The future of magnetic data storage technology

by D. A. Thompson and J. S. Best

In this paper, we review the evolutionary path of magnetic data storage and examine the physical phenomena that will prevent us from continuing the use of those scaling processes which have served us in the past. It is concluded that the first problem will arise from the storage medium, whose grain size cannot be scaled much below a diameter of ten nanometers without thermal self-erasure. Other problems will involve head-to-disk spacings that approach atomic dimensions, and switching-speed limitations in the head and medium. It is likely that the rate of progress in areal density will decrease substantially as we develop drives with ten to a hundred times current areal densities. Beyond that, the future of magnetic storage technology is unclear. However, there are no alternative technologies which show promise for replacing hard disk storage in the next ten years.

Introduction

Hard disk storage is by far the most important member of the storage hierarchy in modern computers, as evidenced by the fraction of system cost devoted to that function. The prognosis for this technology is of great economic and technical interest. This paper deals only with hard disk drives, but similar conclusions would apply to magnetic tape and other magnetic technologies. Holographic storage [1] and microprobe storage [2] are treated in companion papers in this issue. Optical storage is an interesting special case. If one ignores removability of the optical medium from the drive, optical disk storage is inferior in every respect to magnetic hard disk storage. However, when one considers it for applications involving program distribution, or for removable data storage, or in certain library or "jukebox" applications where tape libraries are considered too slow, it can be very cost-effective. It dominates the market for distributing prerecorded audio, and will soon dominate the similar market for video distribution. However, it remains more expensive than magnetic tape for bulk data storage, and its low performance and high cost per read/write element make it unsuitable for the nonremovable on-line data storage niche occupied by magnetic hard disks. The technology limits for optical storage [3] are not discussed in this paper.

The most important customer attributes of disk storage are the cost per megabyte, data rate, and access time. In order to obtain the relatively low cost of hard disk storage compared to solid state memory, the customer must accept the less desirable features of this technology, which include a relatively slow response, high power consumption, noise, and the poorer reliability attributes associated with any mechanical system. On the other hand, disk storage has always been nonvolatile; i.e., no power is required to preserve the data, an attribute which in semiconductor devices often requires compromises in processing complexity, power-supply requirements, writing data rate, or cost.

Improvements in areal density have been the chief driving force behind the historic improvement in hard disk storage cost. **Figure 1** shows the areal density versus time since the original IBM RAMAC* brought disk storage to computing. **Figure 2** shows the price per megabyte, which in recent years has had a reciprocal slope. **Figures 3** and **4**show trends in data rate and access time. Since the long history of continued progress shown here might lead to complacency about the future, the purpose of this paper is to examine impediments to continuation of these long-term trends.

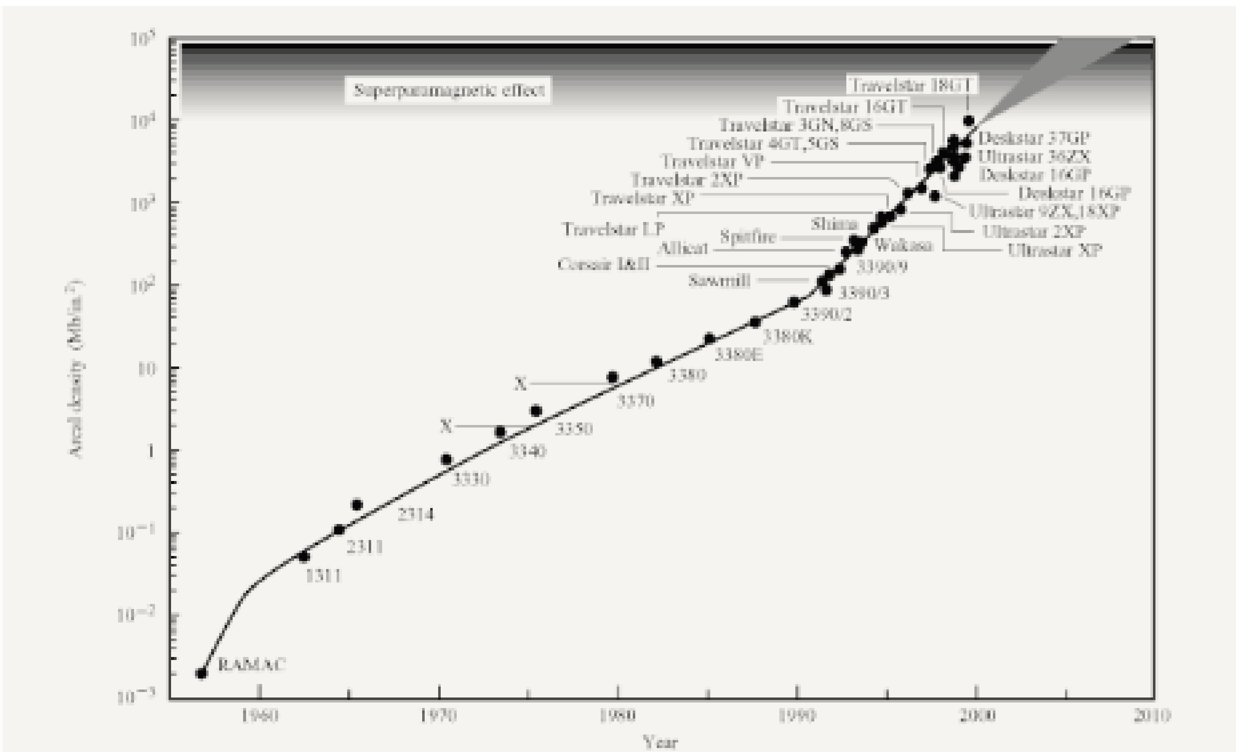

Figure 1

Magnetic disk storage areal density vs. year of IBM product introduction. The Xs mark the ultimate density predictions of References [4] and [5].

