

# Emerging Trends in Data Storage on Magnetic Hard Disk Drives

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## ABSTRACT

The role of the magnetic hard disk drive (HDD) is constantly growing as a result of advances in capacity, performance and price. This article discusses the impact of emerging technologies on future designs. The areal densities of HDDs have been growing at a rate of 60% per year. Magnetoresistive and giant-magnetoresistive sensors have been developed to support this growth. The operation of these sensors is described. Projections are made for the future performance and price of HDDs.

## INTRODUCTION

The magnetic hard disk drive (HDD) plays an important and extremely useful role in every information processing system; in fact this role is constantly growing as a result of advances in capacity, performance and price. Since the first HDD was introduced in 1956, this device has been the recipient of significant additional technology innovations which have extended its value. It is of interest to discuss what emerging technologies are possible, and what impact these will have on future HDD designs.

For 1998, nearly 150 million hard disk drives are forecast to be manufactured, with the total ability to store 600 petabytes (a petabyte is  $10^{15}$  bytes); both statistics are on a per year, worldwide basis [1]. The storage capacity of an average 1998 drive is greater than 4 billion bytes (4 gigabytes) at an average price of less than \$70 per gigabyte.

Figure 1 is a diagram of today's HDD, in which the components are identified. The basic magnetic storage phenomenon occurs when a read/write sensor or head scans the rotating disk surface. At specific concentric rings, or tracks, magnetized regions are created in a write operation, or read if previously written. Precision mechanical systems support this scanning process; a miniature motor buried within the spindle or hub of the disk and an actuator motor operating on a voice-coil principle position the head over the disk. A ramp assembly allows the head to fly aerodynamically over the disk surface during periods of disk rotation, promoting the use of ultra-smooth disks which enable low flying, resulting in

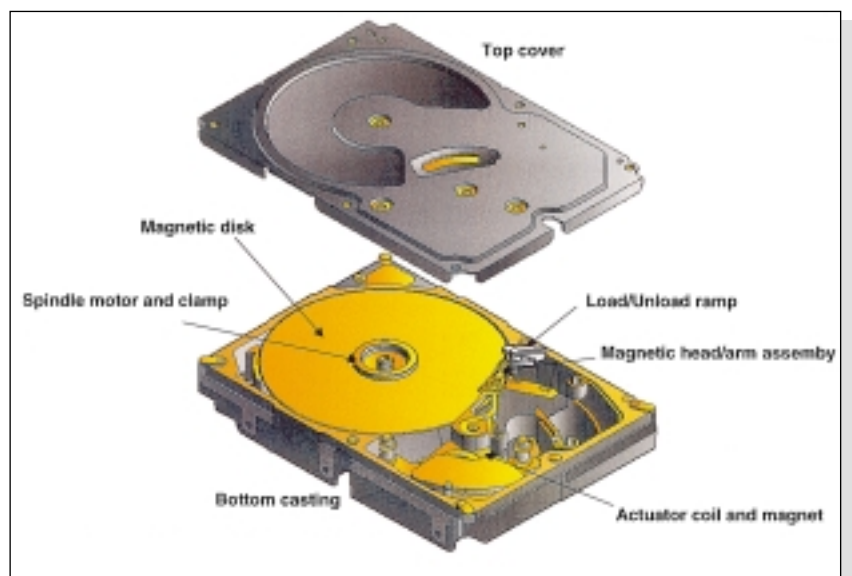


Figure 1. Magnetic hard disk drive.

a maximum in data density. While a high degree of precision is necessary in each mechanical component, the fundamental design is simple. Magnetic impulses during the read operation are converted to analog electrical signals by a sense amplifier and eventually are decoded and error-corrected by a data channel. The electronics content of HDDs is large enough to perform this data function as well as to control each operation and drive the mechanical assemblies. The most common disk in today's HDD products has a diameter of 95 mm.

An obvious evolutionary direction is to increase the storage capacity of the HDD by increasing the packing density of bits on each disk surface, and reading and writing these data bits at the maximum rate.

