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Introduction

1.1 DISK DRIVE INDUSTRY

The progress in magnetic recording technology, particularly that for rigid disk drives, from the mid-1950s to the mid-1990s has been as dramatic as that in semiconductors. Semiconductor memory and rigid disk drives are part of the storage hierarchy of a computer system as shown in Figure 1.1 [1]. Within the high-performance memory system, a hierarchy of performance and cost ranges from bipolar cache memory at the one end to dynamic memory solid-state devices at the other, as shown in the figure. A second sector of the system hierarchy is evolving as stand-alone high-performance drives and libraries of disk drive arrays. If solid-state devices had sufficiently low cost and could be organized as reliable nonvolatile storage, there would be no need for the disk drives. With decreasing semiconductor costs, there is a temptation to consider replacement of disk drives with solid-state memories. For this reason, it is interesting to compare the evolution of the two most dynamic technologies of this era.

Cost per bit is a predominant criterion in these technologies. The cost per bit in each of the technologies is driven by the areal density or area per bit. Much has been written in the technical and popular press about semiconductors, but disk technology has received little attention. Table 1.1 shows a density progression in both semiconductor memory (DRAM) chips and disk drives for the period 1980 to 2000. It is remarkable that the bit area of the disk drives had tracked the bit (cell) area of the semiconductor memories closely throughout the period of 1980 to 1990. The ratio of semiconductor bit price to that of disk drive bit has remained approximately 100 during this period. From 1990 through 2000, the density of disk drives is increasing at a faster pace than that of the semiconductors. With these trends, it is highly improbable that the semiconductor memory bit cost could catch up with the disk drive

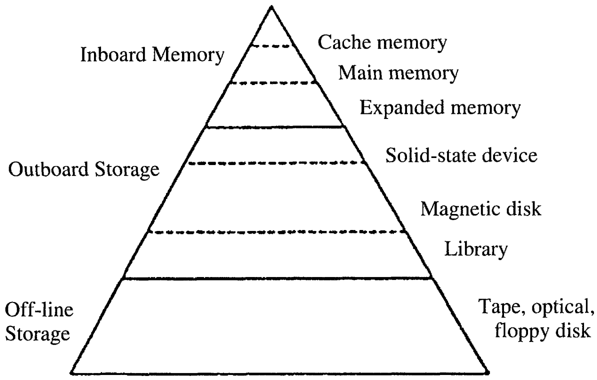

Figure 1.1 Computer storage hierarchy [1].

bit cost within the foreseeable future. In the case of semiconductors, memory cell density increases are usually attributed to improvements in photolithography. In disk drive technology, major advances are taking place due to innovations in magnetic head, media, and channel electronics.

TABLE 1.1 Density of Information Stored in Disk Drives and Semiconductor Devices (Values in parentheses are extrapolations from data between 1987 through 1994.)

	Disk drives		Semiconductors	
	Areal Density (Mb/in^2)	Bit Area (μm^2)	Chip Capacity (Mb)	Bit Area (μm^2)
1980	1.25	52	0.256	50
1987	36	18	1	20
1990	100	7	4	10
1994	500	1.29	64	2.5
1997	(1000)	(0.65)	(256)	(1.0)
2000	(6000)	(0.110)	(1000)	(0.5)

Worldwide disk drive sales volume in 1995 was estimated as 70 million drives with revenues of about $25 billion [2]. Comparatively, global semiconductor memory revenues in 1995 were $44.5 billion. The demand for disk drive storage has been steadily increasing due to the following factors:

1. Increasing demand of desktop computers and workstations.
2. Introduction of a variety of notebook, subnotebook, and laptop computers.
3. Replacement of large mainframe computer drives by arrays of small disk drives.
4. Growth of storage-hungry graphics and multimedia applications.
5. Use of removable small drives in noncomputer consumer applications.
6. Massive and yet unforeseen increases in computer storage requirements of network data bases.

Conversion of information from paper to the more accessible computer media has just begun, yet computer storage is still only a small fraction of the total amount of information stored. So, unless unforeseen conditions intervene, the expansion of the disk drive industry will continue at a high rate in the future.

