (code)
NRZI	modified non-return-to-zero (code)
OD	outer diameter (of disk)
OTC	off-track capability
PBSC	polarizing beam-splitter cube
PC	personal computer
PDF	probability density function
PE	partial erasure
PES	position error signal
PFPE	perfluoropolyethers
PLL	phase-locked loop
PPM	peak-to-peak modulation
PR4	class 4 partial response (channel)
PRML	partial-response maximum likelihood (channel)
PROM	programmable read-only memory
PW	pulse width
PWM	pulse width modulation
QWP	quarter-wave plate
RAM	random access memory
RAMAC	random access method of accounting and control
RE-TM	rare earth-transition metal (alloy)
RLL	run-length limited (code)
rms	root-mean-square
RPM	revolutions per minute
SAL	soft adjacent layer
SAM	sequenced amplitude margin
SDT	spin-dependent tunneling
SI	International System (of units)
SLM	spatial light modulator
SNR	signal-to-noise ratio
SR	shift register
SRAM	static random access memory
TAA	track-averaged amplitude
TCR	temperature coefficient of resistivity
TEM	transmission electron microscopy
TMR	tunneling magnetoresistance
TMR	track misregistration
UHV	ultrahigh vacuum
UV	ultraviolet (light)
VGA	variable-gain amplifier
VLSI	very-large-scale integration
VSM	vibrating sample magnetometer
XOR	exclusive OR (gate)

List of Symbols

$\vec{A}$	Vector form of any variable A
$\langle\rangle$	Average or expected value
$*$	Conjugate of a function or variable, variable after differentiation
∇	Gradient
$\nabla\times$	Curl
$\nabla\cdot$	Divergence
α	Direction cosine, angle between field and easy axis, flux leakage factor, temperature coefficient of resistivity, amplitude loss factor due to partial erasure, convergence parameter to minimize MSE, convergence parameter in clock recovery, attenuation factor to cancel precursor ISI in DFE, damping constant
β	Convergence parameter in gain recovery, factor in head field rise time
γ	Domain wall energy (per unit area), gyromagnetic ratio
γ'	Gyromagnetic ratio in the Landau-Lifshitz equation
γ_w	Domain wall energy per unit wall area
$\varDelta$	Hard transition shift or nonlinear transition shift, parameter related to reading adjacent track
$\varDelta_k$, $\varDelta(k)$	NLTS associated with the kth transition in a series of transitions
Δ	Change of a variable
$\Delta\rho_{\max}$	Maximum change in resistivity
$\Delta\rho_{\max}/\rho_0$	Magnetoresistance ratio
ΔE	Energy barrier to thermal switching
Δf	Frequency bandwidth, resolution bandwidth
Δl	Change in l
δ	Medium magnetic layer thickness, delta-function, skin depth
δ_n	Thickness of the nth particle
ε	Relative dielectric constant
ε_0	Absolute dielectric constant of vacuum
η	White noise spectral density, photodetector quantum efficiency
η_k	Ellipticity
θ	Angle between magnetization and easy axis, angle between magnetization and sense current
θ_1	Angle between spin valve free layer magnetization and sense current
θ_a	Analyzer orientation angle
θ_k	Kerr rotation angle
$\varLambda$	Grating period
λ	Wavelength, relaxation frequency, characteristic length of magnetic flux leakage

λ_s	Saturation magnetostriction constant
μ	Relative permeability, absolute permeability when noted
μ_0	Absolute permeability of vacuum
μ_c	Core relative permeability
μ_{eff}	Effective relative permeability
μ_n	Horizontal magnetization of the nth particle
ρ	Resistivity, electric charge density, information capacity per unit volume
$\rho_{\parallel}$	Resistivity parallel to magnetization
$\rho_{\perp}$	Resistivity perpendicular to magnetization
ρ_0	Minimum resistivity
ρ_j	Resistivity along current direction
ρ_m	Magnetic charge volume density
σ	Stress, electric conductivity
σ_{Σ}	Standard deviation of the total noise at the slicer of MDFE detector
σ_e	Stress along easy axis
σ_h	Stress along hard axis
σ_m	Magnetic charge surface density
σ_n	Effective mean transition jitter
σ_p	Standard deviation of $p(x,y,z)$
σ_{PW50}	Standard deviation of half-amplitude pulse width
σ_t	Standard deviation of t_s
σ_V	Standard deviation of zero-to-peak voltage amplitude
σ_x	Standard deviation of transition center
τ	Access time, head field rise time constant
τ_c	Current rise time
τ_f	Field or flux rise time
τ_h	Intrinsic head field rise time
τ_l	Rotational latency
$\tau_{\min}$	Switching time at critical damping
τ_s	Head settling time
τ_{sk}	Seek time
Φ	Magnetic flux
$\Phi_{\mathrm{sig}}(x)$	Signal flux injected into MR element from ABS
$\Phi_{\mathrm{sig}}(x,y')$	Signal flux propagating in MR element
ϕ	Magnetic potential
$\phi(k,y)$	Spatial Fourier transform of $\phi(x,y)$
$\phi_s(x)$	Surface potential at $y = 0$
χ	Magnetic susceptibility, electric susceptibility, magnetic susceptibility of minor loops
ψ	Attenuation factor of HTS due to the proximity effect, spatial transition shift due to head field rise time
ω	Angular frequency
ω_0	Fundamental angular frequency
ω_1	Low angular frequency during overwrite
ω_2	High angular frequency during overwrite
ω_c	Cut-off angular frequency of a low-pass filter
A	Area, distance between the (normalized) sample values in PRML