## AREAL DENSITY

A measurement of the density of written information on the disk's surface is the areal density, in bits per square inch. This parameter is computed as the track density multiplied by the bit density on each track. Figure 2 indicates that today's HDD products have areal densities greater than 1 gigabit/in<sup>2</sup> and have been increasing at a compound growth rate of 60%, and that the maximum areal density appearing in a customer product today is 4 gigabits/in<sup>2</sup> [2]. Supporting this density progress has been a series of

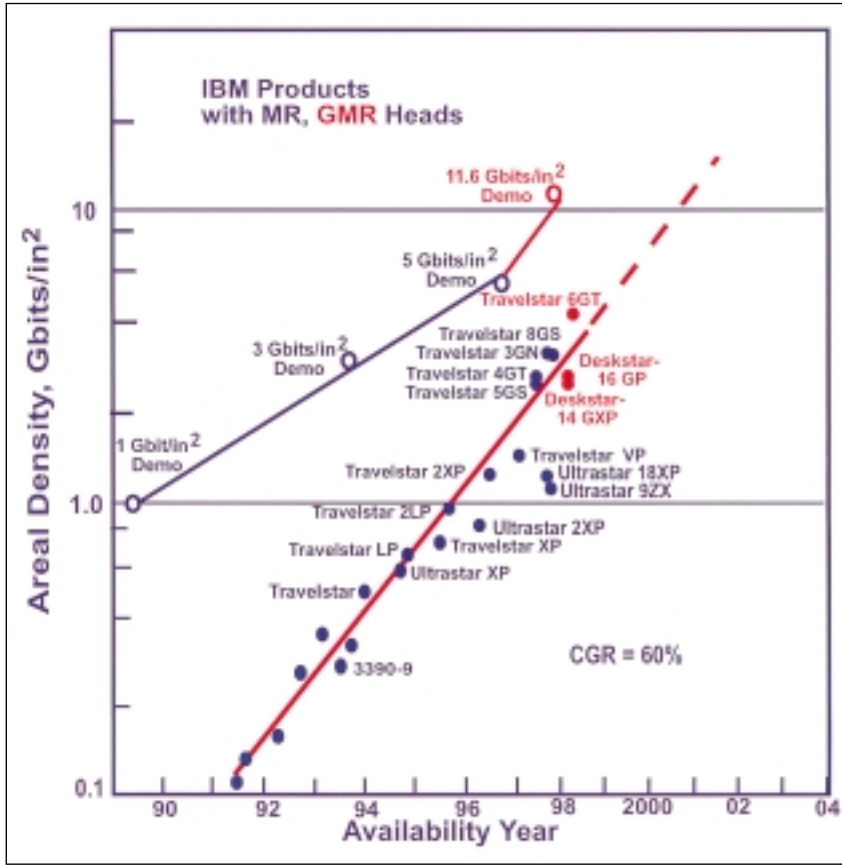


Figure 2. Areal density projection.

laboratory investigations of new head designs and technologies which have resulted in 1, 3, 5, and most recently 11.6 gigabits/in<sup>2</sup>. The intent of these investigations is to develop the head technology to be used in future products, and in fact a product with an areal density of 11.6 gigabits/in<sup>2</sup> will be very probable by the year 2001.

Figure 3 shows the evolution of magnetic heads

to support this growth in areal density. Thin-film inductive heads, used for both reading and writing, were replaced starting in 1991 by magnetoresistive (MR) read sensors combined with inductive write heads, and in 1997 a giant-magnetoresistive (GMR) head was introduced to continue this progress [3]. A laboratory demonstration at 11.6 gigabits/in<sup>2</sup> was performed using this GMR head design. New head design technologies are emerging to provide further areal-density increases, involving advanced GMR structures or, as reported, tunnel junction devices [4]. Figure 4 indicates the scaling process for MR and GMR read sensors since 1991. This evolution involves a reduction in sensor length, which increases the track density, and a reduction in film thickness, which determines the bit density. Each progressive reduction results in higher areal density and a correspondingly higher HDD capacity, and this evolution is expected to continue throughout this decade and into the next.

