Advances in Magnetic Data Storage Technologies

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I. PREFACE

The beginning of magnetic storage is usually attributed to Valdemar Poulsen's 1898 invention of the "telegraphone," which he used to record and reproduce sound. This primitive device has evolved to the hard disk drive (HDD) of today. Beginning with the first commercial HDD in 1955 (the 2-ton IBM 305 with 4.4 Mbytes of storage space), magnetic disk drive technology has integrated many science and engineering disciplines. The demand for inexpensive information storage fueled the rapid growth in areal density, as well as rapid decline in size and cost per gigabyte of data (see Fig. 1). Recently, products with more than 250 Gb/in^2 have been shipped, and densities as high as 520 Gb/in^2 have been demonstrated in the laboratory.[1] Compared to the original IBM 305 drive, hard disk drives today have almost eight orders of magnitude larger bit areal density and are eight orders of magnitude lighter (per megabyte of storage). Sleek storage servers, with capacities of multiple hundreds of terabytes, fitting on one rack, have replaced endless farms of clean air filtered facilities containing thousands of bulky tape and disk drives. Yet, this remarkable quest aimed towards multiple orders of magnitude improvement in areal capacity and performance is hardly close to being over. It is worth reviewing the major technologies that have allowed this ascent, as well as examining future technologies that will enable a steady stream of improvements in the future.

This Special Issue covers advances that have spurred real density growth of magnetic recording technologies, and future technologies that are expected including new architectures of storage systems.

This paper serves as an editor's note for a Special Issue dedicated to advances in magnetic data recording technologies. We begin by discussing challenges, particularly the ability of magnetically stored information in extremely tiny bits to resist thermal fluctuations (superparamagnetic limit), the proper role of hard disk drives versus flash memory in the storage hierarchy, and system issues related to performance, security, and energy usage. Major magnetic recording storage technology trends, such as emergence of perpendicular media, and promising novel magnetic recording concepts, such as patterned media and heat-assisted magnetic recording (HAMR), are overviewed.

This introductory paper then continues with a brief discussion of the topics covered by each paper. Selected technologies have enabled and continue to enable strong areal density growth span advances from thin-film perpendicular media, including new types of media based on exchange coupling, to read channel design. Most of the magnetic recording technologies developed for hard disk drives have found applications in magnetic tape technology, which continues to improve its capacity, performance and utilization. Future technologies that are expected to propel and extend magnetic data recording for the next 10–15 years, covered in this issue, are patterned magnetic media including nanoimprinting, heat-assisted

[1]See http://news.thomasnet.com/companystory/535040.

