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INTRODUCTION

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1.1 INTRODUCTION

What is the earliest form of data storage used by human beings? When this question is posed, answers such as stone, paper, tape, and so on often come up before someone suggests "the brain." Although the brain is the data storage system that nature has provided us with, it is not sufficient for all purposes. Even though the brain can be used for storage of certain kinds of information, how reliably one can retrieve the information depends on the individual and the circumstances. Moreover, information stored in a person's brain cannot be transferred to others after the life of that person. We need data or information storage systems for at least two purposes: (1) to reliably preserve data and information for retrieval when it is needed, and (2) to spread or communicate information/knowledge to others. When humans realized this, they started inventing other means of storing information, such as using stone, clay, paper, and so on as media for data storage.

Magnetic recording was invented more than a century ago by Valdemar Poulsen [1]. It took about 30 years for magnetic tapes to be successfully commercialized [2]. Even though magnetic tapes were good for archival or sound recording, they did not

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possess random access capability, and hence access times were longer compared to other forms of recording available during that period, such as punch cards. To overcome the random-access problem of magnetic recording, IBM invented the first hard disk drive (HDD), which combined the advantages of magnetic recording (multiple read/erase cycles) with random acess capability, and suitably named it RAMAC (random access memory accounting system or random access method of accounting and control). The RAMAC (introduced in 1956) had a capacity of 5 MB, which was achieved using 50 magnetic disks with a diameter of 24 in.—each offering an areal density of 2 kilobits per square inch (kb/in.^{2}). Since then, HDDs have come a long way and now pack 1000 GB in two magnetic disks with a diameter of 2.5 in., each offering an areal density of over 600 gigabits per square inch (Gb/in.^{2}) as of 2011. An areal density increase of the order 10^8 times in a period of close to 50 years is simply remarkable and was possible because of the tremendous efforts to develop the technology behind each component of the HDD. Although most chapters of this book will cover in detail the technology behind the development of the HDD, this chapter will provide an overview of HDD technology, briefly covering the technology from a materials perspective, in line with the theme of this book. This chapter also provides a brief overview of memory technologies that are emerging as alternatives for future memory/storage applications.

1.2 BASICS OF DATA STORAGE

Any data storage system/device needs to satisfy certain basic criteria. The first basic requirement is a storage medium (or media). On this storage medium, the data will be written. The other requirements are that there should be ways to write, read, and interpret the data. For example, let us look at this book as a form of data storage containing the chapters written by the contributing authors. In the printed version of the book, paper is the storage medium. Writing the information (printing) is completed using ink, and reading is carried out with the user's eyes. Interpretation of the data and sometimes even error correction is carried out in the user's brain. Components with similar functions exist in an HDD, too.

Figure 1.1 shows the components of a typical HDD used in desktop personal computers (PCs). Some of the key components that make up an HDD are marked; an HDD has disk media, heads, a spindle motor, an actuator, and several other components. A disk is a magnetic recording medium that stores information, similar to the pages of a book. A head performs two functions, writing and reading information, corresponding to a pen and an eye in our example. A spindle motor helps to spin the disk so that the actuator, which moves along the radial direction, can carry the head to any part of the disk and read or write information. An HDD also has several circuitries in a printed circuit board that serve as its brain, controlling its activity, and receiving and conveying meaningful information from or to the computer or whatever device that uses the HDD.

Several disks (also called platters) may be stacked in an HDD in order to multiply the capacity. In almost all HDDs, the information is stored on both sides of the disks. Figure 1.2 shows the way the data are organized on magnetic disks. The data are stored in circular tracks. The number of tracks that can be packed closely within a given length