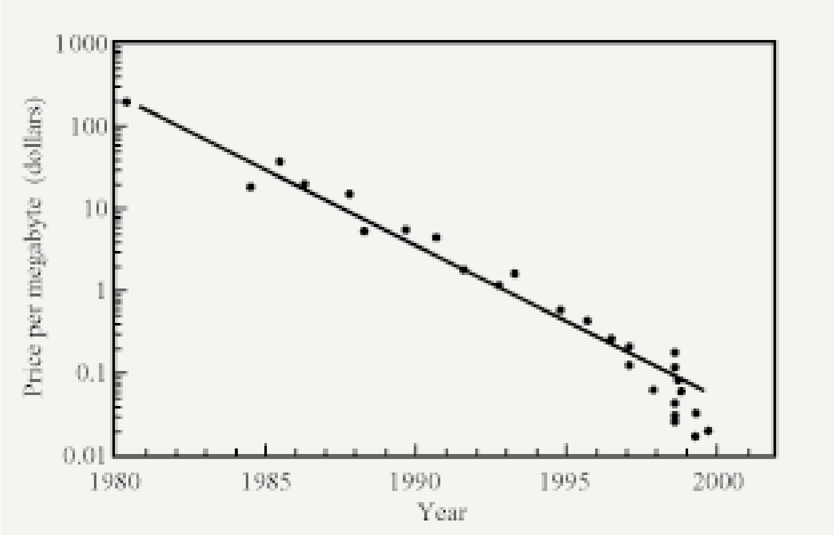

Figure 2

Price history of hard disk products vs. year of product introduction.

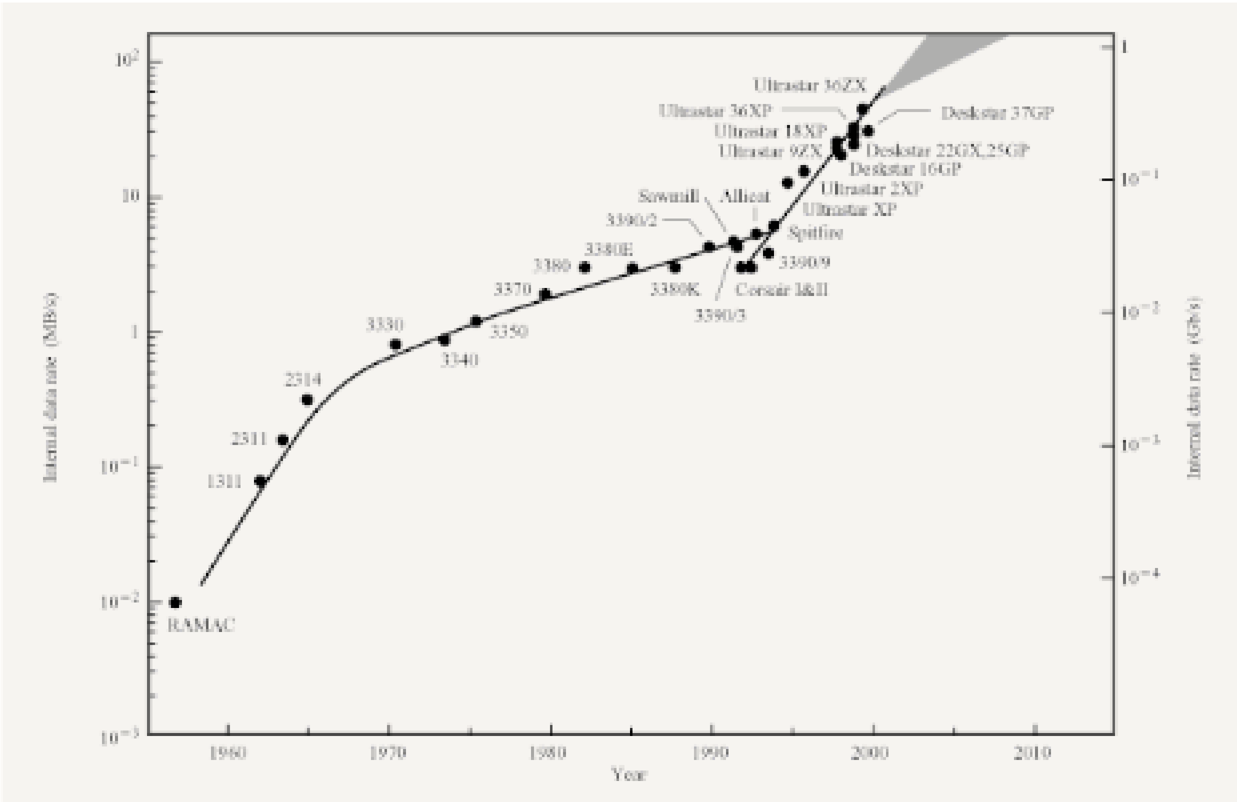

Figure 3

Performance history of IBM disk products with respect to data rate.

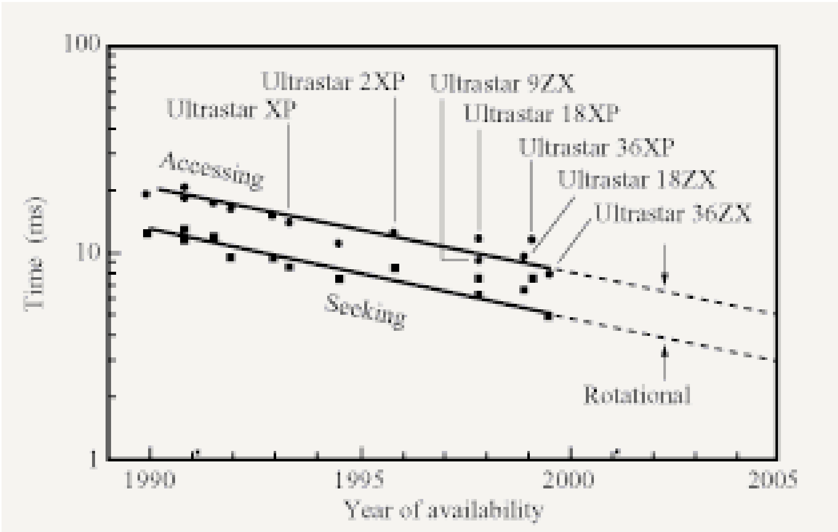

Figure 4

Performance history of IBM disk products with respect to access time.

The sharp change in slope in Figure 1 (to a 60% compound growth rate beginning in 1991) is the result of a number of simultaneous factors. These include the introduction of the magnetoresistive (MR) recording head by IBM, an increase of competition in the marketplace (sparked by the emergence of a vigorous independent component industry supplying heads, disks, and specialized electronics), and a transfer of technological leadership to small-diameter drives with their shorter design cycles. The latter became possible when VLSI made it possible to achieve high-performance data channels, servo channels, and attachment electronics in a small package. It could be argued that some of the increased rate of areal density growth is simply a result of the IBM strategy of choosing to compete primarily through technology. In IBM's absence, the industry might well have proceeded at a slower pace while competing primarily in low-cost design and manufacturing. To the extent that this is true, the current areal density improvement rate of a factor of 10 every five years may be higher than should be expected in a normal competitive market. It is certainly higher than the average rate of improvement over the past forty years. A somewhat slower growth rate in the future would not threaten the dominance of the hard disk drive over its technological rivals, such as optical storage and nonvolatile semiconductor memory, for the storage market that it serves.