Digital Object Identifier: 10.1109/JPROC.2008.2004308

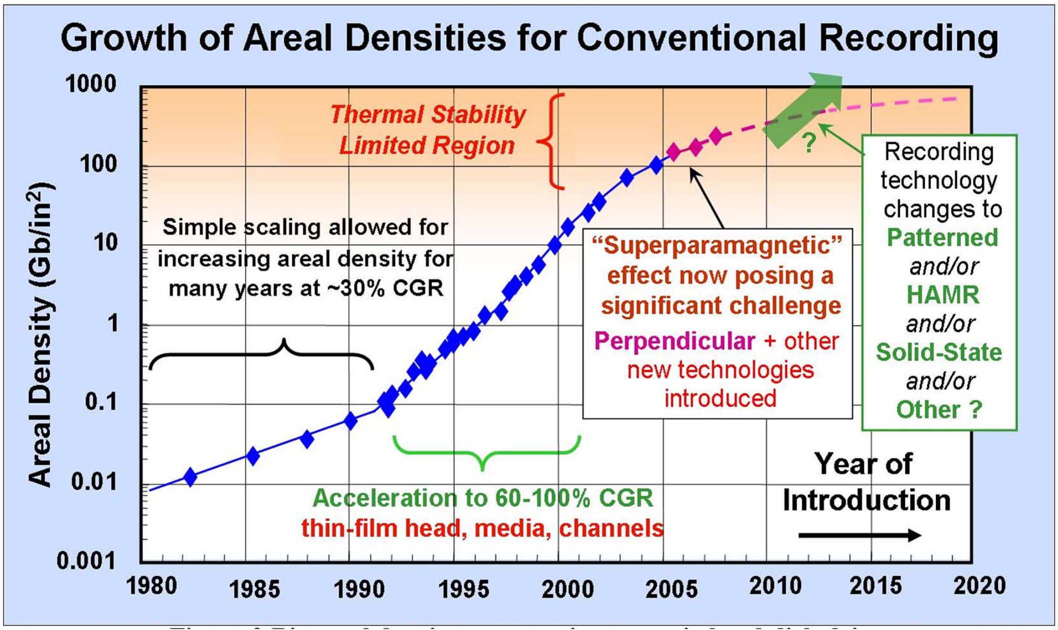

Fig. 1. ***Bit areal density progress in magnetic hard disk drives.***

magnetic recording, and FePt-based self-assembled magnetic media, suitable for both heat assisted and patterned magnetic recording. We have not specifically covered the technology of silicon flash and other advanced electronic cross-point based memories in this Special Issue because this issue is dedicated to magnetic-based data recording technologies; however, we do cover magnetic random access memories (MRAMs), both field and spin-current switched. Finally, on the system-level, we include recent developments and future challenges of storage systems and the emerging role of NAND-based Si flash memories in the storage architecture, including hybrid flash-magnetic media recording systems.

II. CHALLENGES IN MAGNETIC RECORDING

Magnetic storage devices and systems permeate almost every aspect of the digital life, as we store large amounts of data on MP3 players, cell phones, personal and business computers, Web 2.0 applications, and corporate storage systems, among countless other applications. Some estimates even indicate that the growth in digital media archival demands may outpace the ability of the data storage industry to manufacture sufficient storage capacity [1]. The bit areal density progress over the last 50 years has at times outpaced Moore's law (fueled by large demand in storage capacity) and is expected to continue to grow, albeit at a slightly slower pace (see Fig. 1). The fastest pace in bit areal density progress occurred in the 1990s, when the invention of the thin-film head and giant magnetoresistance sense head, plus improvements in thin sputtered media and advancements in digital recording channels, enabled 60–100% compounded growth. An excellent overview of materials advancements for heads and media in magnetic data storage has recently been provided elsewhere [2], [6]. Magnetic recording technology has offered numerous electrical, mechanical, physical, and chemical challenges over the years, and it is quite difficult to summarize them in one Special Issue, much less a single paper. However, some technological, competitive, and system-level challenges may be summarized as follows.

A. Superparamagnetic Limit

At the prevailing laboratory demonstration densities exceeding 500 Gb/in^2, the corresponding bit size is smaller than 1300 nm^2, typically 15 $\times$ 90 nm^2, and contains only a few dozen magnetic grains (the grain size typically being 8 nm in diameter or smaller). The signal-to-noise ratio (SNR) of the magnetic recording process depends on the roughness of the magnetic transitions between neighboring bits. As bits are composed of individual grains (which can take either direction of the magnetic field), the SNR is dependent on the relative ratio between bit size and grain size, or, more precisely, SNR $\propto Wbt/V_g$, where Wbt is the bit volume (bit width $\times$ bit length $\times$ media thickness) and V_g is the grain volume [3]. This implies that scaling of areal bit density of magnetic media (or reduction of bit size) requires scaling (or reduction) of the grain size. However, the grain size cannot be arbitrarily reduced because the superparamagnetic limit is reached at the point when a grain is so small that thermal energy alone is sufficient to cause change in its magnetic orientation. The critical grain volume V_g that determines the onset of the superparamagnetic limit is determined by the condition that stored magnetic energy K_uV_g remains about 40–60 times larger than the thermal energy k_BT, where K_u and k_B are the magnetic anisotropy and Boltzmann's constant and T is the temperature [4]. (Magnetic anisotropy is a measure of the energy required for the magnetization to change direction.) This implies that the size of magnetic grains should remain in the 8 nm range or the magnetic anisotropy of the magnetic material has to be increased—exactly the two paths taken by patterned media and heat-assisted magnetic recording. In the case of patterned media, 1 bit of information is represented by one grain that can be substantially larger than 8 nm while still allowing significant improvements in bit areal density. In the case of HAMR, the media have large magnetic anisotropy (which allows smaller bits through smaller gains). However, the magnetic writing process requires heat assistance in order for the magnetic field of the writer to be capable of inverting bits stored in highly coercive media. (Heat reduces the anisotropy energy and thus the coercivity, which is a measure of the resistance of the magnetization to an applied field.) The current consensus in the HDD industry is that perpendicular magnetic recording may continue to scale up to 500–1000 Gb/in^2, while in the future, patterned media and HAMR will be required to extend bit areal density beyond 1 Tb/in^2.

