

MAGNETOELECTRONICS TODAY AND TOMORROW

Mention magnetics and an image arises of musty physics labs peopled by old codgers with iron filings under their fingernails—good science, this, but not the stuff from which career dreams are spun. Yes, you say, but what about the giant magnetic recording industry—it's still healthy, isn't it? Not according to some. The popular press has made statements about magnetic recording being a technology that has reached its maturity and has limited growth potential. Aficionados of semiconductor memory even advised a few years ago that memory cards based on semiconductor technology would become price competitive with magnetic hard-disk drives by 1995. This prediction has fallen short by two orders of magnitude.¹

The truth is that magnetics is not only alive and well, but is in fact the technical basis of a major world industry that is experiencing above-average growth. Magnetics technology for recording systems has still not come close to its potential performance, and there has been a renaissance in university research on magnetic and magneto-optic recording and the underlying sciences.

The magnetics story doesn't end with recording. New technology and applications are being developed for ultrasensitive magnetic sensors (figure 1 shows an example) and magnetoresistive random-access memory technology. In short, the excitement is back in magnetics.

Recording: The premier magnetics market

By far the most significant market based on magnetics technology is recording, both analog and digital. The worldwide recording industry is large—close to \$100 billion in annual revenues for media and equipment. The United States accounts for about 40% of those revenues,

Magnetism remains the leading technology base of the giant recording industry, while novel magnetic device technologies may enable other large market applications.

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the largest portion of which comes from the magnetic hard-disk segment. Data storage (magnetic disks, magnetic tapes and optical disks) accounts for about 60% of the worldwide recording market revenues; video and audio recording make up the remaining 40%. The anticipated new markets for recording that will result from the confluence of the enter-

tainment, education and commercial markets may increase recording industry revenues by an order of magnitude over the next ten years. Magnetism-based recording technologies are still expected to provide the dominant technical base for this explosive growth.

Figure 2 shows the aggregate recording capacities of hard-disk drives shipped over the past several years. The rapid growth is expected to continue for the next decade. Projections for 1995 indicate a further increase of more than 40% in the shipped capacities.

During the same time period the user price per megabyte of storage has dropped by more than a factor of ten. In the next decade, the price of both magnetic and magneto-optic tape storage is predicted to drop as low as 0.5¢ per megabyte.

Magnetic tape systems span a very broad range of applications in audio, video, instrumentation and data storage. They range in price from under \$50 for low-cost audio systems to over \$1 000 000 for large data-storage libraries. Worldwide, magnetic tape systems, media and components provide annual revenues of over \$35 billion. About 60% of this total is attributable to video recorders and associated media, a market now completely dominated by non-US suppliers. Revenue from media alone currently exceeds \$12 billion.