1.2 DISK DRIVE TECHNOLOGY DEVELOPMENT

Introduced in 1957, the IBM Model 350, or random access method of accounting and control (RAMAC), was the first disk drive [3,4]. This drive, invented at the IBM research laboratory in San Jose, California, consisted of 50 rotating disks mounted on a vertical shaft (See Figure 1.2), each 24 inches in diameter and each having a magnetic medium coating to store data. Access to this data was by a pair of air-bearing supported heads mounted on an access arm that could be moved under servo control to 1 of the 50 disks. The heads were also able to move in and out across the radius of a disk. The storage capacity of the system was 5 MB, and users paid a rental of $130 a month for the system. The disks rotated at 1200 RPM (revolutions per minute), and the data rate of the information was 12.5 kB/s.

The inductive head and magnetic disk material for this drive originated in earlier work on tape recorders and magnetic drums. (Magnetic drums consisted of a rotating drum with a magnetic coating and a series of fixed heads mounted one head per track.) The advantage realized with the new rotating disk technology was the combination of nonvolatile storage of data with very fast access to this data and, at

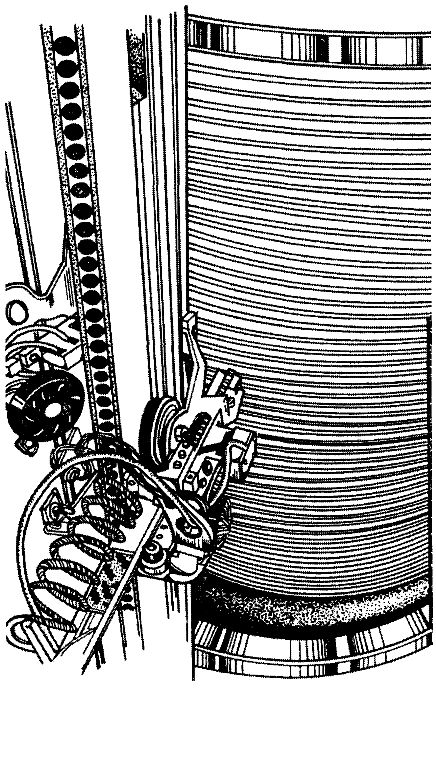

Figure 1.2 IBM RAMAC (1957) [3].

the same time, low cost due to fewer heads. These characteristics filled the technology gap of the data processing industry between inexpensive tape recorders and expensive magnetic cores used at the time for computer memory. One persistent drawback of many of the early magnetic read/write schemes was the requirement of close proximity between the magnetic medium and the read/write head. In tape recorders, for example, the tape is in contact with the tape head; if the tape were to run continuously at a high rate, the tape would soon wear out and possibly the head as well. The key development that led to disk drive technology was the invention of a low-mass, air-bearing slider carrying a magnetic head *floating* at a precise spacing between the head and the magnetic medium. Data or information is written magnetically along circular tracks on a disk. A *bit* is the smallest unit of data or information and consists of a "0" or a "1." The *linear bit density* is the number of bits written along a distance of 1 inch on one of these tracks. The *track density* is the number of tracks per inch along a radius of the disk. The *areal density* is the product of linear bit density and track density. For example, the Travelstar drive announced in 1995 by IBM, which uses magnetoresistive heads, has a linear bit density of 127.2 Kb/in. (50 Kb/cm) and a track density of 7257 T/in. (2857 T/cm), giving an areal density of 923 Mb/in.^{2} (143 Mb/cm^2). Increasing linear bit density over time has depended on the scaling down of three factors:

1. Reduction of the head to disk spacing commonly known as *flying height*.
2. Reduction of the gap size of the head.
3. Reduction of the thickness of the disk magnetic media.

Table 1.2 shows these trends in IBM disk drive characteristics from RAMAC (System 350) in 1957 to 3390 in 1989. Apparently, these three parameters have been reduced in values by about two orders of magnitude over the 32-year period. Table 1.2 spans a total period of 38 years. The linear density has improved by a factor of 1300 during this period. This is the result of progress in inductive head designs and improvements in both ferrite medium prior to 1987 and thin film medium after 1987, and also implementation of magnetoresistive heads since 1990.

Increasing track density over time has depended on improvements in the technology of accurate head positioning. These improvements include reduction in track misregistration, innovations in servo techniques, higher-sensitivity heads, and advances in track width control. Table 1.2 shows that the accompanying improvement in track density over this period is a factor of 355. Some detail on the head and slider technology are also shown in the table.

Many of the developments in heads, disks, interface controls, channel electronics, and packaging have been due to the gradual increase in understanding of the technology and development of tools. However, there are several highlights in the technology that must be pointed out.

