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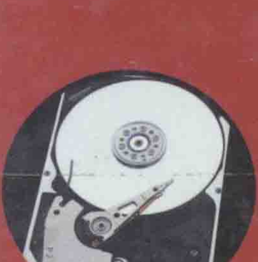
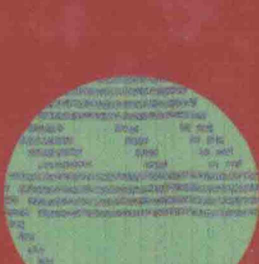
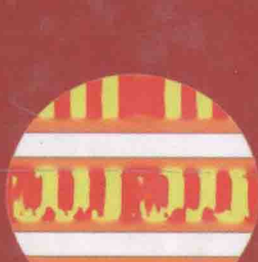
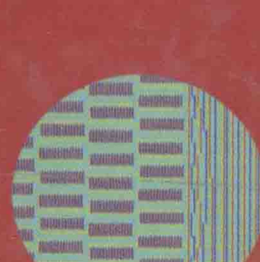

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Spin-Stand Microscopy of Hard Disk Data

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Preface

This book is about the science and technology of fast magnetic imaging and analysis of hard disk data, which has been of substantial research interest lately. In 1999, we proposed a high-speed, massive magnetic imaging technique called *spin-stand microscopy*. It is the first magnetic imaging technique where imaging is performed ex-situ on a rotating disk mounted on a spin-stand. This technique is one of the fastest scanning-based microscopy techniques. It is noninvasive and has nano-scale resolution. For these reasons, it provides unique capabilities for the visualization of magnetization patterns recorded on hard disks. This book covers in depth the theory of spin-stand microscopy, its experimental implementation, and its applications in the areas of hard disk recording and beyond.

The ubiquitous use of spin-stands in the research, development, production and testing of hard disk drives makes this book a valuable reference for the hard disk recording community. This book is also of direct relevance to the magnetic microscopy professionals who are always searching for new techniques to perform microscopic imaging on magnetic materials in a rapid and accurate manner. Finally, this book will be beneficial to engineers and scientists involved in computer forensics, commercial data recovery as well as the design of reliable archival data storage systems.

Since the spin-stand microscopy technique is a new technology developed by the authors and their collaborators, this book is the first one on the market on this subject. This book is an outgrowth of the research performed by the authors and their collaborators who, over the last decade, have acquired an extensive knowledge and experience in the fast magnetic imaging and analysis of hard disk data on a spin-stand. In order to make the materials accessible to a broader audience, this book is self-contained with no prior assumptions on readers' familiarity with either magnetic recording or magnetic microscopy. The interdisciplinary nature of spin-stand microscopy is consistently stressed. The outline of the book is as follows.

There are two main parts in the book. Part I deals with the theory of spin-stand microscopy and consists of the first five chapters. Part II focuses on the applications of spin-stand microscopy and consists of the last four chapters.

Chapter 1 is an introductory chapter that covers the necessary background materials. Topics discussed include the technological evolution of hard disk drives; basics of hard disk recording technology; a survey of selected magnetic microscopy techniques; and a brief overview of the spin-stand microscopy technique.

Chapter 2 introduces the hardware of the spin-stand system. The scanning mechanism of the spin-stand microscopy technique is described. This chapter emphasizes the experimental aspects of the imaging technique to obtain two-dimensional "raw" images. Different triggering techniques are considered. The advantages of the spin-stand microscopy technique are listed and compared with other magnetic microscopy techniques.

Chapter 3 presents the theoretical foundation of the image reconstruction technique that is used to retrieve actual magnetization images from raw spin-stand images. This chapter provides a complete description of the image reconstruction algorithm. This algorithm enables the recovery of vectorial magnetization from the scanned 2D "raw" scalar images. The algorithm is based on the notion of the head response function. In order to test the effectiveness of the reconstruction algorithm, the spin-stand microscopy technique is applied to the imaging of overwritten data. The spin-stand images of the overwritten data are then compared with the corresponding ones obtained by using magnetic force microscopy.

Chapter 4 deals with experimental techniques for extraction of the head response function. First, it is demonstrated that the accuracy of the head response function can be substantially enhanced by the method of "spatial averaging." Then, the accuracy of image reconstruction is further improved by the method of scaling which is based on a self-similarity argument.

Chapter 5 presents novel numerical methods for the removal of intersymbol interference (ISI) from spin-stand images. One of the methods is based on the response function characterization of giant-magnetoresistive heads used in microscopy. It is demonstrated that the ISI-free readback image corresponding to the actual underlying magnetization patterns can be extracted from the ISI-distorted readback signal through deconvolution. Another method is based on the Hilbert transform and it is also quite efficient as far as the removal of ISI is concerned. A novel 2D generalization of Hilbert transform for three-dimensional magnetic fields in magnetic recording is presented. This Hilbert transform is of interest in its own right.

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The second part of the book deals with the diverse applications of spin-stand microscopy in hard disk recording and data forensics, and it consists of the last four chapters.

