THEORY OF MAGNETIC RECORDING

H Neal Bertram

This book is a comprehensive text on the theory of the magnetic recording process. It gives the reader a fundamental, in-depth understanding of all the essential features of the writing and retrieval of information for both high density disk recording and tape recording. The material is timely because magnetic recording technology is currently undergoing rapid advancements in systems capacity and data rate.

A major contribution to the growth in magnetic recording technology is the recent development of advanced thin film materials for both recording media and transducers. In addition, sophisticated signal processing schemes are being implemented in order to achieve ultra large recording densities as well as high data transfer rates. A comprehension of the basic physics and engineering aspects of magnetic recording is essential if these developments are to be understood and to be utilized in the design of future systems. This text gives a thorough grounding in four basic areas of magnetic recording: structure and fields of heads and media, the replay process, the recording process, and medium noise analysis. In addition to these fundamental issues, key systems questions of non-linearities and overwrite are also discussed. A complete chapter is devoted to the emerging technology of magneto-resistive heads. A parallel treatment of time and frequency response is given to facilitate the understanding and evaluation of signal processing schemes. Using the information presented in this text, the reader should be able to design and analyze key experiments for head and medium evaluation and for overall system testing.

This text, which is unique in its scope, will be valuable for both senior undergraduates and graduate students taking courses in magnetic recording. It will also be of value to research-and-development scientists in the magnetic recording industry. An important element of the book is the inclusion of a large number of homework problems. The author assumes that the reader has had basic introductory courses in physics, in electricity and magnetism, and in applied mathematics.

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To my beloved Ann,
to our dear son Seth,
and with love and gratitude to my parents,
Manya and Barry Bertram

Contents

Preface

Magnetic recording is a technology that has continually undergone steady and substantial advancement throughout its history. Typically, in the last two decades areal densities in computer disk recording have increased by over two orders of magnitude. This development has occurred via the simultaneous growth in new materials for heads and media, advanced signal processing schemes, and mechanical engineering of the head–medium interface. In addition, there has been substantial growth in the theoretical understanding of the magnetic behavior of heads, media and, in general, the magnetic recording process. Fundamental understanding of the physics of magnetic recording is necessary not only for system design, but so that the specific behaviour of magnetic components can be analyzed, either analytically or numerically, saving time-consuming and expensive experimentation. For example, it is difficult to produce all the media variations required to perform a thorough comparison of different modes of recording, such as longitudinal and perpendicular recording.

In recent years there have been many publications that cover the fundamentals and applications of the magnetic recording process. These books or papers have been either technically oriented discussions of specific topics or have provided an introduction at an elementary level to the basics of magnetic recording. The philosophy of this book is to provide a pedagogical introduction to the physics of magnetic recording. The level is advanced and all basic aspects of magnetic recording are included: magnetic fields of heads and media, the linear replay process, the non-linear recording process including interferences, and medium noise. The basic mathematical tools for magnetic recording analysis will be developed, however, this text will not simply be a presentation of results and convenient formulae, it will attempt to give a thorough understanding, offering the reader the tools necessary to understand why results occur, to develop models, to design experiments, or to understand in-depth theoretical analyses in the current literature.

Because this text will emphasize the physical sense of processes and phenomena, the mathematical development will focus on analytic expressions rather than numerical results. General formulations will be given at the beginning of each chapter or section, however, simplified examples will be presented so that physical insight into the magnetic recording process can be stressed. When complete analytical expressions are not possible, approximate approaches will be emphasized, such as in the slope model for digital recording, or fields and transforms of thin film heads. Over the last decade there has been considerable development of media and heads for perpendicular recording. Even though conventional longitudinal recording has remained the dominant mode of high density recording (for reasons which are not entirely related to magnetic phenomena), in this text results for both modes are given in parallel. Not only does such a presentation give physical insight into magnetic phenomena, it provides the background in case perpendicular recording is utilized in the future or for the development of other modes such as canted grains utilized in metallic tape for 8mm video.

In the development of the recording process in this book, a parallel presentation of temporal and spectral analysis will be given. Magnetic recording systems are generally analyzed in the time domain. In digital magnetic recording a magnetization transition from one saturation direction to the opposite corresponds to an encoded '1' of information in a bit cell. Errors occur, for example with simple peak detection, if noise and interferences shift the apparent zero-crossing or replay pulse peak to an adjacent cell. Thus the temporal analysis of recording phenomena, such as bit shift is important. However, the frequency response of the recording channel is also useful. The spectral envelope of the fundamental component of square wave recording is the system transfer function, which is necessary for any applications where equalization is employed. Spectral analysis is also useful for analysis of recording parameters. Playback expressions in magnetic recording involve convolutions of head fields and recorded magnetization profiles, so that Fourier transforms or frequency analysis allow for the separation of head parameters, such as gap length and spacing, and medium parameters, such as transition length.