**MR/GMR OPERATION**

Figure 5 details the basic MR and GMR read structures. For MR sensors a constant electrical current is passed through a film of nickel/iron (NiFe) alloy, creating a magnetic field in the material. As the sensor approaches a magnetized region on a disk, the new magnetic field of the magnetized region results in a change in the magnetic field direction in the NiFe film, producing a voltage change. As shown, this voltage change is nonlinear with the disk magnetic field, and designing an efficient electronics system to interpret these magnetic signals would be difficult. However, by placing a second film, magnetically soft, in proximity with the NiFe MR film, but separated from it by a high-resistance spacer, the direction of magnetization is maintained near 45° in the NiFe and the change in voltage is linear and a maximum. This structure, labelled SAL (soft adjacent layer), is the basis for most MR heads in the industry today. An efficient sense amplifier and data channel design

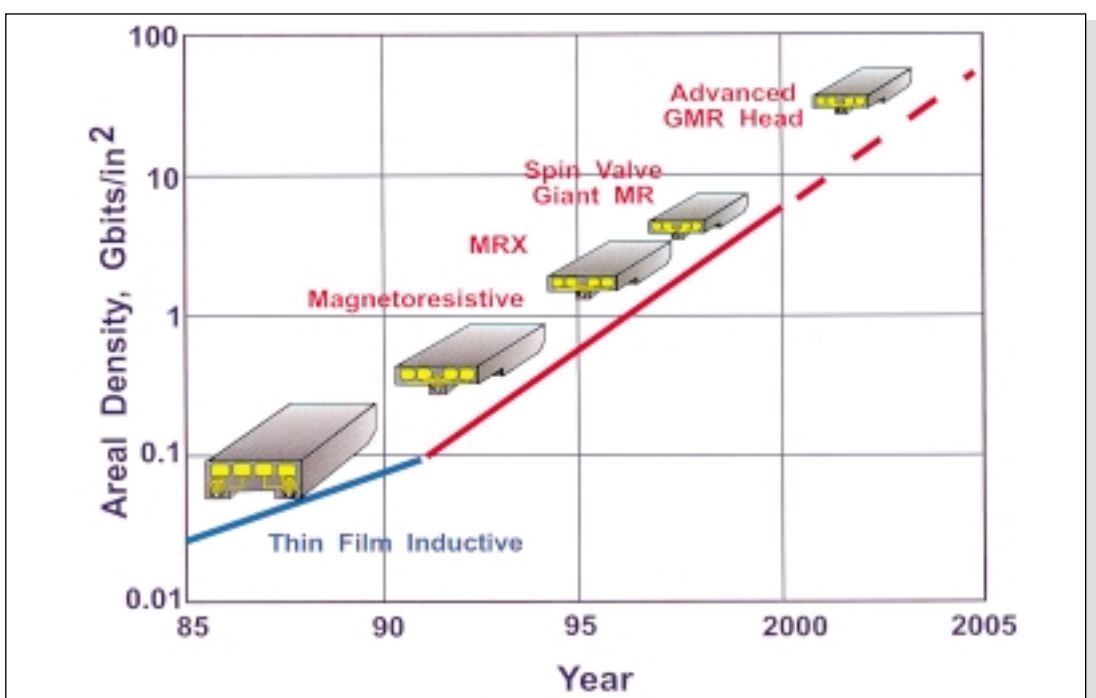


Figure 3. Evolution of magnetic heads.

is possible with HDDs using SAL MR heads.