In Chapter 6, the spin-stand microscopy technique is applied to the imaging of recorded patterns on disks removed from commercial hard drives. Challenges related to the eccentricity of the disk and the instability of the trigger are examined and solutions are provided. Special techniques of entire-track spin-stand imaging and track centering are discussed in detail. The method of track following using piezo-controlled head movement is thoroughly developed. Spin-stand images of hard disks from drives of different generations are presented as examples.

Chapter 7 presents the procedures and results of using the spin-stand microscopy technique as a tool for data forensics. The conceptual aspects of data detection, decoding and error corrections pertinent to spin-stand data forensics are briefly discussed. Extensive demonstration of spin-stand forensics of hard disk data from drives of different generations is shown via the examples of recovery of JPEG images.

In Chapter 8, the vectorial magnetization of recorded data is investigated. Specifically, the distribution of transverse component of magnetization of recorded tracks is extensively studied for different track widths and various recording frequencies (densities). The fact that only the curl-free component of magnetization can be retrieved using spin-stand imaging is demonstrated.

Chapter 9 deals with the spin-stand study of thermal relaxation (viscosity) of recorded patterns. The distinction between intrinsic thermal relaxations and data-dependent thermal relaxations is emphasized. It is shown that the thermal relaxations of the latter type can be efficiently studied by observing the decay of higher-order harmonics of the recorded patterns. Spin-stand results of thermal relaxation experiments are presented. Finally, the spatial and vectorial characterization of thermal relaxations of recorded patterns is studied via spin-stand microscopy and dynamic images of magnetization relaxations are presented.

During the time of our ongoing research on spin-stand microscopy, magnetic data storage technology has undergone dramatic evolution. This evolution has resulted in drastic reduction of giant magnetoresistive (GMR) head dimensions. The experimental results presented in this book inevitably reflect this evolution. These results correspond to different generations of GMR heads, which were available at the time when the specific experiments were performed.

We want to express our gratitude to Dr. Charles Krafft for the longstanding fruitful collaboration. We are very grateful to our Ph.D. students

Patrick McAvoy, Chun-Yang Tseng, and Sergiy Tkachuk who actively participated in the research on spin-stand microscopy and whose accomplishments are partially reflected in this book.

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Part I

Spin-Stand Microscopy: Theory

CHAPTER 1

Introduction

The goal of this introductory chapter is to orient the readers to the status of hard disk data storage and retrieval. It begins by highlighting the technological evolution of hard disk drives. The issues related to data loss are subsequently discussed. This is followed by a survey of selected magnetic microscopy techniques available for the imaging of hard disk data. Finally, the core topic of the book, the spin-stand microscopy technique is introduced along with advanced spin-stand-based data forensic methods.

1.1 TECHNOLOGICAL EVOLUTION OF HARD DISK DRIVES

How much new information is created in a year? That is the question raised and answered by the study [1] conducted by the School of Information Management and Systems at the University of California, Berkeley. According to the study, about 5 exabytes (1 exabyte = 10^{18} bytes) of new information was created in 2002 and 92% of this information is stored in magnetic media. Currently, hard disk drives are the dominant magnetic storage devices because they offer the best overall combination in non-volatility, reliability, large capacity, high data transfer rate, and low production cost. Data from disk drive manufacturers shows that the estimated number of total hard drives sold in 2006 exceeded 400 million units and will exceed 650 million units by 2010, generating worldwide market revenues on the order of tens of billion dollars per year.

Hard disk data storage technology is evolving at a remarkable pace that has few equals. The phenomenal advancement in this technology has been achieved as a result of continuous and coordinated progress in such diverse areas as physics and processing of novel magnetic nano-film structures, mechanics of positioning and flying with extremely small tolerances as well as development of novel techniques for coding, detection and digital signal processing of high-density recorded data. The design of modern disk drives is a fusion of various scientific disciplines entailing magnetics, surface physics, material science, tribology, control theory, information and communication theories. This interdisciplinary nature of disk drive technology is exemplary of the merge between human ingenuity and engineering prowess.

Since the invention of the first hard drive by IBM in 1956, the technological evolution of hard drives has been nothing short of phenomenal. The first commercial hard drive, called the RAMAC (Random Access Method of Accounting and Control), had a total capacity of 5 MB, contained 50 disks each 24 inches in diameter, had an access time of one second and data transfer rate of 0.5 MB per second, and cost $50 000 [2]. By contrast, today's typical disk drives can hold capacities in excess of 500 GB, use 3.5 inch disks, have an access time of 6 ms and a data transfer rate of 150 MB per second, and cost about $200. The cost per megabyte—a very important figure of merit for hard drives—has decreased 25 million-fold in half a century!

Perhaps the most significant indicator of the phenomenal progress of disk drive technology is the exponential increase in areal density—the amount of information stored per unit area of disk surface. Areal density, measured in number of bits per square inch, is the product of track density (number of tracks per inch) and linear density (number of bits per inch). From a system perspective, track density is currently limited by the mechanical precision of radial actuators to accurately seek a target track and the ability of the servomechanism to stay on this track. Linear density, on the other hand, depends on head and media properties, the flying height, the disk rotational speed, and the sophistication of the channel to detect and decode the track data.