B. Silicon Flash-Based Memories

Although they have been available for many years, silicon flash-based memories have recently become more popular for use in high-end enterprise and mobile applications, as their cost (per gigabit of memory) continues to decrease at a rapid 40–60% annual rate. Although their costs remain more than an order of magnitude greater than HDDs, the performance of solid-state drives based solely on silicon can compensate in some applications. Flash-based memory does not suffer from mechanical positional latencies of the hard disk drives and typically has access times of the order of 0.1 ms, behaving as a truly random access memory (HDDs typically exhibit access times on the order of several milliseconds for high-performance drives and up to 15–20 ms for inexpensive models). This amounts to a potential storage revolution similar to the revolution caused by differences between magnetic tapes and HDDs (that used to be called direct access storage device exactly because of fast access compared to magnetic tapes). This challenge is not likely to displace magnetic hard disk drives but may alter overall storage architecture where faster Si flash-based memories may become faster, nonvolatile cache memory for large arrays of magnetic hard disk drives.

However, from the technology point of view, Si flash memories are close to their maturity and face many challenges of their own. The most significant challenge of Si flash is the thickness of the oxide film of the floating-gate metal oxide semiconductor transistor (that stores information as charge on the insulated encapsulated floating gate). As the gate length is reduced (to increase effective areal density), the oxide thickness has to be proportionally reduced, currently reaching the point where the oxide film is so thin that charge retention (memory) becomes degraded trough trap assisted tunneling [5]. This leads to a reduced number of erase cycles available for Si flash, and in turn reduces the number of times Si flash can be read or written. Similarly to patterned media, further scaling of flash memories may require introduction of novel lithography technologies, such as nanoimprinting. In the short term, some of these challenges can be addressed by device design improvements, architectural improvements (such as storing multiple levels per cell), and attempts at three-dimensional integration, while in the long term, transition to cross-point memories based on nonsilicon materials such as phase change, ferroelectric, or magnetic materials will become required.

C. Storage Systems

As overall storage demand keeps growing (largely due to growing amount of digital data stored on Internet but also due to improvements in storage cost and capacity), the storage and archival libraries are facing complex real-time storage management issues. Some of these issues are traditional enterprise storage issues such as scalability, reliability, and performance that have been successfully addressed with arrays of hard disk drives. Recently, due to the increased cost of energy and related environmental issues, much emphasis has been placed on the energy efficiency of storage, which has led to new categories of storage subsystems [such as massive arrays of idle disks (MAID)]. On the other side, due to the progressively larger amount of private information being placed either on portable computers or on internet portal servers, data security (and, in particular, data at rest security) is also becoming one of the important required features of both individual disk drives and overall storage systems. Finally, the emergence of Si flash-based memories and solid-state drives allows for interesting novel storage architectures, both on the single drive level (such as hybrid disk drive) and on the storage system level, where Si flash plays the role of the fast, nonvolatile cache memory that improves overall system performance.

III. SPECIAL ISSUE

In this Special Issue, we present state-of-the-art reviews that demonstrate how key novel magnetic recording technologies and system-level architectures impact information storage and enable future growth in areal density, memory capacity, and utilization of hard disk drives. We address technologies such as perpendicular magnetic recording, exchange coupled composite media, advances in magnetic recording data channels, and magnetic tape. We also consider future magnetic storage technologies including HAMR, patterned media, MRAM cross-point memories, FePt self-assembled media, and advances and challenges in storage systems, together with the role of Si NAND flash memory in storage architecture. The contributing researchers include key experts from top universities and industrial research laboratories engaged in storage research. These papers provide an excellent survey of the state of the art in magnetic storage research and highlight successes and future research challenges in this vibrant field of study. We have classified these papers into three main categories:

A. State-of-the-Art Magnetic Recording Science and Technology

In the last several years, all hard disk drive manufacturers transitioned from longitudinal to perpendicular magnetic recording technology, which enabled continuation of bit areal density progress and is the most significant technological change that has occurred in the HDD industry in the last ten years. The paper on perpendicular recording technology by Tanaka from Toshiba describes major challenges and solutions that brought CoPtCrO/Ru-media based perpendicular disk drives from research to commercialization. Each and every technological improvement in magnetic recording that increases the total number of bits stored on one drive (such as perpendicular recording) brings new challenges in reliably reading and writing large amounts of data flowing in and out from the read channel. The paper on the read channel by Kavcic from the University of Hawaii and Patapoutian from Seagate serves as an excellent tutorial on the read channel design and outlines novel technologies that have found implementation in current HDD controllers, as well as future read channel directions. Special emphasis has been given to read channel models, channel detectors, capacity computation methods, error-correction codes, and data access techniques. The paper by Dee from Sun Microsystems, Inc., provides an interesting overview of magnetic tape technology that has successfully served as a data backup solution for more than 50 years, primarily because of its long shelf life and favorable cost structure. This paper provides an overview of tape media, recording heads, mechanics including servo, tape read channel, and automation. Novel solid-state MRAM technology based on the magnetoresistive effect that combines the nonvolatility of magnetic recording media with the speed of static random access memory (SRAM) and density of dynamic random access memory (DRAM) is discussed in the paper by Zhu from Carnegie–Mellon University. The paper by Zhu provides an overview of both field-driven magnetization switching designs and spin torque transfer driven switching designs. Although the toggle MRAM chip was first commercialized in 2003, MRAM technology is still in an active research and development phase within many industrial and academic groups, and this paper discusses the important scalability and competitiveness issues.