As areal density continues to increase, MR heads eventually experience a reduction of this voltage change, resulting in lower signal amplitudes. This drop-off occurs near 5 gigabits/in<sup>2</sup>. A new sensor design, the GMR head, exhibits a significant voltage change and signal amplitude at areal densities in excess of 5 gigabits/in<sup>2</sup>. In GMR sensors, two films separated by a very thin conducting spacer provide the voltage-change response to a disk's magnetic field. GMR sensors exploit the fundamental quantum nature of electrons, and follow the principle that conduction electrons with their spin direction parallel to the films' magnetic direction can move freely through the structure, producing little voltage change. One film in the GMR structure has a fixed magnetic orientation, pinned by contact with an antiferromagnetic exchange film. The second film has a variable magnetic orientation determined by the disk's magnetic field. When both fixed and pinned films have a parallel magnetic orientation, conduction electrons may travel long distances through each film, crossing the spacer. Magnetic fields originating from recording data bits on the disk surface rotate the free film's orientation, preventing electron travel because of frequent collisions by the electrons. The magnetic orientation swings within the free NiFe film are much greater in GMR sensors than in MR sensors, producing increased signal amplitude changes, nearly twice as large, which are ideally suited for high areal densities. GMR heads are in production today for use in high-capacity HDDs for server, desktop and mobile computer platforms. New HDD designs employing GMR heads are likely to continue the 60% growth rate in areal density in the near future, resulting in progressively higher HDD capacities.

**PERFORMANCE**

Figure 6 indicates that the data rate, the rate at which bits of data are written to and read from the rotating disk, is increasing with time at a significant pace. This originates from increases in bit density as well as disk rotation rate. Today's server products have internal data rates in excess of 20 megabytes/sec and this is expected to at least double by the year 2000. The performance of the electronic data channels will exceed 500 MHz to allow these very high data rates, requiring the very latest CMOS processing at photolithographic line widths approaching 0.25 μm. This trend in internal data rate closely determines the interface rate at which the HDD communicates with a computer. A new trend in high-data-rate electronics, from the data channel to the arm amplifiers and the controller chips, will be combined with higher levels of electronics integration to reduce the circuit chip count, thereby minimizing the electronics price and power dissipation and improving performance.

Data channel design will evolve from the conventional PRML (partial-response maximum-likelihood) channel technology to new levels of high-speed data detection, analysis and encoding/decoding. Many of these designs are currently in the testing phase in the laboratory. Additional challenges in the design of inductive write heads, as well as the write driver circuitry, will constitute a new field for the magnetic physicist to address, based on magnetic signals with very short pulse widths at 500 MHz and greater.