The earliest recording heads were made of laminated Mu-metal (NiFeMoCu) with gaps formed by copper shims. A major improvement in the mid-1960s was the replacement of Mu-metal by ferrite. The high resistivity of ferrite meant that

TABLE 1.2 Thirty-Eight Years of Progress in Disk Drive Technology

Year	Model	Bit Density Kb/in	Track Density T/in	Areal Density Mb/in^2.	Flying Height nm	Gap nm	Media thickness nm	Head	Slider
1957	350	0.1	20	.002	20000	25000	30000	Mu-metal	Aluminum
1962	1301	0.52	50	.026	6250	12500	13575	Laminated Mu-metal	Stainless steel
1966	2314	2.2	100	.220	2125	2625	2125	Epoxy bonded ferrite	Alumina
1971	3330	4.04	192	.776	1250	2500	1250	Glass bonded ferrite	Barium titanate
1973	3340	5.64	300	1.69	450	1500	1025	Integrated ferrite	Taper flat ferrite
1980	3380	15.2	800	7.68	320	600	550	8 turn thin film	Ceramic
1984	3380E	16.1	1386	22.3	254	600	500	18 turn thin film	Ferrite
1987	3380K	15.2	2088	32.8	216	550	432	31 turn thin film	Ceramic
1989	3390	27.5	2241	61.6	160	550	230	31 turn thin film	Ceramic
1992	0663-E12	59	2685	158	—	—	Thin film	Magneto-resistive	Ceramic
1995	Travelstar 2LP	127.2	7257	923	—	—	Thin film	Magneto-resistive	Ceramic

head lamination was not required. In addition, ferrites are easy to shape and grind. Ferrite surfaces are wear resistant and do not corrode. Many subsequent improvements in ferrites have continued to make them competitive as an alternative head technology. One such advancement is the metal-in-gap (MIG) head. Placement of high-magnetization metal (Sendust) in the gap of ferrite heads made the use of continuous-metal, thin film medium disks possible. Thin film disks resulted in a path to higher linear densities. Continuous progress in film disks through reduction in defects, lowering of medium noise, and control of corrosion have continued to boost areal densities. An important step in head technology came in 1979 with IBM's introduction of thin film heads. This technology allowed heads to be fabricated by the same photolithographic techniques used in the semiconductor industry. This approach led to still higher linear densities and track densities.

The most recent leap in technology came in 1991 with IBM's announcement of the production of the magnetoresistive head. Magnetoresistive (MR) heads are combined with new low-noise, thin-film disk media to provide a new range of capabilities for disk drives. The MR head provides 5 to 10 times higher sensitivity compared to ferrite or thin film heads. Increases in track density are achieved by making dual element heads in which the *write* element of the head is the usual thin film inductive head and the *read* element the head is an MR sensor. Another attribute of the MR head is that its sensitivity does not vary with disk rotational velocity; hence, it is possible to provide high bit densities for small disk drives used in laptop computers.

Table 1.2 describes IBM disk file evolution and fairly well portrays the industry progress. However, it should be noted that significant progress was pioneered by several other manufacturers as well. Noteworthy among them:

1. Fujitsu's F 6525 Eagle II file, announced in 1982, had 24.4 Kb/in. linear density and 22.2 Mb/in.^{2} areal density, achieved with sputtered medium on a 10.8 in. disk, ferrite head, and head-disk spacing of about 150 nm.
2. Maxtor's XT-8760E, announced in 1987, had 31.5 kb/in. linear density and 43.5 Mb/in.^{2} areal density.
3. In 1993, Seagate shipped a 7200 RPM, 95 mm (3.5 in.) disk drive that has 4.17 ms average rotational delay, and an asynchronous data rate of 20 MB/s.
4. Areal technology in 1993 produced a 65 mm (2.5 in.) disk drive with glass substrate disk to reduce head-disk spacing. The linear density of 80 Kb/in. and areal density of 220 Mb/in.^{2} were achieved in the drive with an inductive thin film head.

Additional comparative study of disk files from several manufacturers can be found in [5].

1.3 DISK DRIVE HEAD TECHNOLOGIES

Most dramatic changes in disk drive technology have happened in head development and manufacturing. This is the reason why three chapters in this book are dedicated to heads. Table 1.3 presents a qualitative comparison of four head technologies. A plus (+) refers to a favorable property while a minus (−) refers to a less desirable attribute. The ranking of heads is based on state of the art in the early 1990s and is subject to change depending on future developments.