Our technology roadmap for the next few years shows no decrease in the pace of technology improvement. If anything, we expect the rate of progress to increase. Of course, this assumes that no fundamental limits lurk just beyond our technology demonstrations. Past attempts to predict the ultimate limits for magnetic recording have been dismal failures. References [4?6] contain examples of these, which predicted maximum densities of 2 Mb/in. ^{2}, 7 Mb/in. ^{2}, and 130 Mb/in. ^{2}Today's best disk drives operate at nearly a hundred times the latter limit. In each case, the upper limit to storage density had been predicted on the basis of perceived engineering limits. In the first two examples, the prediction was that we would encounter serious difficulties within five years and reach an asymptote within ten years. In this paper, we also predict trouble within five years and fundamental problems within ten years, but we do not believe that progress will cease at that time. Instead, we expect a return to a less rapid rate of areal density growth, while product design must adapt to altered strategies of evolution. However, the present problems seem more fundamental than those envisioned by our predecessors. They include the thermodynamics of the energy stored in a magnetic bit, difficulties with head-to-disk spacings that are only an order of magnitude larger than an atomic diameter, and the intrinsic switching speeds of magnetic materials. Although these problems seem fundamental, engineers will search for ways to avoid them. Products will continue to improve even if the technology must evolve in new directions. Some hints of the required changes can be predicted even now. This paper is primarily about the problems that can be expected with continued evolution of the technology, and about some of the alternatives that are available to ameliorate the effects of those problems.

Scaling laws for magnetic recording

Basic scaling for magnetic recording is the same as the scaling of any three-dimensional magnetic field solution: If the magnetic properties of the materials are constant, the field configuration and magnitudes remain unchanged even if all dimensions are scaled by the factor s, so long as any electrical currents are also scaled by s. (Note that current densities must then scale as $1/s$.) In the case of magnetic recording, there is the secondary question of how to scale the velocity or data rate to keep the dynamic effects mathematically unchanged. Unfortunately, there is no simple choice for scaling time that leaves both induced currents and electromagnetic wave propagation unchanged. Instead, surface velocity between the head and disk is usually kept unchanged. This is closer to engineering reality than other choices. It means that induced eddy currents and inductive signal voltages become smaller as the scaling proceeds downward in size.

Therefore, if we wish to increase the linear density (that is, bits per inch of track) by 2, the track density by 2, and the areal density by 4, we simply scale all of the dimensions by half, leave the velocity the same, and double the data rate. If the materials have the same properties in this new size and frequency range, everything works as it did before (see **Figure 5**).

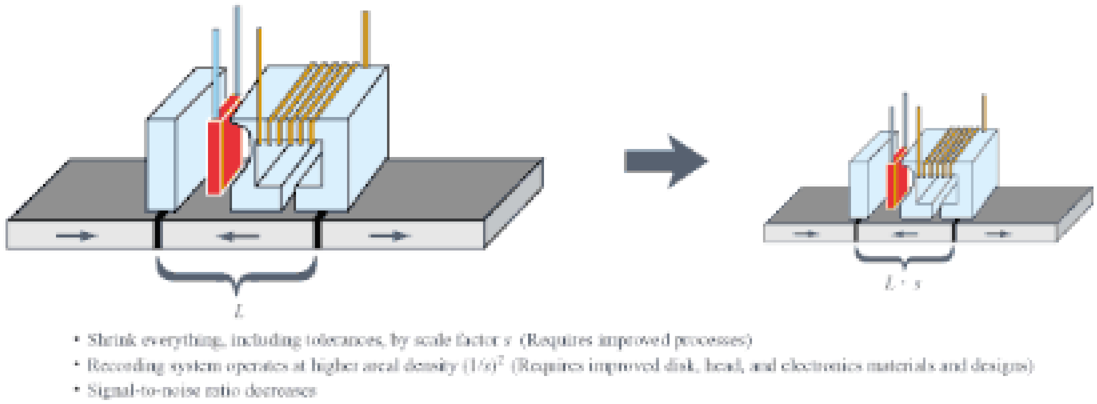

Figure 5

Basic scaling for magnetic recording.

That constitutes the first-order scaling. In real life, there are a number of reasons why this simple scaling is never followed completely. The first is that increasing the data rate in proportion to linear density may be beyond our electronics capability, though we do increase it as fast as technology permits. The second reason is that competitive pressures for high-performance drives require us to match the industry's gradual increase in disk rpm (with its concomitant decrease in latency); this makes the data rate problem worse. The third reason is that an inductive readback signal decreases with scaling, and electronics noise increases with bandwidth, so that the signal-to-noise (S/N) ratio decreases rapidly with scaling if inductive heads are to be used for reading. For magnetoresistive (MR) heads, the scaling laws are more complex, but tend to favor MR increasingly over inductive heads as size is decreased. The fourth reason is that the construction of thin-film heads is limited by lithography and by mechanical tolerances, and we therefore do not choose to scale all dimensions at the same rate; this has led to the design of heads which are much larger in some dimensions than simple scaling would have produced. This violation of scaling has produced heat-dissipation problems in the heads and in the electronics, as well as impaired write-head efficiencies. The fifth reason is that the distances between components have not decreased as rapidly as the data rates have increased, leading to problems with electrical transmission-line effects. The last reason, which will ultimately cause very fundamental problems, is that the materials are not unchanged under the scaling process; we are reaching physical dimensions and switching times in the head and media at which electrical and magnetic properties are different than they were at lower speeds and at macroscopic sizes. We are also approaching a regime in which the spacing between head and disk becomes small enough that air bearings and lubrication deviate substantially from their present behavior, and where surface roughness cannot be scaled smaller because it is approaching atomic dimensions (**Figure 6**).