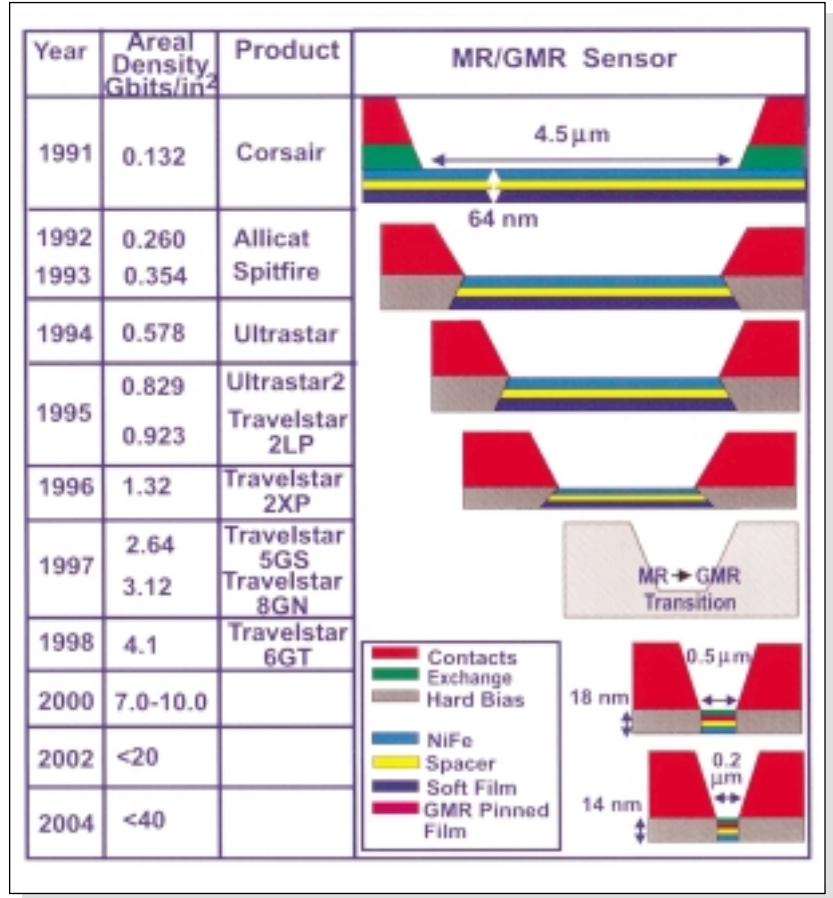


Figure 4. Projected evolution of MR/GMR sensors.

**PRICE**

Figure 7 shows the reduction in price per megabyte for HDDs compared with DRAM electronic circuits [5]. On the basis of improvements in areal density at 60% per year, and assuming only a modest decline in unit price, the price per megabyte would be expected to improve by nearly 40% per year for HDDs, as shown. If areal density progress were to continue at this 60% rate, HDD prices would be expected to decline further, attaining a \$0.03 per megabyte level by the year 2000. Eventually, the price per megabyte would be expected to be reduced below this level in the next decade.

**SUMMARY**

The addition of new technology has been shown to expand the capabilities of HDDs over the past 40 years, and this storage device is an integral part of every information processing system. New head technologies have been a key element in this progress, and this is expected to continue with the transition from MR to GMR heads. New head and disk structures are under investigation in the laboratory which will expand areal densities beyond 10 Gbits/in<sup>2</sup> by the year 2000.

Figure 8 indicates that a significant evolution in disk drive form factor has occurred over the past 10-20 years. HDD sizes have progressively decreased from 14 inch diameter disks in the 3380 family of HDDs to the 3.5 inch form factor which constitutes the high-