TABLE 1.3 Relative Merits of Various Heads

Parameter	Ferrite	MIG	Thin Film	MR
Linear Density	−−	−	+	++
Track Density	−−	−	+	++
Data Rate	−	−	+	++
User Experience	++	+	+	−
Cost/Complexity	++	+	−	−−

The linear density of ferrite heads is low because the low magnetization of the ferrite material creates low writing fields. MIG heads have higher magnetization, and thin film heads and MR heads provide still higher write magnetization fields.

The track density limitations of ferrite and MIG heads are due to head material and processing constraints. Some progress is likely in this field with single-crystal ferrites and incorporation of thin film technology. Track definition for thin film and MR heads is controlled by lithographic processes. The higher sensitivity of the MR head allows narrow tracks with acceptable signal levels.

The data rate for ferrites and MIG heads is limited by high coil inductance. Thin film heads have considerably lower inductance compared to ferrite heads because of miniaturized geometry. However, as the number of turns for thin film heads increases, the inductance and capacitance of the head circuit result in self-resonance, which eventually limits reading at high data rates. The MR head read sensor is effectively a single-turn read element and therefore does not suffer from these high-frequency reading problems.

Table 1.3 further indicates that over the years a great deal of experience has been built up from earlier technologies like the ferrite head. The MR head, in contrast, is relatively new and has several manufacturing and application challenges that require extra care and often add to the product cost.

Figure 1.3 [6] shows the progress and density constraints of these head technologies. One-sided and two-sided MIG heads are making progress in increasing densities. However, with progress in thin film and MR heads, importance of MIG

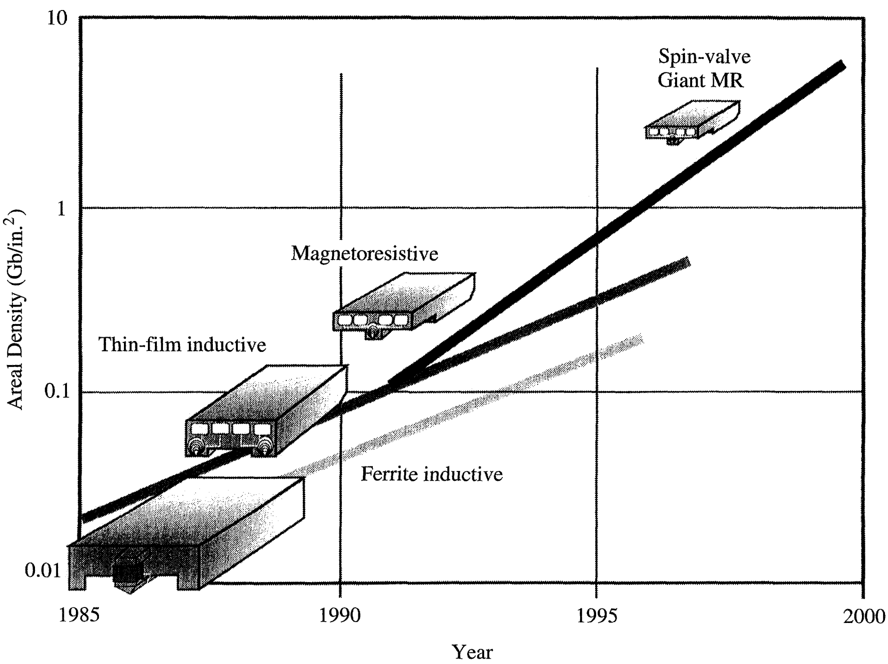

Figure 1.3 Magnetic head perspective (1994) [6].

heads for disk drives is declining. Thin-film head densities are increasing beyond prior expectations, through innovations in slider technology and reduction in inductance factor (discussed in Section 5.8). The MR head characteristics are ideal for disk drives of all sizes. The areal density limit is over several gigabits per in^2. For multigigabit per in^2 areal densities, newer approaches such as GMR (giant magnetoresistance) heads may be required. Ferrite, thin film, and MR heads are discussed in Chapters 4, 5 and 6, respectively, while GMR is described in Chapter 11. Many factors influence these limits. Improvements and innovations in any of these technologies cannot be ruled out. We shall discuss some of the reasons for these limits and point out exploratory efforts under way to extend these limits in these chapters.