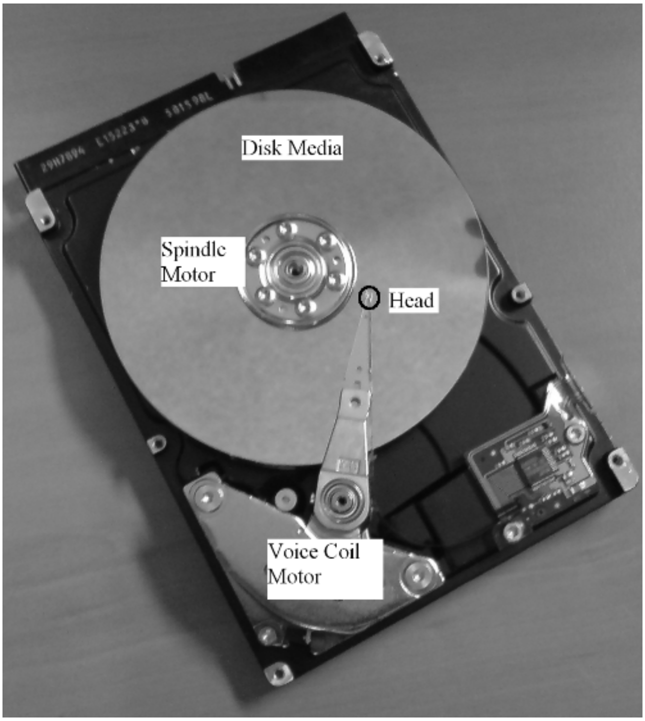

Figure 1.1. Picture of a hard disk drive and various components.

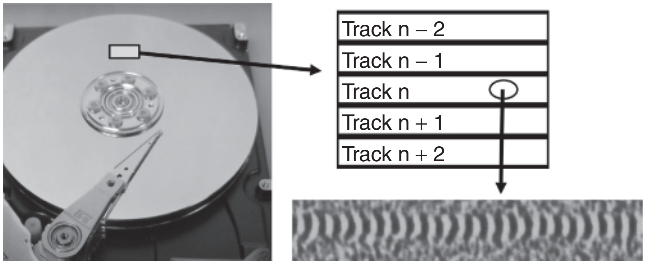

Figure 1.2. Illustration of hard disk media, various tracks, and the way the bits are arranged in tracks. The contrasting lines indicate the magnetic field emanating from the media.

is called track density and is expressed in tracks per inch (TPI). The number of bits that can be stored along the track is measured in terms of bits per millimeter (bits/mm) or bits per inch (bits/in.) and is called linear density. For a particular track density, media with better performance can achieve larger linear density than the inferior disk. The areal density, which is the number of bits that can be stored in a given area, is a product of the track density and the linear density, and is often expressed as bits per square inch (bpsi). Within the tracks there are addressed sectors in which the information can be written or read. The randomness in access or storage of information from or in an address provided by a central processing unit (CPU) comes from the ability to move the head to a desired sector. In state-of-the-art HDD, the total length of tracks on one side of a 65 mm disk covers a distance of 42 km, almost a marathon run. As of 2011, in each track the bits are packed at a density of 1.5–2 million bits in an inch.

1.3 RECORDING MEDIUM

There has to be a medium for storing information in a data storage device. In magnetic recording, a disk that comprises several magnetic and nonmagnetic layers serves as the recording medium [3]. Whether the medium is tape or disk, magnetic recording relies on two basic principles. First, magnets have north and south poles out of which its magnetic field emanates and can be sensed by a magnetic-field sensor. The sensing of a magnetic field by a magnetic-field sensor provides a way of reading information. Second, the polarity of the magnets can be changed by applying external magnetic fields, which is usually achieved using an electromagnet. This provides a way of writing information. Earlier magnetic recording media such as audio tapes, video tapes, and so on were mostly used for analog applications. HDDs are digital devices, which make use of strings of 1 and 0 to store information.