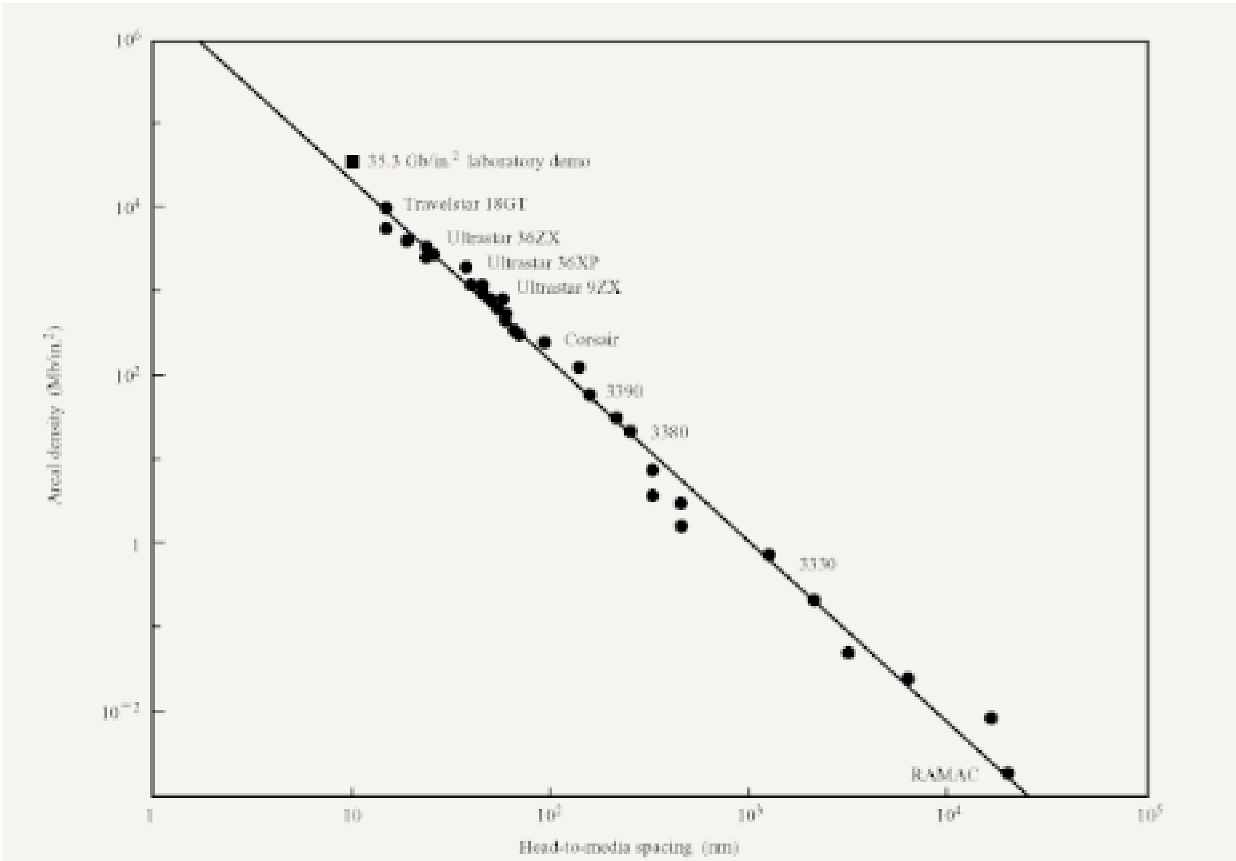

Figure 6

Head-to-media spacing in IBM magnetic hard disk drives vs. product areal density.

In spite of these difficulties, we have come six orders of magnitude in areal density by an evolutionary process that has been much like simple scaling. The physical processes for recording bits have not changed in any fundamental way during that period. An engineer from the original RAMAC project of 1956 would have no problem understanding a description of a modern disk drive. The process of scaling will continue for at least another order of magnitude in areal density, and substantial effort will be expended to make the head elements smaller, the medium thinner, and the spacing from head to disk smaller. In order to keep the S/N ratio acceptable, head sensitivity has been increased by replacing MR heads with giant magnetoresistance (GMR) heads [7]. In the future, we may need tunnel-junction heads [8]. Although it is impossible to predict long-term technical progress, we have sufficient results in hand to be confident that scaling beyond 40 Gb/in. ^{2}will be achieved, and that our first major deviation from scaling will occur as a result of the superparamagnetic limit.

The superparamagnetic limit and its avoidance

The original disk recording medium was brown paint containing iron oxide particles. Present disk drives use a metallic thin-film medium, but its magnetic grains are partially isolated from one another by a nonmagnetic chromium-rich alloy. It still acts in many ways like an array of permanent magnet particles. The superparamagnetic limit [9] can be understood by considering the behavior of a single particle as the medium is scaled thinner.

Proper scaling requires that the particle size decrease with the scaling factor at the same rate as all of the other dimensions. This is necessary in order to keep the number of particles in a bit cell constant (at a few hundred per cell). Because the particle locations are random with respect to bit and track boundaries, a magnetic noise is observed which is analogous to photon shot noise or other types of quantization noise. If the particle size were not scaled with each increase in areal density, the S/N ratio would quickly become unacceptable because of fluctuations in the signal.

Thus, a factor of 2 size scaling, leading to a factor of 4 improvement in areal density, causes a factor of 8 decrease in particle volume. If the material properties are unchanged, this leads to a factor of 8 decrease in the magnetic energy stored per magnetic grain.

Consider the simplest sort of permanent magnet particle. It is uniformly magnetized and has an anisotropy that forces the magnetization to lie in either direction along a preferred axis. The energy of the particle is proportional to sin ^{2}, where is the angle that the magnetization makes to the preferred axis of orientation. At absolute zero, the magnetization lies at one of two energy minima (equals 0 or 180°, logical zero or one). If the direction of the magnetization is disturbed, it vibrates at a resonant frequency of a few tens of gigahertz, but settles back to one of the energy minima as the oscillation dies out. If the temperature is raised above absolute zero, the magnetization direction fluctuates randomly at its resonant frequency with an average energy of kT . The energy at any time varies according to well-known statistics, and with each fluctuation will have a finite probability of exceeding the energy barrier that exists at = ±90°. Thus, given the ratio of the energy barrier to kT , and knowing the resonant frequency and the damping factor (due to coupling with the physical environment), one can compute the average time between random reversals. This is an extremely strong function of particle size. A factor of 2 change in particle diameter can change the reversal time from 100 years to 100 nanoseconds. For the former case, we consider the particle to be stable. For the latter, it is a permanent magnet in only a philosophic sense; macroscopically, we observe the assembly of particles to have no magnetic remanence and a small permeability, even though at any instant each particle is fully magnetized in some direction. This condition is called *superparamagnetism* because the macroscopic properties are similar to those of paramagnetic materials.

Real life is more complicated, of course. There is a distribution of actual particle sizes. The particles interact with one another and with external magnetic fields, so the energy barrier depends on the stored bit pattern and on magnetic interactions between adjacent particles. There can be complicated ways in which pairs of particles or fractions of a particle can reverse their magnetizations by finding magnetization configurations that effectively give a lower energy barrier. This alters the average particle diameter at which stability disappears, but there is still no escaping the fact that (whatever the actual reversal mechanism) there will be an abrupt loss of stability at some size as particle diameter is decreased. If our present understanding is correct, this will happen at about 40 Gb/in.^{2} Tests on media made with very small particles do show the expected loss of stability, though none of these tests are on media optimized for very high densities (see **Figure 7**). IBM is attempting to better understand these phenomena through its membership in the NSIC (National Storage Industry Consortium, which includes academia and industrial companies) and our own research projects.