1.4 SCOPE OF THE BOOK

There are several books on the subject of magnetic recording. They generally cover a wide range of magnetic recording applications, including tape recording, audio recording, and sometimes magneto-optical recording. To discuss the subject in adequate detail, this book is confined to magnetic recording on rigid disks. We describe the essential elements of rigid disk recording heads, disk media, electronic channels, and the integration of components into a disk drive. There is a long history of developments in these fields, and more innovations are taking place all the time. We offer the reader an up-to-date perspective on the technology, including relevant theory, modeling, current component design practices, design limitations, and potential innovations. Material from publications and patents up to early 1996 is included to keep the book current and useful to professionals engaged in the industry. This book is written primarily for practitioners in the disk drive industry or graduates interested in entering this field. Graduate students of science or engineering should be able to follow the content with little or no difficulty. An attempt has been made to keep the material simple and explanatory rather than detailed or exhaustive. References are provided for those who wish to explore specific topics in greater detail. Illustrations are used profusely to clarify the text and the geometries involved. Mathematics in the book are kept at a graduate student level. Examples and their solutions are given to clarify concepts and to provide help in handling magnetic unit conversions. Every attempt is made to report the latest developments in the field by emphasizing significant, new ideas and concepts. The disk drive technology involves many disciplines such as physics, chemistry, electrical, and mechanical engineering and material sciences. Also, the technology is divided into sectors such as heads, media, electronics, processing, manufacturing, development, research, and marketing. Individuals working in one area often have difficulty understanding the requirements and jargon of the other areas. One of the book's motives in providing this self-study information is to promote understanding and communication among complementing sectors. Here, managers may find helpful technical and general information to broaden their perspective about the technology and the industry.

1.5 OUTLINE OF TOPICS COVERED

A short introductory comment on each chapter is given here. This first chapter explains the importance of rigid disk drives in computers and data processing industry. Historical progress of disk drive technology is examined to get a perspective on future developments in the field. Major components of the technology responsible for dramatic enhancements in the field are briefly reviewed.

Chapter 2 explains topics of magnetism that are useful in understanding the material covered later in this book. The topics on basic magnetism cover: the origin of magnetism, magnetic fields, dipole moment, demagnetization, magnetic circuits, and magnetic and electrical units. Fundamental laws of magnetism include Ampere's law and Faraday's law. Magnetic testing of materials include properties of hard and soft materials and B-H loop (magnetic flux density B as a function of applied magnetic field H) measurements. Also, the following properties of materials are explained: anisotropy, exchange, magnetostriction, magnetoresistance, and magnetic domains. These topics are important in understanding the magnetoresistive sensor and its future evolution.

Chapter 3 covers the principles of magnetic recording. It begins with a qualitative discussion of reading and writing data with a ring head. Next, the field from a ring head is illustrated and described quantitatively. An example of head field calculation is given to clarify the importance of this parameter and to emphasize how it relates to the development of new head materials. Magnetic circuits are used to develop formulas for head efficiency and deep gap field. The general output "read signal" for a ring head is obtained using the principle of reciprocity. The signal is discussed for three types of magnetic transitions. Voltage equations and pulse-width equations are described with examples of their uses in the design and modeling of head-disk systems. The writing process is discussed with graphical illustrations. Side writing, reading, and erasing due to fringing fields are explained.

Chapter 4 begins with a description of the generic ferrite head structure in a typical slider. After a short history of the development of ferrite head materials and a listing of properties for a "good" recording head, the concept and motivation for metal-in-gap heads are discussed. A variety of MIG head structures is illustrated along with the processes used in the construction of both monolithic and composite heads. After considering the limitations of conventional MIG heads, the progress made in the construction and performance of new heads made in the last five years is described. The last part of the chapter points out possible materials and structures under development to extend the usefulness of ferrites and MIGs.

Chapter 5 starts out with a historical perspective and motivating factors for the development of the thin film head. After the discussion of three-dimensional structure of a typical film head, a (simplified) process to fabricate these heads is described. Characteristics of thin and thick film heads are addressed next. The film head writing process and an equivalent circuit of inductive and MR heads for reading is described. Simple equations for thin film head efficiency and inductance are discussed. The signal output of a thin film head is described with simplified equations, while a more exact form is provided in an appendix. Limitations on thin film head bit density are reviewed using analytical and experimental results. Developmental activities on high-moment pole materials, horizontal heads, and other innovative structures for advancing thin film head performance are summarized. Instability in thin-film voltage waveform is discussed in the last section.