Over the past years, the rate of increase in track density has been greater than that of linear density, resulting in ever-decreasing bit aspect ratio (BAR or bit width to bit length ratio). In 2005, hard disk drives boast a track density about 150 kilo-track-per-inch (ktpi) and linear density of 800 kilo-bit-per-inch (kbpi), leading to a bit aspect ratio (bit-per-inch/track-per-inch) of about 5:1 and areal density over 100 giga-bit-per-square-inch (Gb/in^2). These numbers are well beyond the limit once thought insurmountable due to the superparamagnetic effect. This effect implies that thermal fluctuations due to ambient temperature are sufficient to spontaneously flip the magnetization orientation of isolated grains inside the bit regions and, when enough of these flippings occur, the recorded information is lost [3–6].

Historically, areal density increased at an annual compound growth rate (CGR) of 25% throughout the 1970s and 1980s. In the early 90's, the growth rate increased to 60% per year. This was due mainly to the development of magnetoresistive (MR) heads to replace the traditional inductive heads for reading. Unlike inductive read heads which detect *temporal* changes of magnetic flux, MR read heads sense *spatial* variations of magnetic fields produced by recorded patterns of magnetization. Toward the late 90's, as a result of the revolutionary development of giant-magnetoresistive (GMR) heads and introduction of advanced read detection channels like PRML (Partial Response Maximum Likelihood), the areal density has been further increased.

This impressive upsurge in data density opens the paths for hard drives to find applications apart from personal computers. Hard disk drives are increasingly being integrated into consumer electronics products. Digital cameras, camcorders, video game consoles, MP3 music players and mobile phones are beginning to embrace hard drives with very small form factors as their storage platforms.

The technological advancement of hard disk drives is the result of extensive multi-disciplinary research in the magnetic recording industry and universities. It is truly a scientific marvel and an engineering feat that hard drives can pack in so much data so fast at so low a cost. Research in magnetic recording is being pursued in the directions of increasing the areal density of storage, increasing the rate of data transfer, decreasing the data access time, and decreasing the cost per megabyte [7]. These are the four figures of merit for hard disk drives, with areal density and cost being the most significant. The higher areal density can directly translate to lower cost and indirectly to higher data transfer rate. Indeed, higher areal density would mean fewer components (platters, heads, and electronics) and thus results in reduced costs. Higher areal density also permits more data to be delivered within a fixed time span, thereby indirectly boosting the data transfer rate. Here, the distinction must be made between two kinds of data transfer rate. The *internal* data transfer rate is the rate at which data is transferred from the disk platter to the head. It is the product of linear density (bit/inch) and linear speed (inch/second). The *external* data transfer rate or the *interface* rate, on the other hand, is the rate at which data are exchanged between the hard drive controller and the host computer. The latter rate is usually the faster of the two. For a more detailed exposition of the components and technology of modern hard disk drives, the reader is referred to Appendix A of this book.

Having reviewed the technological evolution of hard disk drives, the next section deals with the need for advanced hard disk data microscopy methods.

1.2 SURVEY OF SELECTED MAGNETIC MICROSCOPY TECHNIQUES

As the demand for higher data areal density continues to increase, so has the need for advanced scientific instrumentation that can support the corresponding research in high-density magnetic recording. One important aspect of this research is the imaging of the recorded patterns on hard disks. The imaging of these patterns can provide a wealth of information on the overall recording capabilities of the disk drive systems. Insight gained by studying these imaged patterns can then be utilized toward achieving higher areal density and improved performance of the hard drives. Since the magnetization patterns on the hard disks are recorded in ever smaller length scales, magnetic microscopy techniques with ever higher resolution are needed in order to study these patterns.

There are various microscopy techniques for imaging magnetization patterns recorded on hard disks. Most microscopy techniques are indirect and measure only the external fields produced by the magnetization patterns rather than the magnetization itself. These techniques can be further differentiated into two broad categories based on their scanning mechanism.

In the first category, no scanning by a probe is performed on the sample. Rather, outside agents are made to interact or impinge upon the sample surface and the effects of the resultant magnetic interaction are observed via high-resolution microscopes. The Bitter technique, for example, images the patterns coated with a thin film of ferro-fluid [8,9]. The ferro-particles are attracted to the regions of the strong field produced by the pattern magnetization. The resulting patterns of particles (Bitter patterns) are then observed under either an optical microscope or a scanning electron microscope (SEM). In Lorentz microscopy, an electron beam is directed at the sample, deflected by the Lorentz force produced by the pattern magnetization, and the deflections are measured using a SEM or a TEM (transmission electron microscope) [10–12].

In imaging techniques of the second category, commonly called the scanning probe microscopy (SPM), the sample is raster-scanned with an extremely fine (sharp) tip. The tip is mounted on a flexible cantilever, allowing it to follow the surface contour of the sample. In magnetic force microscopy, this tip is coated with a ferromagnetic material such that when it moves in proximity to the sample, forces of interaction between the tip and the sample-magnetization-induced magnetic field influence the movement of the cantilever. These resultant forces are then detected by special sensors. For instance, in magnetic force scanning tunneling microscopy (MFSTM) [13–17], the probe sample separation is recorded by

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