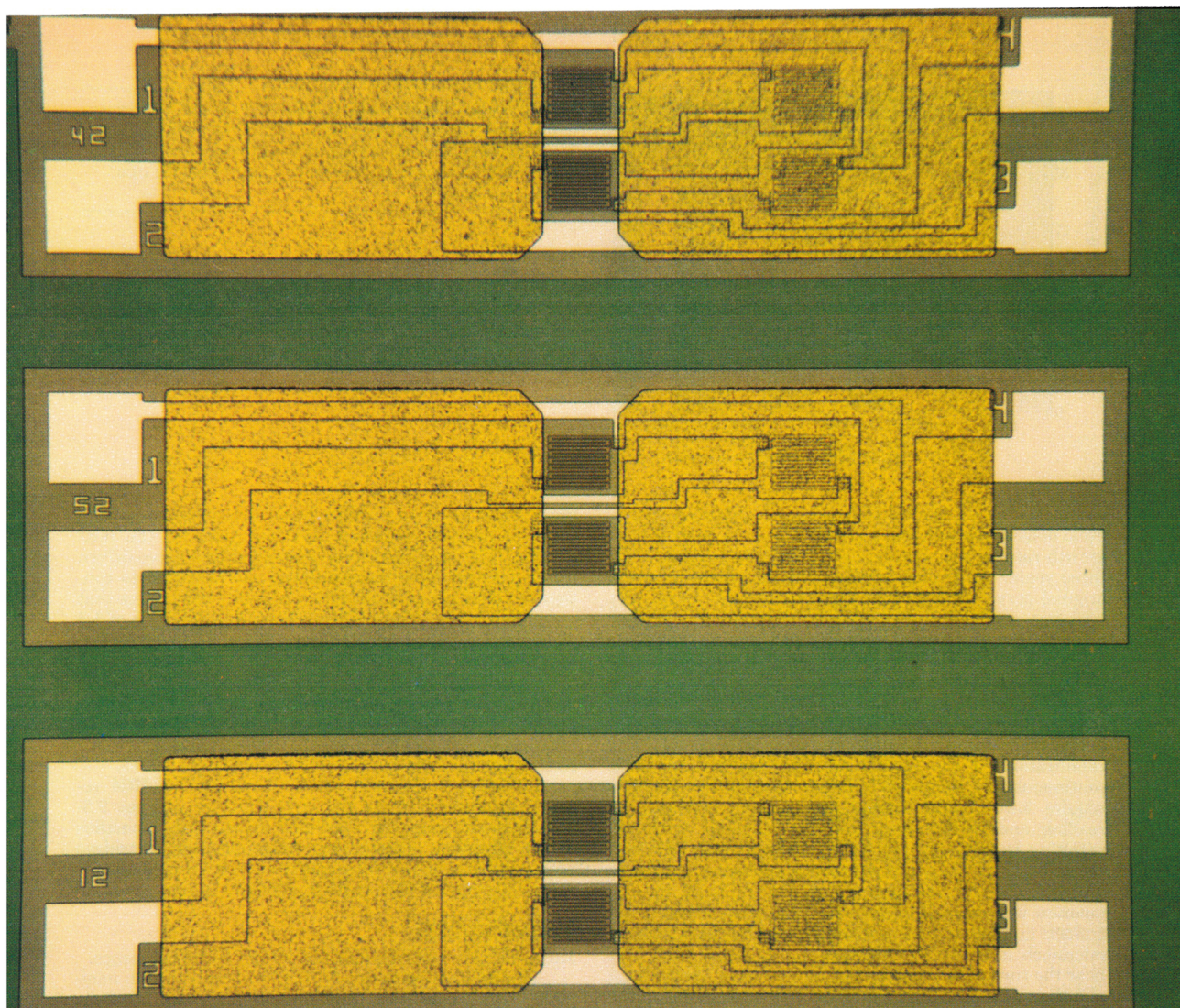
There are at least three opportunities for market growth in recording:

▷ Expanding business, education, health and governmental markets

▷ Expanding entertainment services, driven largely by video, including high-definition television, games, virtual reality, photo CDs and movies on demand

▷ Potentially large growth in personal information systems for financial records, health records and personal libraries.

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The market pull

In the business sector, mass storage requirements are now best summarized in terms of petabytes of digital data; a petabyte is 10^{15} bytes. The medical market in the United States, for example, annually generates diagnostic images and related medical data that would require over 3 petabytes of storage if it were to be accessible over a digital network. A single full-chest radiograph requires 10^8 bits for its digital representation. In one year the diagnostic radiology segment of a large hospital generates over 2 gigabytes of data. Similarly, petabyte-size storage requirements are arising in government, banking, insurance, finance, entertainment and education, not to mention high-energy physics labs.

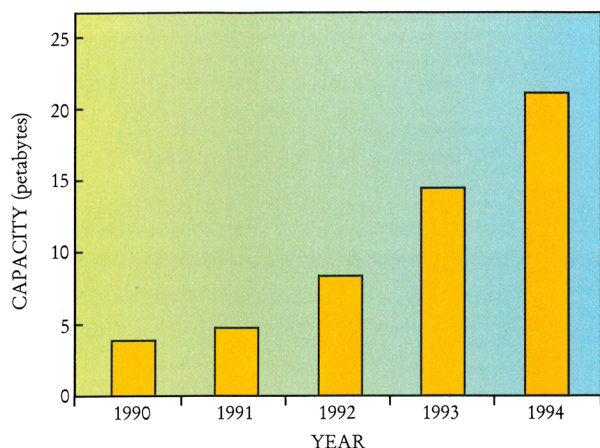
Multimedia systems for the consumer market include network-based interactive services (movies on demand, interactive television, games and so on), digital interactive consumer electronics (CDs, interactive CDs and photo CDs) and other multimedia communications services. This market segment alone is predicted to grow to over \$10 billion by 1997 and to increase at compound annual growth rates in excess of 100%. Recording technologies are a major component of this market. The various opportunities are consistent with the current vision of a

MAGNETIC FIELD SENSORS made from giant magnetoresistive materials. The resistance of these materials changes in the presence of a magnetic field. Here we see three bridge sensors on an undiced wafer. The shielded sensors are visible through one of the thick flux concentrators. The four resistors on each die are connected as a bridge. Similar bridges have been fabricated with integrated circuits to form integrated magnetic-field sensors. (Courtesy of Nonvolatile Electronics Inc, Eden Prairie, Minnesota) **FIGURE 1**

central communications highway fed by high-performance computing systems, displays and printers and, of course, digital storage. Magnetic and magneto-optic recording will comprise a major response to meeting the needs of the developing market applications.