Figure 1.3 illustrates the recording process using longitudinal recording technology. In this technology the polarities of the magnets are parallel to the surface of the hard disk. When two identical poles are next to each other (S–S or N–N), a strong magnetic field will emerge from the recording medium, but no field will emerge when opposite poles (S–N) are next to each other. Therefore, when a magnetic-field sensor (a giant magnetoresistive [GMR] sensor, for example) moves across this surface, a voltage will be produced only when the GMR sensor goes over the transitions (regions where like poles meet). This voltage pulse can be synchronized with a clock pulse. If

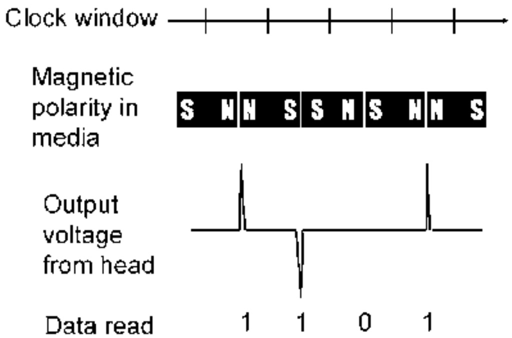

Figure 1.3. Illustration of the recorded pulses from magnetic transitions and the recording principle.

during the clock window the GMR sensor produces a voltage, the voltage is represented as “1.” If no voltage is produced during the clock window, the absence of voltage is represented by “0.” This is a simple illustration of how 1s and 0s are stored in hard disk media. The fundamentals of magnetism and the details of longitudinal recording technology, which will lay the foundation for most of the chapters in the book, will be discussed in Chapters 2 and 3, respectively. In perpendicular recording technology, which is the current way of recording information on HDDs, the magnetizations lie out of plane [3, 4]. In this technology the magnetic field emanates from the center of the bit cells rather than the transitions. More details about perpendicular recording media will be provided in Chapter 4.

1.4 HEADS

The head is a tiny device (as shown in Fig. 1.1) that performs the read–write operation in an HDD. Head technology has undergone tremendous changes over the years. In the past, both reading and writing operations were carried out using an inductive head. Inductive heads are transducers that make use of current-carrying coils wound on a ferromagnetic material to produce magnetic fields. The direction of the magnetic field produced by the poles of the ferromagnetic material can be changed by changing the direction of the electric current. This field can be used for changing the magnetic polarities of the recording media (writing information). Chapter 5 discusses the physics of write heads and the materials used for this purpose.

Inductive heads can also be used for reading information, based on Faraday’s law, which states that a voltage will be generated in a coil if there is a time-varying flux (magnetic field lines) in its vicinity. When a magnetic disk with information rotates, the field emanating from the recording media bits will produce a time-varying flux, which will lead to a sequence of voltage pulses in the inductive head. These voltage pulses can be used to represent 1s or 0s. Inductive head technology was the prevailing technology for reading information until the early 1990s. However, in order to increase the bit density, the size of the bit cells had to be reduced. Moreover, the $M_r\delta$ (remanent moment-thickness product) also was reduced as technology progressed in order to reduce the medium noise, which resulted in a decrease in magnetic flux from the bits. The inductive heads were not sensitive enough to the increasingly reduced magnetic field from the smaller bits as technology progressed. To address this problem, more advanced read sensors were introduced into the head design. Modern HDDs have heads with two elements: one is a sensor for reading information (similar to an eye when reading a book), and the other is an inductive writer for writing information. Such components where the sensor and writer are integrated are called integrated heads or, simply, heads.

The HDDs used magnetoresistive (MR) heads for some time (early to late 1990s) before switching to the prevailing GMR sensors. Unlike inductive heads, MR and GMR heads work on the basis of change in the resistance of the sensor in the presence of a magnetic field. The GMR sensor is in fact made of several magnetic and nonmagnetic layers. GMR devices make use of the spin-dependent scattering of electrons. Electrons have "up" and "down" spins. When an electric current is passed through a magnetic material, the magnetic orientation of the magnetic material will favor the movement of electrons with a particular spin—up or down. In GMR devices, the magnetic layers can be designed in such a way that the device is more resistive or less resistive to the flow of electrons, depending on the direction of the field sensed by the sensors. Such a change in resistance can be used to define 1 or 0 for digital recording. Although write-head research is mostly limited to the companies that manufacture heads, read-sensor research is carried out widely. This is especially so because read sensors are not only technologically challenging but are also academically interesting. Therefore, this book has two chapters on read sensors: Chapter 6 focuses on the fundamentals of read sensors, and Chapter 7 provides an overview of future research and technologies for read sensors.