This text is divided into four primary sections plus an overview. In Chapter 1 a review of the technology, including materials utilized for heads and media is given. In addition a review of cgs and MKS unit systems is given, although the text is entirely in the MKS system. Chapters 2–4 comprise an in-depth discussion of magnetic fields for heads and media. This first section is designed to give the reader a solid foundation in magnetostatic fields, in particular the magnetostatic fields associated with magnetization patterns in media. In the second section comprising Chapters 5–6, the linear theory for calculating playback voltages from general magnetization patterns is presented. In addition to an in-depth development of the reciprocity principle, general and specific expressions are derived for single and multiple recorded transitions. In particular peak response ('roll-off curve') and spectral analysis of square wave recording are compared. In Chapters 7–9 the record process is presented for both thin films and tapes, including a discussion of non-linear phenomena such as bit shift and overwrite. In Chapters 10–12 modeling of varieties of medium noise: additive, modulation, transition, and correlation effects, is covered for both thin films and thick particulate tape. In the final chapter varieties of signal-to-noise expressions are derived along with error rates for simple zero-crossing detection. At the end of each chapter 'problems' are given that test the reader's understanding of the material presented.

This text grew out of the first year graduate course that the author has given for many years at the University of California at San Diego, in the Department of Electrical and Computer Engineering and as member of the Center for Magnetic Recording Research. This material is reasonably self-contained, however, an undergraduate-level background in static electromagnetic fields, mathematical methods such as complex variables and Fourier transforms, and random processes would facilitate a reading of this text.

The writing of this text occurred primarily during two sabbatical periods, in Paris, France and Cambridge, Massachusetts. I am grateful to my hosts during these periods who provided an atmosphere conducive to productive work. I would also like to thank my many colleagues over the years of my career in magnetic recording, who stimulated and, indeed, educated me on many aspects of the physics of magnetic recording. Without these interactions this book could never have been written. In addition, there were many people who contributed substantial time in the preparation of the figures and in general assistance in the preparation of the final copy. Particular gratitude goes to Dr Samuel Yuan and Betty Manoulian. Without their dedicated assistance during the final months of preparation of the manuscript, the book could not have been completed.

Dr Neil Smith carefully read Chapter 7 and made many helpful suggestions. He is to be especially thanked, not only for illuminating discussions, but also for providing many figures for that chapter. In addition, thanks go to Dr Yashwant Gupta, for preparation of many of the figures in the early stages of writing. I am grateful to Dr Lineu Barbosa and to Peng Qingzhi for carefully reading Chapters 10–12 and to Herbert Lin for examining Chapters 8–9. I would like to express special thanks to Dr Giora Tarnopolsky for his invaluable help during the final stages of preparation of this book. Finally, I would like to thank my wife, Ann, not only for the moral support and encouragement to see the project through, but also for a careful editing of the manuscript.

The theory of magnetic recording processes is in large part an application of the general theory of electromagnetic fields. It is a very beautiful mathematical, as well as physical subject, and it is hoped that the reader will find the same aesthetic pleasure in this material that the author has found.

H. Neal Bertram

1
Overview

Magnetic recording is the central technology of information storage. Utilization of hard disk drives as well as flexible tape and disk systems provides, inexpensively and reliably, all features essential to this technology. A data record can be easily written and read with exceedingly fast transfer rates and access times. Information can be permanent or readily overwritten to store new data. Digital recording is the predominant form of magnetic storage, although frequency modulation for video recording and ac bias for analog recording may persist in consumer applications. Data storage is universally digital. Superb areal densities for disk drives and volumetric densities for tape systems are achievable with extremely low error rates. In the last decade there have been extraordinary advances in magnetic recording technology. Current densities and transfer rates for disk systems are typically 60Mbits/in^2 and 10Mhz, respectively, but systems with densities of 1–2Gbits/in^2 are realizable (Wood, 1990; Howell *et al.*, 1990; Takano, *et al.*, 1991). The ability to coat tape with extremely smooth surfaces has permitted the development of very high density helical scan products (S-VHS, 8mm video) (Mallinson, 1990). The digital audio helical scan recorder (DAT) is representative of very high density tape recording with linear densities of greater than 60kbits/in, track densities of 250 tpi, and volumetric densities on the order of 50Gbits/in^3 (Ohtake, *et al.*, 1986). High data rate tape recording systems near 150MHz have been developed (Ash, *et al.*, 1990; Coleman, *et al.*, 1984). In general, densities and data rates of magnetic recording systems have been increasing at a rate exceeding a doubling every three years.