The technology push

Magnetic recording has enjoyed a remarkable growth in performance over the last two decades. A key measure of this is areal density, the number of bits stored per unit area. For disk recording, areal density is the product of the longitudinal bits per inch (measured circumferentially around the disk) and the tracks per radial inch. (It is traditional among those working in magnetic recording to



AGGREGATE RECORDING CAPACITIES of hard-disk drives shipped over the past several years. A petabyte is 10^{15} bytes. A further increase of more than 40% is projected for 1995; the rapid growth seen here is expected to continue for the next decade. **FIGURE 2**

use inches as the metric of length.) As figure 3 shows, areal density has followed a steady 27% compound annual growth rate for the past decade—it doubles roughly every three years. Beginning around 1990 an inflection in the original curve suggests that an increased rate of at least 40% has emerged due to greater competition. At that rate, 10 Gbits/in² would be reached by the year 2005.

The current state of the art for in-track bit density is 129 000 bits per inch, increasing at an apparent rate of about 22% per year. The number of tracks per radial inch is growing at a slightly higher rate, approaching 30% per year, and present values are close to 4500 tpi. The ramifications of the growth rates for bpi and tpi must continuously be balanced. Higher in-track bit densities require lower flying heights (the spacing between the reading and writing head and the magnetic medium), resulting in tribology problems. Higher track densities create off-track noise and positioning problems. As figure 4 shows, the physical spacing between the head and the medium will reach 2 microinches this year, about 1 microinch in 1998 and 0.6 microinches by the year 2000 (a microinch is about 25 nanometers). It is expected that near the turn of the century full contact between the head and the medium will be required. Linear densities in the meantime will approach 200 000 bits/inch in 1997 and 400 000 bits/inch by 2001.

Magnetic tape technology has experienced a similar growth rate. The areal density of video systems has increased by a factor of 500 since its successful introduction in 1956. The improvement in data storage density is even more striking, with more than a 100 000-fold improvement since its introduction in 1953. Density improvement has been translated into substantial cost reduction. The areal densities of analog videocassette recorders and fixed-head linear drives have increased at about 18% per year for the last 25 years. Digital rotary

areal densities have increased and are expected to continue to increase at about 25% per year for the next decade. The areal densities of stepped and servo-driven linear systems have increased and are projected to continue to increase at about 50% per year. We project that commercial tape drives will reach storage densities of 1.5 gigabytes/in² and 1 terabyte/in³ in 1998 and 5 gigabytes/in² and 5 terabytes/in³ in 2003.

Optical recording is expected to increase in capacity and transfer rate by a factor of about 20 over the next decade. Rewritable systems will be based largely on magneto-optical technologies that exploit the smaller mark sizes made possible by new short-wavelength lasers.

Christopher Bajorek and C. Denis Mee of IBM recently projected that by the year 2000 we will see 2.5-inch-diameter magnetic hard-disk drives with capacities of 3.4 gigabytes, quarter-inch magnetic tape cartridges with capacities of over 50 gigabytes and 3.5-inch-diameter read-write optical disks with 3 gigabytes of user storage.²

Magnetic disks

Magnetic disk systems face six critical technical issues.

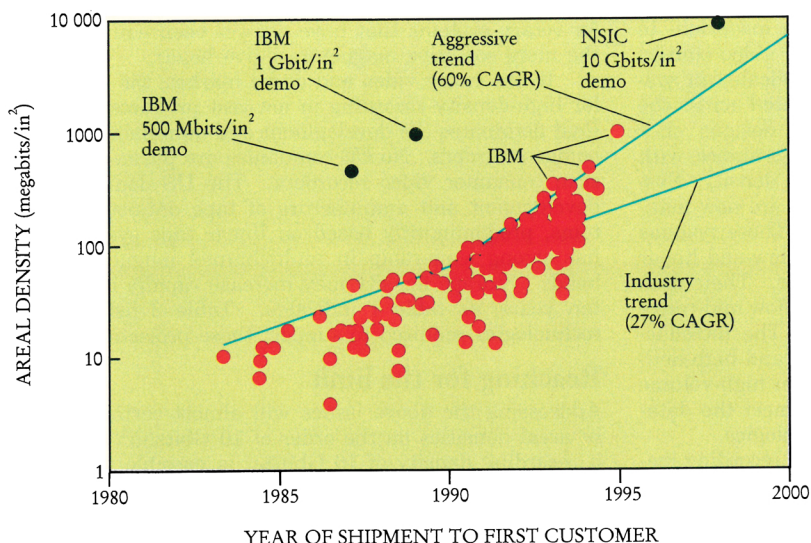
Head development. An important advance in magnetic heads made from thin films is now being commercially introduced. Since the discovery of magnetic recording almost a century ago, most systems have used an inductive head for writing and reading. Inductive heads employ coils to both induce a magnetic field (write mode) and sense a recorded area (read mode). Now, a more powerful reading head, the magnetoresistive head, has been introduced into disk products. The MR head employs a sensor whose resistance changes in the presence of a magnetic field. Its performance gain has enhanced the density of storage by up to 50%.