1.5 MATERIALS ASPECT OF THE HEAD–DISK INTERFACE

In an HDD, the head flies in close proximity to the media in order to read and write information. The component that carries the read sensor and the write head is called a slider. The slider has air bearings that provide the relevant aerodynamics for flyability at a specific height for which it has been designed. The flying height of the sliders has been reduced over the years to sub-10 nm levels [5]. In recent years, the sliders even comprise a technology called "thermal flying height control." This technology uses a microheater embedded in the slider that can be heated using a current to cause nanometer-level expansion near the reader and writer, allowing the possibility of reducing the flying height to sub-5 nm levels, especially when reading and writing operations are carried out [6]. When the head flies at close proximity to the disk medium, there may be intermittent contacts between the head and disk, which might cause damage to the head and/or hard disk medium, resulting in data loss. In order to minimize the damage involved, the hard disk medium is usually coated with a thin lubricant layer, which among many other advantages provides a way to reduce the friction and wear during sporadic contacts. However, there are many challenges in lubricant technology. Chapter 8 provides a detailed discussion of lubricants.

In addition to the lubricant layer, the hard disk medium also has an overcoat layer, which has been some form of carbon film for several years. The carbon overcoat protects the medium from corrosion and wear. The hardness of the carbon overcoat prevents the medium from wear, and the uniformity of the carbon coating helps the medium from being corroded. The overcoat also provides a surface that is suitable for the lubricant to adhere to. In the past, carbon overcoats were very thick (several hundred nanometers). However, tremendous improvement has been made in carbon overcoat technology, resulting in overcoats with thicknesses of about 2 nm and yet providing superior wear and corrosion protection. For future recording applications, it is necessary to obtain even thinner overcoats as an enabler for smaller magnetic spacing (the spacing between the top magnetic layer of the medium and the bot.tommost magnetic part of the read sensor) [7]. There are several challenges associated with the overcoat. These are covered in Chapter 9.

1.6 TECHNOLOGIES FOR FUTURE HDDS

In addition to the different aspects of technologies related to current and future HDD technology covered in Chapters 3–9, it is also essential to look at some technologies on the horizon that are unique and different from the existing technologies. It is widely accepted that the future HDDs may use heat-assisted magnetic recording technology, patterned media technology, or a combination of the two. The need for these technologies arises from the media trilemma issue to be discussed in detail in Chapter 4. However, in brief, the media trilemma is the difficulty faced in trying to optimize the signal-to-noise ratio (SNR), thermal stability, and writability. The SNR obtained from a recording medium should be kept high for reading information reliably, which requires small grains in the recording medium. However, the small grain size of the medium will cause thermal stability issues, whereby the magnetization of the grains may be susceptible to undergoing thermal reversals leading to data loss. The thermal stability problem may be overcome by using recording media with a high anisotropy constant, but this will result in writability issues. The trilemma is unavoidable at a certain stage, and hence researchers have to look at ways to overcome or delay them. Longitudinal recording technology reached its limit a few years back, and hence in 2006, perpendicular recording technology was introduced. However, perpendicular recording technology in its current form will also reach its limit soon. Therefore, alternative technologies such as heat-assisted (or energy-assisted) recording and patterned media are considered as they provide certain advantages.

In heat- or energy-assisted recording, the recording media material makes use of a high anisotropy material with a high thermal stability even for small grain sizes, thus providing a high SNR. Writing information on a high anisotropy material will not be possible with the existing write-head materials. Heat-assisted recording addresses this problem by making use of thermal energy to minimize the energy barrier for reversal at the time of writing. This may be achieved, for example, by focusing a small beam of laser to locally heat the samples. Since the disk is rotated away from the laser beam after the writing process, and the laser beam is off at times other than the writing time, the high anisotropy constant of the recording media material makes the information stable. Chapter 10 discusses heat-assisted recording technology from a system perspective, and Chapter 11 focuses on the materials aspect of heat-assisted recording. Together, these two chapters provide detailed information on heat- or energy-assisted magnetic recording.