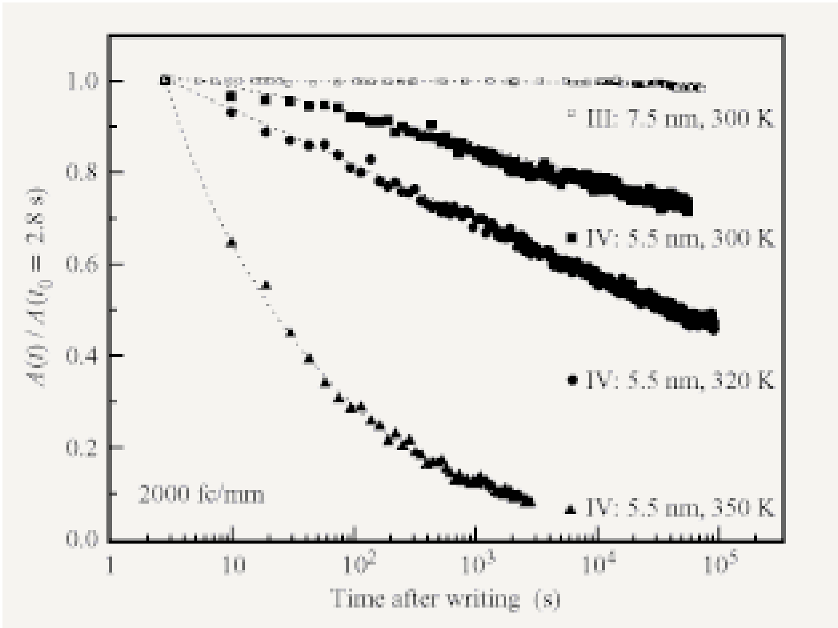

Figure 7

Thermally activated signal decay for IBM experimental media of two different thicknesses, with comparably different grain volumes. The thinner medium is tested at three different temperatures at 2000 flux reversals per mm. *A* is signal amplitude. Figure courtesy of D. Weller and A. Moser [9]; ©1999 IEEE, reprinted with permission.

Today's densities are in the 10-Gb/in. ^{2} range. If simple scaling prevails, superparamagnetic phenomena will begin to appear in a few years, and will become extremely limiting several years after that. But simple scaling will not prevail. It never has been strictly observed. For example, we have not left the material parameters unchanged. The stored magnetic energy density increases roughly as the square of H_c, the magnetic switching field, which has crept upward through the years (**Figure 8**). It could, in principle, be increased another two to four times, limited by write-head materials and geometries [10]. Also, the particle noise depends partly on the ratio of linear density to track density. (Those particles entirely within the bit cell do not add much noise; it is the statistical locations of the particles at the boundary that do.) Thus, the particle noise energy scales with the perimeter length, i.e., roughly as the cell aspect ratio. The noise voltage scales as the square root of the noise energy per bit cell. Today, for engineering reasons, the ratio of bit density to track density is about 16:1. It could perhaps be pushed to about 4:1 for longitudinal recording, before track edge effects become intolerable. This would allow the particle diameter to be approximately doubled for the same granularity noise, which would help stability.

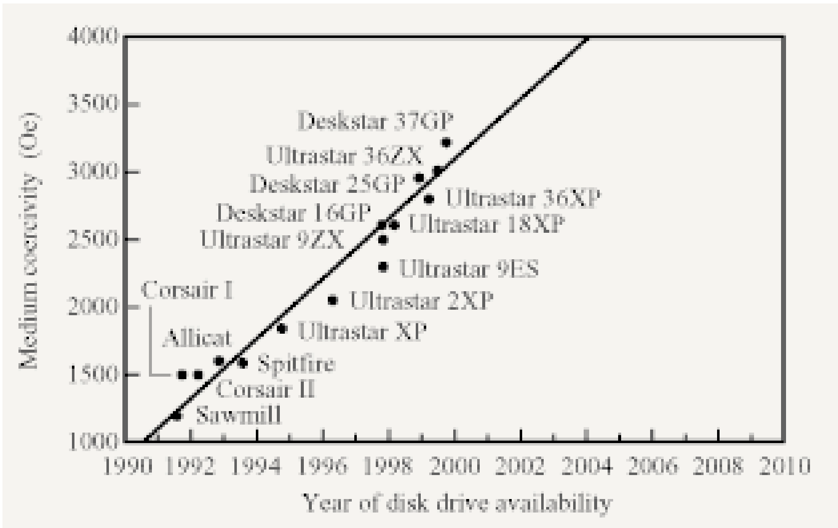

Figure 8

Evolution of disk coercivity with time for IBM disk products. These are approximate nominal values; ranges and tolerances vary.

Over the years, the required S/N ratio has decreased as more complex codes and channels have been developed and as error-correcting codes have improved. Both could be improved further, especially if the data block size is increased. When it becomes necessary, another factor of 2 increase in areal density could be obtained in this way at the cost of greater channel complexity and of lower packing efficiency for small records [11].

Thus, by deviations from scaling, it is reasonable to expect that hard disk magnetic recording will push the superparamagnetic limit into the 100?200-Gb/in. 2range. At present rates of progress, this will take less than five years. If engineering difficulties associated with close head spacing, increased head sensitivity, and high data rates prove more difficult than in the past, the rate of progress will decrease, but there will not be an abrupt end to progress.

More extreme measures

This section discusses more extreme solutions to the superparamagnetic limit problem, as well as some alternatives to magnetic recording.

Perpendicular recording [12] (in which the medium is magnetized perpendicular to the surface of the disk) has been tried since the earliest years of magnetic recording (see **Figure 9**). At various times it has been suggested as being much superior to conventional longitudinal recording, but the truth is that at today's densities it is approximately equal in capability. However, it presents a very different set of engineering problems. To switch from one scheme to the other would cause a fatal delay in development for anyone attempting it in this industry, where the areal density doubles every eighteen months. Enthusiasts have spent millions of dollars and billions of yen trying, and merely have scores of Ph.D. theses and a few thousand technical papers to show for their efforts.