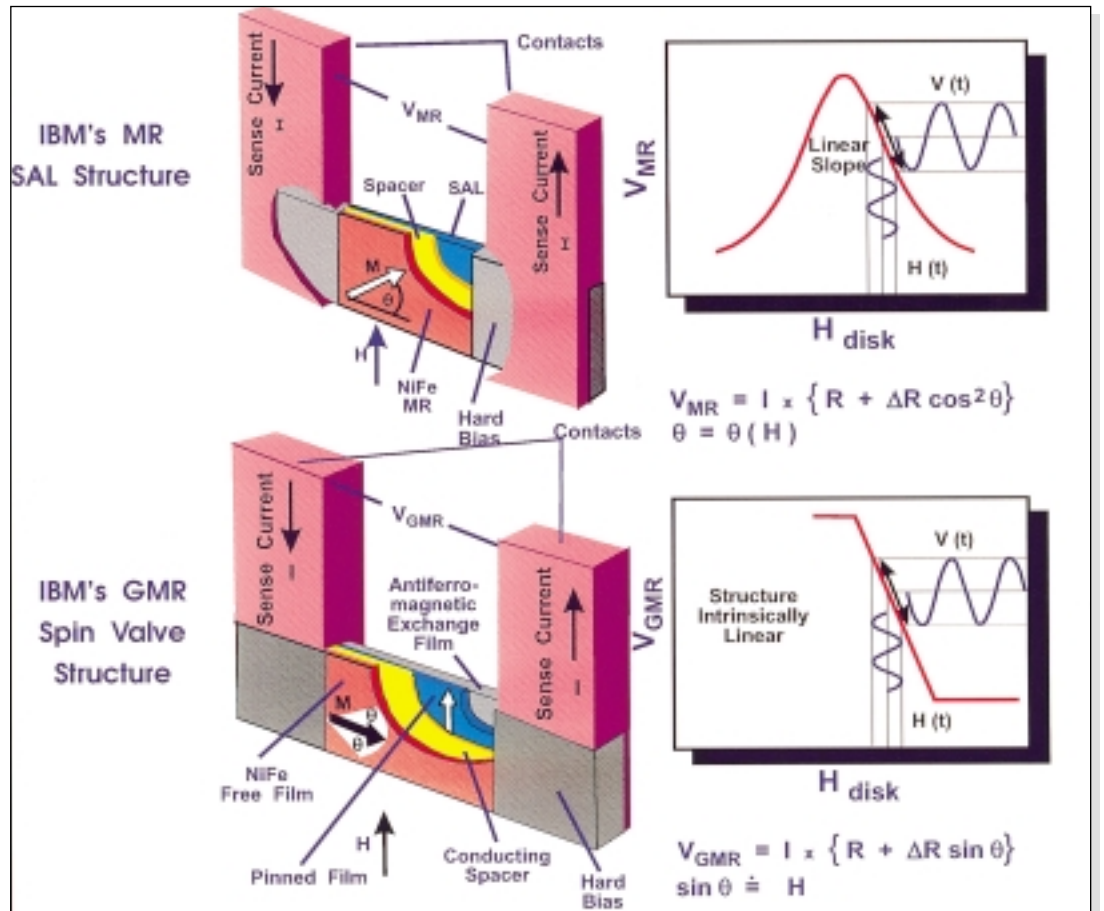
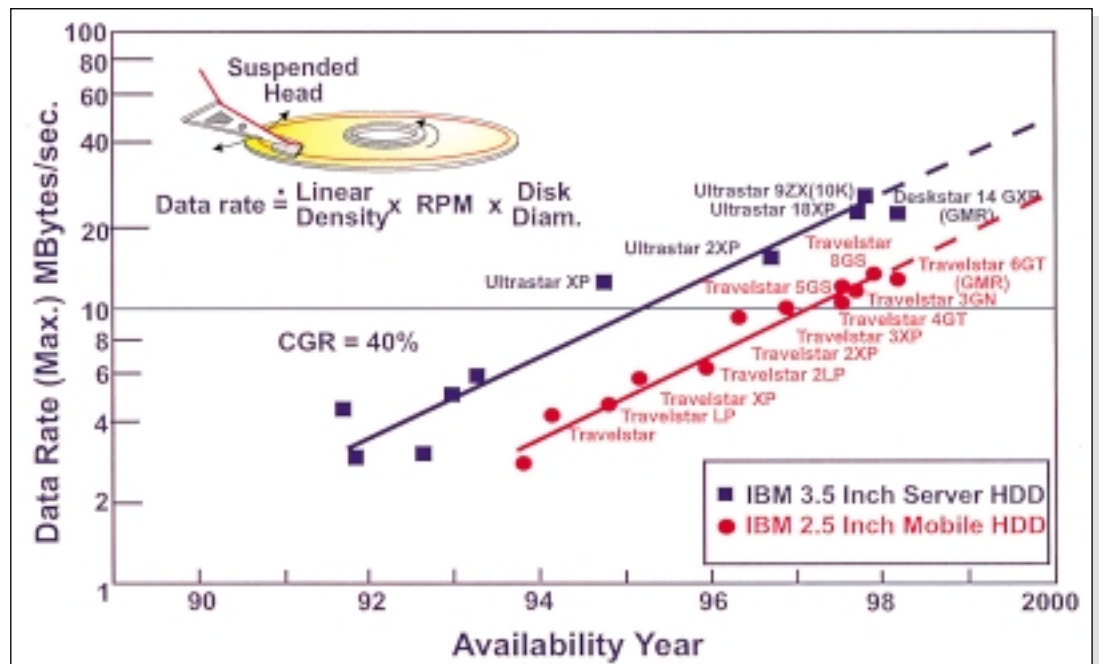


Figure 5. Structures of MR and GMR read sensors.

capacity, high-performance HDD of today. The capacity of this form factor is 18 gigabytes today and would be expected to approach 100 gigabytes into the next decade. Beyond this, further capacity

increases are possible, concurrent with areal density. The 2.5 inch form factor used today for the mobile computer platform can also be seen to increase in capacity beyond 100 gigabytes in the next decade. Since

Figure 6. Trend of internal [media] data rate.