Chapter 6 discusses magnetoresistive heads. Historical development and relative advantages of an MR head are discussed. MR head structure and processing are described as are MR sensor theory and its characterization curve, and the necessity for transverse biasing of an MR sensor. Permanent magnet, shunt, soft adjacent layer (SAL), barber pole, and dual stripe biasing methods are reviewed. Because narrow track disk drive sensors suffer from Barkhausen noise, with resultant instability in its signal, the methods of controlling this noise with longitudinal biasing are described. Electromigration and other reliability issues are addressed next. Yoke-type and other novel MR head structures are described. Analytical modeling of shielded-biased sensors is described and resultant equations are used to express MR signal characteristics in terms of head geometry, flying height, and media parameters. MR sensor design issues are illustrated through several graphical plots. Asymmetric track reading of the MR sensor is addressed last.

Chapter 7 summarizes historical transition of disk media from particulate to thin film type. Thin film disk structure and functions of different layers (substrate, underlayer, thin magnetic film, and overcoat) are explained. Manufacturing processing and equipment are discussed and illustrated in some detail. Macro- and micromagnetics of thin film material are described emphasizing the factors for improving signals and reducing noise. Disk tribology including surface preparations, overcoats, and lubrication procedures are discussed next. The characterization and testing methods for materials, surface topography, and finished disk testing during manufacturing and material development are summarized. Instrumentation and procedures are simply explained for nonspecialists. Disk technology future directions for substrate, magnetic film, and head-medium interactions are described.

Chapter 8 covers topics on the recording channel, coding of data, signal-to-noise considerations, and practical measurement techniques used in the development of a drive. Principles of peak detection and partial response maximum likelihood (PRML) coding for channels are explained in a simple step-by-step procedure, and differences between the two are clarified. Issues related to equalization and filtering are simplified through illustrations. On-track intersymbol interference and noise contributions by head, medium, and electronics are discussed, and procedure for measurements and analysis of signal-to-noise ratio are described.

Chapter 9 considers drive integration from an electrical point of view. The development of a disk drive requires many engineering compromises. The components go through several design iterations and testing cycles. Error rate is a critical parameter in designing bit, track, and areal densities of a disk drive. The process of drive integration is to design the head, disk, channel electronics, and servo so that the drive operates with low error rates. Essentials of practical servo control techniques are described with applications of dedicated and sector servo principles. Terms such as off-track performance, window margin, bath tub curve, 747 curve, and track misregistration (TMR) are explained.

Chapter 10 on head-disk interface begins with the historical development of air-bearing sliders and reviews self-acting air-bearing, taper flat, and self-loading sliders. Gas lubrication for air-bearing theory is abstracted with one- and two-dimensional Reynolds equation and illustrations of pressure profiles of well-known slider types. Methods of characterizing head-disk interface and measuring flying height are described next. Capacitive, optical, and piezoelectric methods used for these measurements are outlined. The terminology and processes used in mechanical integration of head-disk interface are reviewed. Contents of numerous papers related to issues of friction, stiction, contact start-stop (CSS), take-off velocity, and so on, are condensed here. Description of new slider designs developed within the last five years and reported in technical literature is summarized in Section 10.7: Advanced Slider Designs. Approaches to contact recording summarize the state of the art on this subject.

Chapter 11, the last chapter, examines the future trends in disk drive technology. Historical progress in linear, track, and areal densities and flying heights are described to project densities up to the end of the 1990s. Next, 1, 2, and 3 Gb/in^2 experiments are analyzed as an exercise in the scaling of components for 6 Gb/in^2 density in year 2000. A section describes principles of giant magnetoresistance, spin valve, and spin-valve head. Optical servos for magnetic recording and application of discrete track recording are reviewed from published papers. The perpendicular recording and special advantage of combining it with contact recording are summarized. Two disk drive applications that might steer the technology significantly are (1) arrays of small drives to simulate functions of reliable large storage systems, and (2) small drives for notebook and subnotebooks. These applications are described in two sections. Ongoing research in components and electronics for disk drives are summarized and, finally, highly advanced and speculative concepts for the next decade and beyond are explained.

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