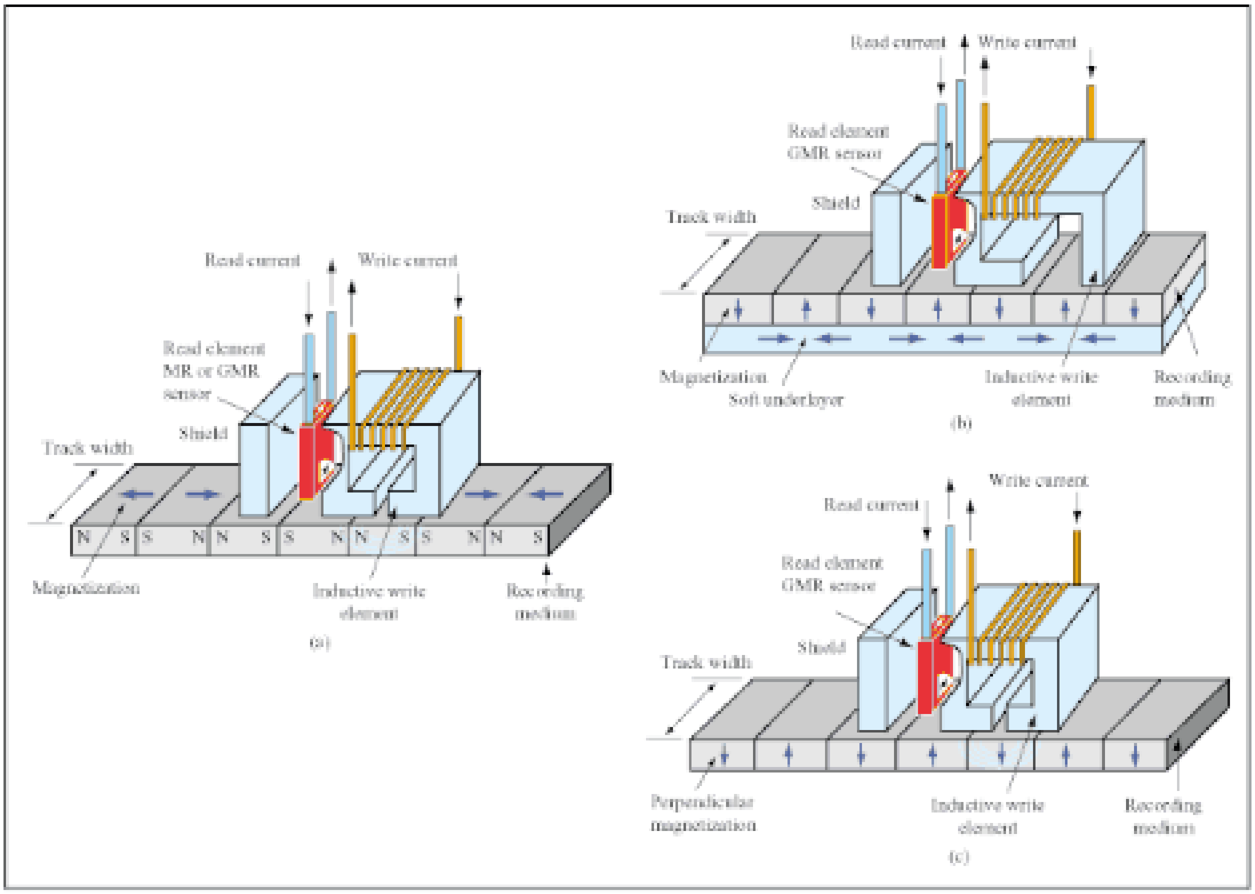

Figure 9

(a) Longitudinal magnetic recording. (b) Type 1 perpendicular recording, using a probe head and a soft underlayer in the medium. (c) Type 2 perpendicular recording, using a ring head and no soft underlayer.

However, there is good reason to expect that the superparamagnetic limit will be different for perpendicular recording than for conventional recording. The optimal medium thickness for perpendicular recording is somewhat larger than for longitudinal recording because of the different magnetic interaction between adjacent bits. Thus, the volume per magnetic grain can be correspondingly larger. The write field from the head can also be larger, because of a more efficient geometry, so that the energy density in the medium can be perhaps four times higher. The demagnetizing fields from the stored bit pattern may also be less, reducing their impact on the energy threshold for thermal switching. It is possible in perpendicular recording to use amorphous media with no grains at all; the thermal stability of the domain walls in those media is unknown, but the optical storage equivalents are known to be stable to extremely small bit sizes. Perpendicular recording also suffers less from magnetization fuzziness at the track edges, and thus should be better suited to nearly square bit cells. For these reasons, it is considered possible (but not certain) that perpendicular recording might allow a further factor of 2 to 4 in areal density, at least so far as the superparamagnetic limit is concerned; hence the renewed interest in perpendicular recording in IBM, in NSIC, and elsewhere.

Another factor of 10 could be obtained for either longitudinal or perpendicular recording if the magnetic grain count were reduced to one per bit cell (see **Figure 10**). This would require photolithographic definition of each grain, or of a grain pattern from a master replicator that alters the disk substrate in some way that is replicated in the magnetic film [13]. Optical storage disks today use such a replication process to define tracks and servo patterns. This scheme would require the same sort of replication on a much finer scale, including definition of each magnetic grain this way, and also a synchronization scheme in the data channel to line up the bit boundaries during writing with the physical ones on the disk. There is no reason that this would not be possible. Patterned media fabrication is not practiced today because direct photolithography of each disk is considered too expensive, and because patterning the magnetic grains by deposition on a substrate prepared by replication has not yet been demonstrated. NSIC is working on it, in collaboration with some of IBM's academic partners who have previously worked on grooved optical storage media.

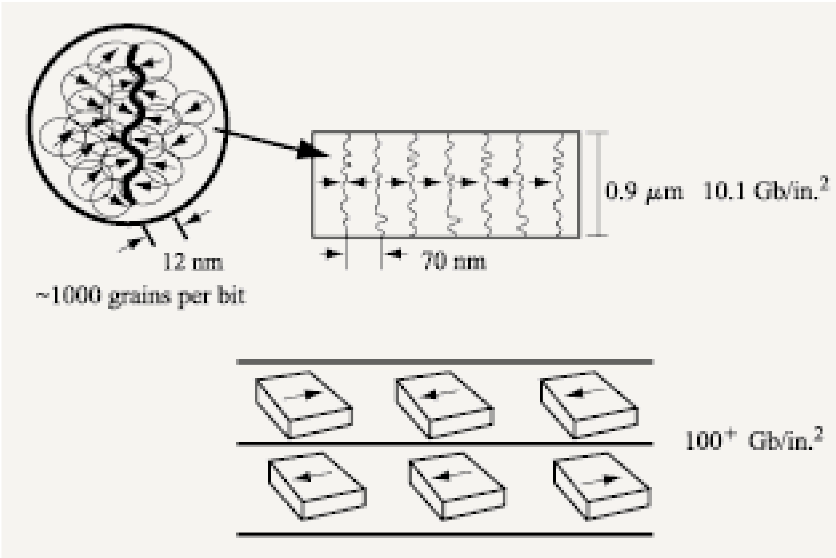

Figure 10

Magnetic transitions for schemes involving many grains per bit and one grain per bit.