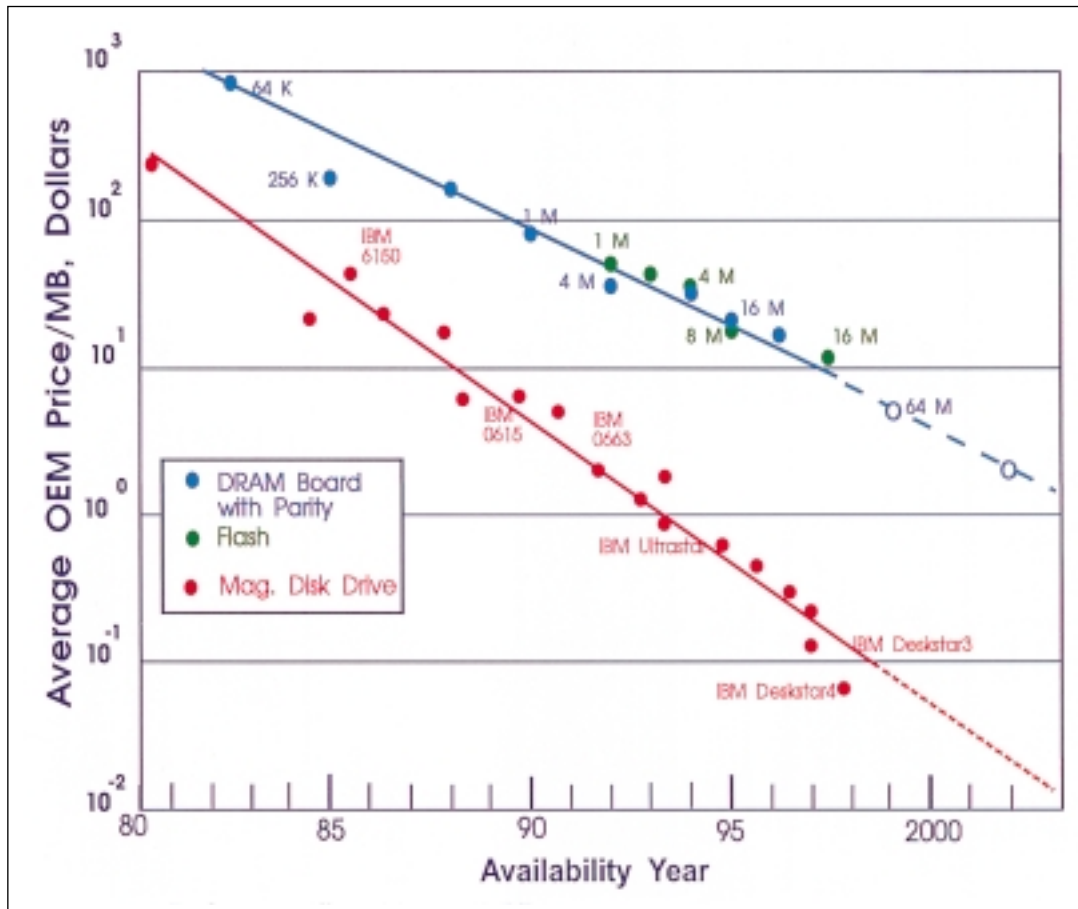


Figure 7. Projection of average price per megabyte for HDDs and DRAMs.

the internal data rate is moderated with smaller-diameter disks, it is possible to expect extension of 65 mm disks, used in 2.5 inch HDDs, into the high-rotation-rate and high-performance market in the future.