For rigid disk computer applications, thin film media with their high magnetizations and extremely thin coatings are now utilized in all new computer drives. Understanding micromagnetic processes in these materials enabled development labs to produce films with a substantial reduction in noise or magnetization fluctuations (Yogi, *et al.*, 1990a,b). These improved thin film materials have made possible the evolution in storage. Magnetic particles that make up tape have evolved into ever smaller and more uniform grains with high magnetizations and coercivities. In addition metal evaporated thin film tape is utilized in advanced video products (Chiba, *et al.*, 1989; Luitjens, 1990). Thin films also provide advanced technology for soft materials that comprise magnetic heads for all recording systems. Advanced heads are either entirely thin film or utilize thin films at the gap region of a ferrite core structure. For extremely advanced recording in the 1–2Gbits/in^2 range, thin film magnetoresistive heads are required in order to achieve signal to noise ratios limited only by medium noise. Magnetoresistive heads, due to their high, speed-independent, playback sensitivity, will eventually become commonplace in recording systems. The first commercial application in a high density disk drive is a 1 Gigabyte drive (IBM Corsair). In general, the science of multilayer films plays a dominant role in the formation of optimum thin film recording media and advanced inductive and magnetoresistive heads. For a review of materials for magnetic recording see Berkowitz, 1990.

Materials and magnetization processes

All advanced recording media are made of distinct fine grains. Granular structures yield the large coercivities and permanent magnetizations required of 'hard' magnetic storage materials. These properties coupled with extremely small particle size yield excellent signal to medium noise ratios, as well as minimal interference in recorded data patterns from non-linearities, residual overwrite or erasure, and extraneous fields. Magnetic tape is composed of elongated distinct particles of dimensions typically ~250Å × 250Å × 1000Å with net anisotropy axis along the particle long axis. Tape materials include γFe_2O_3, Co-γFe_2O_3, (surface passivated) Fe, CrO_2 or BaFe with particle magnetizations on the order of 370–500 kA/m (370–500 emu/cc) and tape coercivities in the range 24–120 kA/m (300–1500 Oe) (Köester & Arnoldussen, 1989). Tape coatings are extremely smooth with surface roughness on the order of 50nm (Wierenga, *et al.*, 1985; Robinson, *et al.*, 1985), and particles are usually well oriented in the direction of relative head medium motion (Fig. 1.1). Tape M-H major loops exhibit typical squarenesses S, S* ~0.85. Particle volume loading is ~30% by volume, and saturation remanent

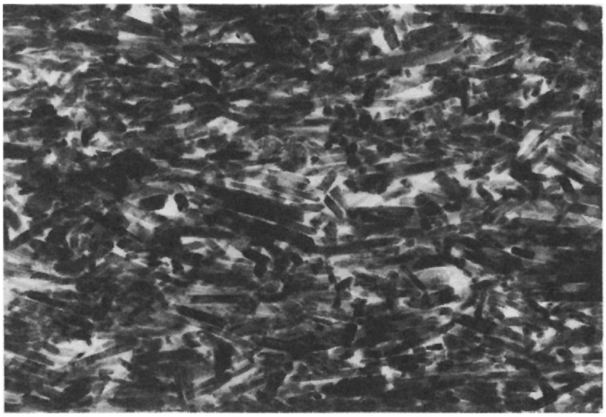

Fig. 1.1. TEM of cross-section of tape composed of oriented CrO_2 particles. Courtesy of Eberhard Köester, BASF, Ludwigshaven, Germany.

magnetizations (B_r) of 0.15T (1500 G) for oxide materials to 0.25T (2500 G) for metallic particles are achieved. Tape media is coated on a 'polyurethane base-film' varying in thickness from 10–12μm. Although the magnetic layers are typically 3–5μm thick, optimized high density digital recording utilizes only about 0.5μm of the surface layer for recording magnetic signals.

High quality magnetic thin films utilized as recording media are generally composed of a Co dominant alloy sputtered on a suitable growth enhancing underlayer. The films are polycrystalline with the grains or 'particles' on the order of 200–500Å in diameter in the film plane (Fig. 1.2). For longitudinal films the grain easy axes (Co hcp axis) are either random in the plane or oriented along the head–medium motion direction. For perpendicular films the Co easy axes are perpendicular to the film plane within a cone of $\sim 5°$. In evaporated metal tape the grains grow at an angle to the film plane of $\sim 30°$. In all film recording media the grains are believed to extend uniformly through the film thickness, which is ~200–500Å for longitudinal films, ~2000–5000Å for perpendicular films and ~1500Å for metal evaporated tape (Luitjens, 1990; Köester & Arnoldussen, 1989). In all cases high quality films are produced only if the grains are magnetically well segregated with negligible magnetic or intergranular exchange coupling (Bertram & Zhu, 1992).

The magnetization of recording media averaged over regions that comprise many grains is in general a vector relation of the applied field