It would be foolish to expect that moving the superparamagnetic limit to the Tb/in. 2range is sufficient to guarantee success at that density. Other aspects of scaling will be very difficult at these densities. It will require head sensitivities of the order of thirty times the present values, track densities of the order of a hundred times better than today's (with attendant track-following and write-head problems), and a head-to-medium spacing of the order of 2 nm (i.e., about the size of a lubricant molecule). See Figure 6 . This sounds like science fiction; however, today's densities would certainly have been considered science fiction twenty years ago. It will be difficult, but not necessarily impossible.

Nevertheless, there are alternative storage technologies under consideration, as evidenced by the companion papers on holographic and AFM-based storage techniques. **Figure 11** shows a long-term storage roadmap based on these considerations.

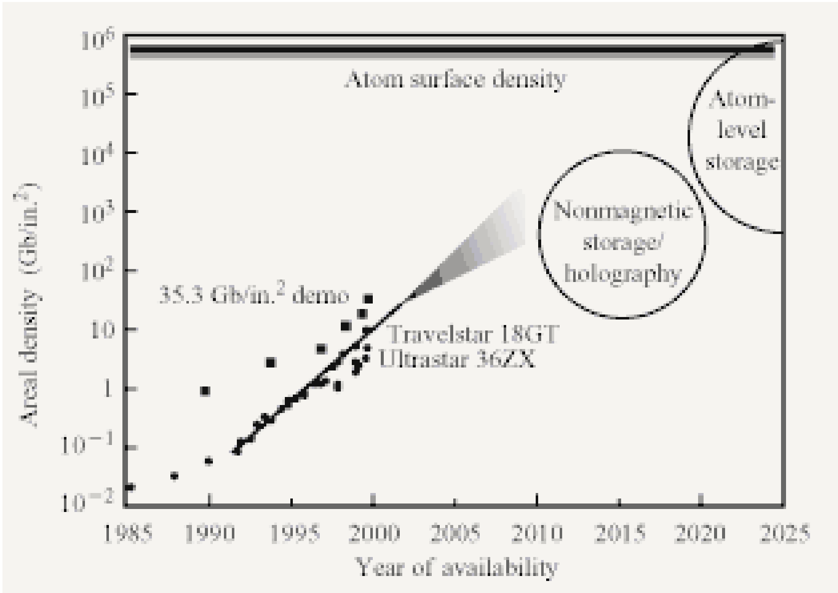

Figure 11

Long-term data storage roadmap.

Problems with data rate

After cost and capacity, the next most important user attribute of disk storage is "performance," including access time and data rate. Access time is dominated by the mechanical movement time of the actuator and the rotational time of the spindle. These have been creeping upward, aided by the evolution to smaller form factors (Figure 4), but orders-of-magnitude improvement is not to be expected. Instead of heroic mechanical engineering, it is often more cost-effective to seek enhanced performance through cache buffering.

Data rate, on the other hand, is not an independent variable. Once the disk size and rpm are set by access time and capacity requirements, and the linear density is set by the current competitive areal density, the data rate has been determined. There is a competitive advantage to having the highest commercial data rate, but there is little additional advantage in going beyond that. In recent years, data rate for high-end drives has stressed the ability of VLSI to deliver the data channel speed required. Since disk drive data rate has been climbing faster than silicon speed, this problem is expected to worsen (see **Figure 12**). Ultimately, this problem will force high-performance disk drives to reduce disk diameter from 3.5 in. to 2.5 in. Since capacity per surface is proportional to diameter squared, this change will be postponed as long as possible, but it is considered inevitable. We have already reduced disk diameter from 24 in. to 14 in. to 10.5 in. to 5.25 in. to 3.5 in. Laptop computers using 2.5-in. drives have the highest areal density in current production, though disks of this diameter are currently used only for applications in which size, weight, and power are more important than cost per bit or performance. The difficulty of providing sufficiently high-data-rate electronics (along with mechanical problems at high rpm) is expected to force a move to the smaller form factor for even high-performance drives at some time in the next five years. This would be normal evolution, and is not the problem addressed in this section.

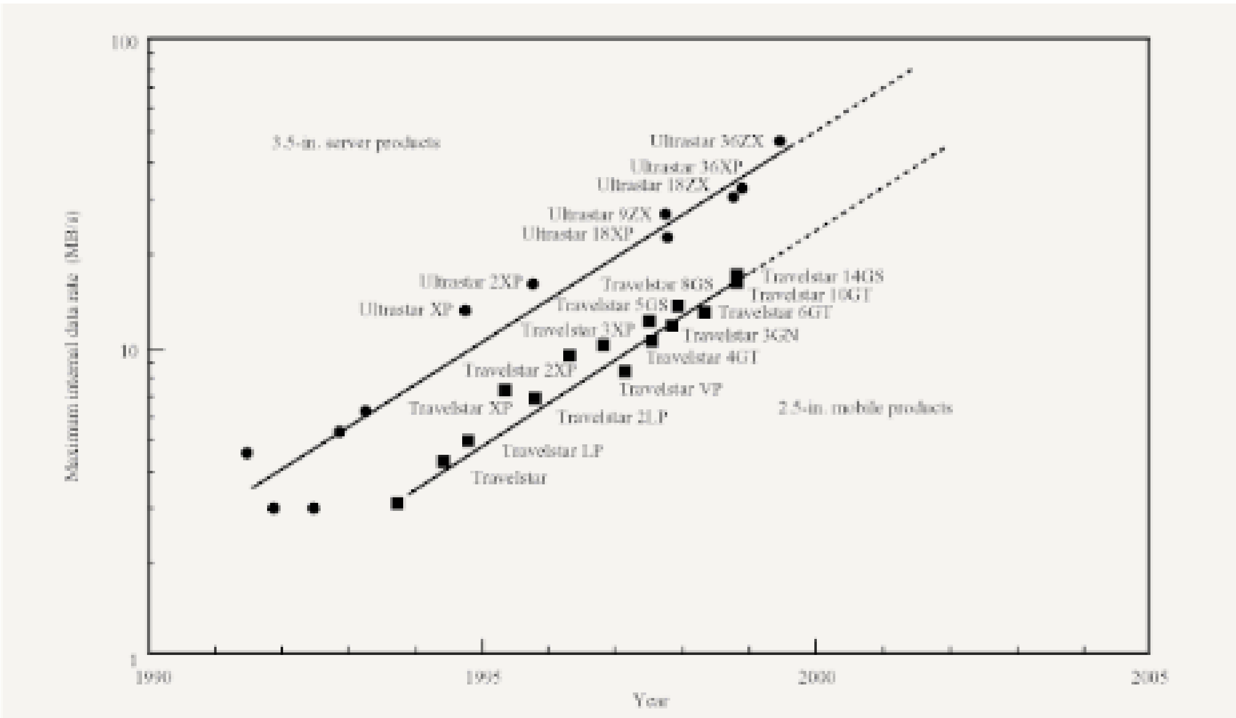

Figure 12

Data rate history for high-performance (3.5-in.) and low-power (2.5-in.) drives.