The attractive price and expanded capacity of HDDs would be expected also to extend their application to consumer, non-information-processing markets. Figure 8 shows a 1 inch drive design, containing GMR heads, a load/unload mechanism and other advanced features. If this design is possible, it could be very competitive in mobile applications such as digital cameras, hand-held communication devices and other areas where flash memory cards are used today. While Figure 7 demonstrated the obvious price-per-megabyte advantage of HDDs over flash or DRAM memory, a 1 inch drive would have a higher price per megabyte than the average higher-capacity HDD, although this would still be much lower than the equivalent semiconductor storage device.

Additional advances in materials and structures of disk media will concurrently improve areal density and performance. The transition of the disk substrate to glass or glass/ceramic has improved the mechanical properties related to the modulus, as well as the ultimate smoothness of the substrate and overlying magnetic film. Glass appears to be the ultimate direction for all HDDs of the future. Improvements in magnetic materials and structures will address the superparamagnetic effect, reported to be important at areal densities beyond 40 gigabits/in<sup>2</sup>. These

improvements will involve new, more magnetically stable films such as samarium-cobalt and very small grain sizes, below 10 nm. All of these represent a challenge to the HDD designer and magnetic physicist, but are in the realm of strong possibilities for future HDDs. The usefulness of this device and the absence of alternative storage technologies will ensure that significant investigations will continue to be directed towards improvements in capacity and performance.

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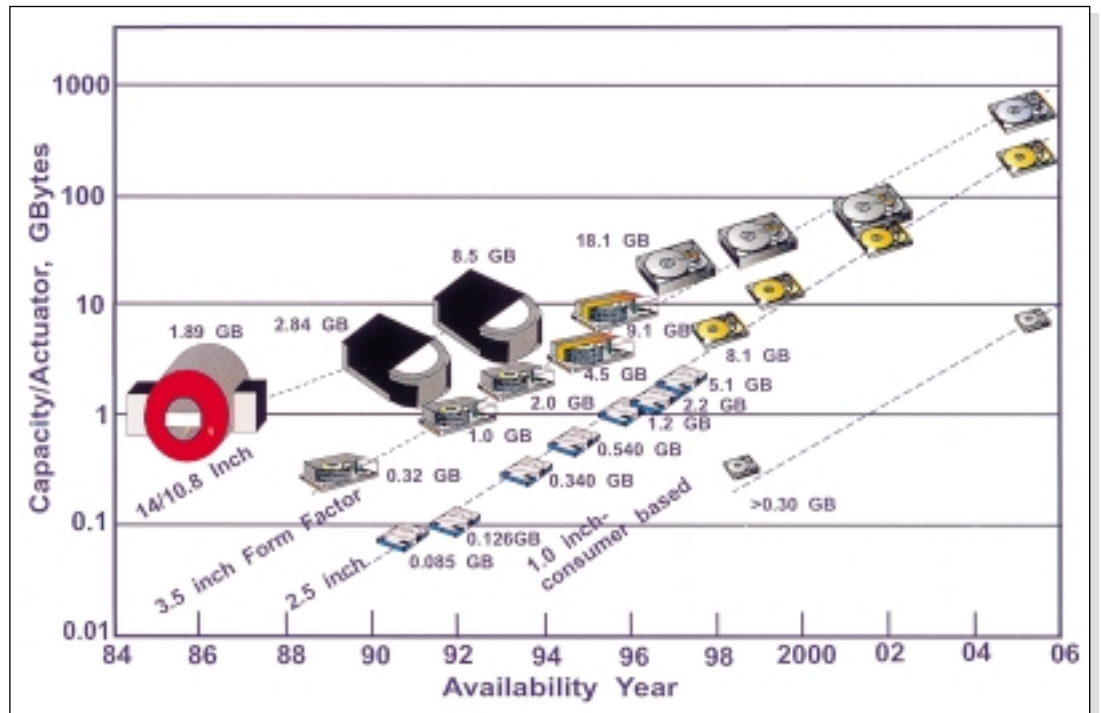


Figure 8. Evolution in disk drive form factor.

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