Another unconventional scheme to tackle the media trilemma is to increase the volume (V) of the magnetic unit to tackle thermal stability problems. In conventional recording many magnetic grains store one bit, and the bit boundary is decided mainly by the grain boundary. Therefore, when the volume of the magnetic unit is increased, the bit boundary will be broader, limiting the areal density. However, bit-patterned media recording makes use of well-defined bit boundaries that could be made of nonmagnetic materials or voids created by lithography or other procedures. In this case, the grains in the magnetic unit could be exchange coupled strongly to act as a single domain with high thermal stability. In conventional magnetic recording, strong exchange coupling could lead to bit boundaries that are very wide. However, the strong exchange coupling in the magnetic entity of a bit-patterned media does not affect the bit boundary because the bit boundary is defined by the lithography process. Since the volume of the magnetic entity in patterned media for a particular areal density is much larger than that of a grain in conventional recording, thermal stability and writability are not sacrificed. Chapter 12 gives a detailed coverage on patterned media technology. Whether heat- or energy-assisted recording or patterned media recording technology will take over perpendicular recording is not clear at this moment, but it is quite likely that the two technologies may be integrated at certain point of time.

1.7 MEMORY TECHNOLOGIES

HDDs enjoyed unmatched advantages over their competitors for several decades. Because of the high areal density (bits per area) growth achieved in early 2000s, it was possible for HDDs to be used for several applications, such as portable digital music and video players. HDDs with 1-in. disk media were made with compact-flash (CF) and custom-made interfaces, offering higher capacities at cheaper prices than that is possible with semiconductor memories. Apple™ made iPods using such a 1-in. small form factor (SFF) and 1.8-inch HDDs. However, the invasion of HDDs into areas occupied by semiconductor memory did not last long. iPod-Nano MP3 players, featuring semiconductor memories, were released in the next few years as a sign of the threat faced by HDDs. HDDs with 1-in. disk media were phased out in the next few years, and it seems that 1.8-in. HDDs are under threat from solid-state-memory-based storage. Although HDDs still enjoy a significant advantage in 2.5-in. and 3.5-in. disk drives because of their higher capacity and cheaper price, they face a steady threat from solid-state memory devices.

Flash memory—the current competitor for HDDs in certain areas—is also facing technological challenges beyond sub-22 nm scaling. It has been proposed that phase change memory or phase change random access memory (PCRAM) and/or magnetic random access memory (MRAM) may emerge as alternatives for flash memory. It has been proposed that PCRAM can be potentially scaled down to 5 nm, but the question remains as to whether the associated semiconductor technology can also be scaled down to that level. Not to fail in comparison, MRAM also has the potential (based on the thermal stability of FePt materials to be discussed in Chapter 11) to be scaled down to sub-5 nm, but several questions need to be answered before reaching such limits. Nevertheless, the potential scalability of these two candidates makes them good alternatives to flash memory in the long run. As there have been several books on semiconductor-based memories, this book does not cover flash memory. However, two chapters have been dedicated to PCRAM and MRAM. Chapter 13 reviews the developments and challenges of PCRAM, and Chapter 14 provides an overview of the developments and challenges of MRAM.

1.8 SUMMARY

To summarize, the book has been organized as follows: Chapters 2 and 3 discuss the fundamentals of magnetism, magnetic recording, and media technology, and lay the foundation to understand Chapters 4–12. Chapter 4 provides a discussion of the fundamentals and advances in perpendicular recording media technology. Chapter 5 discusses write-head technology, and Chapters 6 and 7 discuss the fundamentals of read technology and the challenges and advances in read technology. Chapters 8 and 9 deal with the head–disk interface aspects of HDDs, focusing on lubricants and overcoats, respectively. Chapters 10–12 concern the emerging technologies for HDDs, namely, heat-assisted magnetic recording and patterned media technology. Chapters 13 and 14 provide an overview of the fundamentals, challenges, and prospects of memory technologies such as PCRAM and MRAM, which are emerging as potential candidates for storage of information.

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