Both heads and media have magnetic properties which begin to show substantial change for magnetic switching times below 10 ns [14]. This is the scaling problem that is most important after the superparamagnetic limit. The fundamental physics is complicated; a very simplified synopsis follows.

An atom with a magnetic spin also has a gyroscopic moment. When an external magnetic field is applied to make it switch, the magnetization does not start by beginning to rotate in the direction of the applied torque. Like a gyroscope, it first starts to precess in a direction at right angles to the direction in which it is being pushed. If there were no damping or demagnetizing fields, the magnetic moment would simply spin around the applied field at an ultrahigh or microwave frequency (50?2000 MHz, depending on the geometry, etc.), without ever switching. Since there is some damping, it does eventually end up in the expected direction, but this takes a few nanoseconds. In addition, the eddy currents previously mentioned produce fields in a direction to oppose the switching and to slow it down. Also, some portions of a magnetic head switch by a slow process of wall motion at low frequencies. They can switch more rapidly by rotation, but this process takes a higher applied field, so the head is less efficient at high speeds. All of these effects combine to make a head increasingly difficult to design with a high efficiency and low phase shift at high frequencies. Scaling to smaller dimensions increases efficiency and thus helps to alleviate the problem. Laminated and high-resistivity materials reduce eddy currents. Nevertheless, above one gigabit per second it will be difficult to achieve efficient writing head structures. For this reason, we may see an increasing shift to 2.5-in. and smaller diameters, where the data rate is lower for a given rpm and bit density along the track.

The recording medium also suffers from high-frequency effects. One is used to thinking of the medium having the same switching threshold for data storage (a few billion seconds) and for data writing (a few nanoseconds). For present particles, this has been nearly the case, but as we approach the superparamagnetic limit, thermal excitation becomes an important part of the impetus for a particle to switch [9]. The statistical nature of thermal excitation means that the probability that a particle will switch will increase with time. This translates to one coercivity for very long periods, and another, substantially higher, one for short periods. **Figure 13** shows this effect for several films, including the two whose signal decay is shown in Figure 7 . In Figure 13 , the data points can be compared to theoretical curves shown for various values of 1/ *C*, which is the ratio of the energy barrier for a particle's magnetic reversal to *kT* (Boltzmann's constant times the absolute temperature). Values of 1/ *C*greater than 60 lead to media which are very stable against decay, but Figure 13 shows that even they display substantial frequency effects.

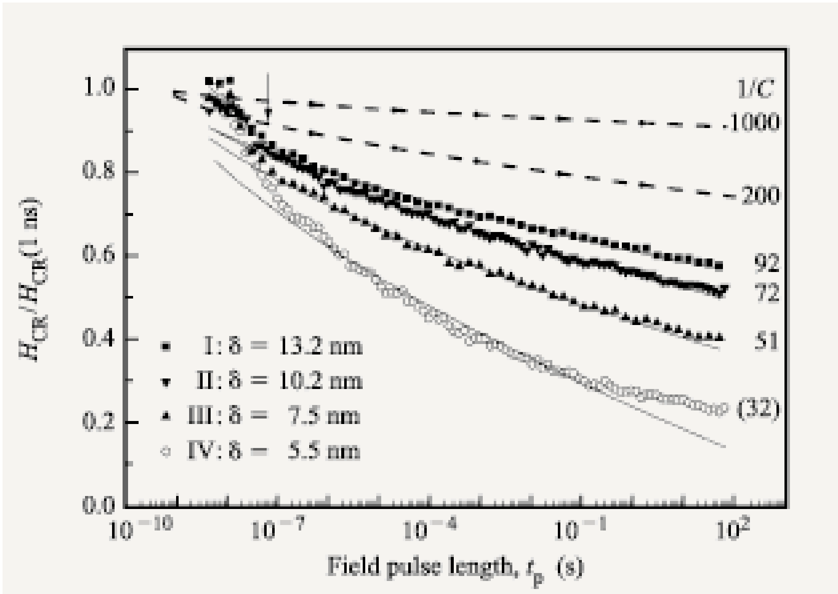

Figure 13

Time dependence of coercivity for experimental IBM media at 300 K. The magnetic field H_{CR} required to write a bit at high speed can be much greater than the field that will erase it over long time periods. δ is the film thickness. The vertical axis denotes the field necessary to erase the medium using the pulse length on the horizontal axis, divided by the field necessary for a 1-ns pulse to do so. Figure courtesy of D. Weller and A. Moser [9]; ©1999 IEEE, reprinted with permission.

These effects will only increase as the particles become smaller and the energies involved come closer to kT . The result is that it becomes increasingly difficult to write at high data rates, and what is written becomes distorted owing to the varying frequencies that are found in an actual data pattern. In contrast to the situation for frequency problems in the head, scaling the media particles to smaller sizes makes the problem worse.

Note that some of these problems are independent of areal density. One can avoid them by slowing down the disk. To the extent that every drive maker experiences the same engineering difficulties, this will simply mean that high-performance drives may have smaller disks and a higher price per bit than low-performance drives. This situation already exists to some extent today and will only become worse in the future. The long-term growth of data rate in disk drives can be expected to increase more slowly than it has in the past, after we reach about 75 MB/s.

Conclusions

There are serious limitations to the continued scaling of magnetic recording, but there is still time to explore alternatives. It is likely that the rate of improvement in areal density (and hence cost per bit) will begin to level off during the next ten years. In spite of this, there are no alternative technologies that can dislodge magnetic recording from its present market niche in that time period. After ten years, probe-based technologies and holography offer some potential as alternative technologies. We cannot predict confidently beyond about 100 times present areal densities.

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References and notes

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