B. Future Magnetic Storage Technologies

This section provides an indication of the future of magnetic storage and novel materials. Nanotechnology and nanofabrication solutions are offered that solve superparamagnetic limit and related thermal stability problems, and extend bit areal density growth. In the paper on exchange coupled composite (ECC) media by Victora and Shen of the University of Minnesota, this novel type of media that extends perpendicular magnetic recording into 1 Tb/in^2 areal density is discussed. This paper reviews recent work on composite media, exchange spring media, synthetic antiferromagnet ECC media, and corresponding experimental results. The thermal stability of ECC media is potentially two to three times larger than that of the conventional media, and therefore offers a route to extensions of perpendicular media by improving the grain size reduction. The paper by Kryder *et al.* from Seagate describes the concept and outlook of HAMR, which utilizes high anisotropy magnetic films and a magnetic head with integrated near field optical light emitter, and sub-100 nm spot sizes. This detailed review serves as an excellent tutorial to HAMR and discusses HAMR recording physics, optical emitter design and light delivery, recording head integration, HAMR media design, head–disk interface issues, and systems design perspective. Challenges in top-down nanofabrication of patterned media, and nanoscale challenges in making future disk drives, are described in the paper by Dobisz *et al.* from Hitachi Research. The authors provide a detailed introductory overview of a modern HDD and discuss the thermal stability problems of state-of-the art media, patterned media as its solution, nanoscale lithography for patterned media (including e-beam lithography and nanoimprint lithography), metrology, and system integration challenges. The nanofabrication of a new type of media based on self-assembly of high anisotropy FePt nanoparticles is described in the paper by Wang from the University of Minnesota. This type of media shows promise both for HAMR media and as self-organized magnetic array (SOMA) patterned media. This paper provides a detailed overview of FePt nanoparticles, development of deposition techniques in the gas phase, fabrication of monodispersed highly ordered FePt nanoparticles, magnetic orientation issues, and self-assembly of FePt nanoparticles.

C. Storage Systems

The impact of Si-based NAND flash memory and its role in storage architectures is discussed in a paper by Sanvido *et al.* from Hitachi Research. The authors provide a tutorial overview of flash technology, including its architecture and performance, fabrication trends, interface issues, reliability, and failure mechanisms. The authors accent flash-assisted HDD caching architectures, including both hybrid HDD and external flash caching. Finally, solid-state drives and their comparison to HDDs in terms of cost and performance are discussed.

Recent advances and future challenges of storage systems are discussed by Du from the University of Minnesota. The author reviews the transition of hard drives from directly attached to global storage devices by discussing communication protocols, comparison of traditional and object storage device based architecture models, two-tier architectures, and fault-tolerant designs. Additional challenges, such as emergence of MAID, increased importance of energy efficiency, and data storage cryptographic security are also discussed.

IV. CONCLUSION

We hope that readers find this Special Issue of these PROCEEDINGS both educational and informative. We have tried to provide a good mixture of the most recent technological advances that are already implemented in products, as well as the most important current research topics. There are many important technologies and current research areas that are not represented in this issue—the reason being that magnetic data storage encompasses so many different scientific and technological disciplines that no one special issue can successfully provide coverage of all of them. It appears that the key issues of today (successful integration of solid-state and magnetic storage in multitiered architecture, solution of magnetic stability problems through patterned media and/or HAMR for continued bit areal density growth, and successful design of reliable, secure, and energy efficient storage systems) will be interesting and important problems in the future as well. Innovative resolution of these problems will allow magnetic data storage, which has been a key storage technology for the last 50 years, to remain so over the next 50 as well. ■

Acknowledgment

The Guest Editors would like to thank all the authors for their valuable contributions, as well as numerous reviewers who unselfishly offered their time to provide feedback on the papers in this issue. They would also like to thank professionals from PROCEEDINGS OF IEEE, especially Publications Editor Jo Sun and Managing Editor Jim Calder.

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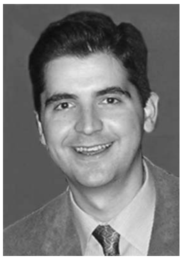

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