Furthermore, new materials research with much more sensitive magnetoresistive materials, known as giant magnetoresistive materials, promise increased performance advantages over the inductive head design. (Gary Prinz describes the GMR phenomenon in his article on page 58.) The maximum change of resistance achievable with GMR materials can be many times larger than that provided by traditional magnetoresistive materials such as Permalloy. Beyond that, there is yet another new class of materials (also described by Prinz) known as colossal magnetoresistive materials.³ These materials exhibit a resistance change of over 1000% in the presence of a magnetic field.

Commercial conversion to MR heads is only just starting. At present the US leads in introducing MR heads into disk drives and magnetic-tape data storage

Table 1. Tape storage density projections

	1998	2003
Volumetric density (terabytes/in ³)	1	5
Areal density (gigabits/in ²)	1.5	5
Linear density (kilobits/in)	150	200
Track density (tracks/in)	10 000	25 000
Data rate (megabits/sec)	20–1000	50–2000



AREAL DENSITIES of commercial disk drives over the past decade. A 27% compound annual growth rate represents a doubling roughly every three years. The inch (one inch equals 2.54 centimeters) is the traditional unit of length in this industry. (Courtesy of NBT Consulting, Minneapolis, Minn.)
FIGURE 3

products. To achieve the targeted performances, we expect continuing development of MR technology, evolving into GMR technology and, perhaps someday, CMR materials. Signal outputs must increase to offset the increased noise and lower signals that occur with higher bandwidths and a larger number of tracks per inch. GMR offers improvements in the MR strip sensitivity dR/R to provide higher signal amplitudes.

Media development. The industry will push existing longitudinal recording media (those in which domains are magnetized parallel to the plane of the medium) to the limits of thermal stability. Longitudinal recording will probably give way to perpendicular recording, in which the domains are magnetized perpendicular to the media surface. Evolution of longitudinal media implies the discovery and development of new material systems having the smaller grain structures, higher coercivities and thinner films that are consistent with the needs of higher recording densities. Above all, the media materials of the future must have a smoothness commensurate with the fact that head-media spacings will be on the order of a few nanometers. For ultrahigh volumetric densities, magnetic tapes must also use new thin (few micron) supports that have a dimensional stability well beyond those of current supports.

Head-disk interface. Flying height control is nearing its limit. Present flying heights are approaching 50 nm, and it is anticipated that near the turn of the century systems will have to be designed for direct contact between the head and the medium. A thorough understanding of the fundamental characteristics of thin-film materials (5–10 nm), thin lubricants (5 nm) and the tribology of the head-disk interaction will be necessary to fabricate successful systems. In spite of the eventual need for full contact, reliability must continue to improve. Present state-of-the-art head reliability is more than 1 million hours.

Signal processing. The challenge for signal processing is to deliver acceptably low error rates in spite of the signal-to-noise ratios diminishing as the number of bits per inch and tracks per inch continue to increase. Designers must come up with new coding and decoding techniques that over time allow progressively lower signal levels while improving error rates. Each new generation of signal processing must deliver the same or better error rate, which implies that each generation's data-recovery channel must show a

signal-to-noise gain to offset the combined signal losses from the head-media-preamplifier combination. With increased bit densities and higher rotational velocities come higher data rates, which will reach 300 million bits per second near the year 2000. The ability of silicon to handle these high data rates becomes a concern, not to mention the cabling and packaging problems between the preamplifier and the head transducer.

Data tracking. As track density approaches 25 000 tracks per inch, positioning tolerance requirements become tighter than the mechanical precision of the spindle. To compensate, one needs not only higher-precision spindles, but also low-mass micropositioners to track the out-of-tolerance motion. Micromachined silicon microactuators are one of the technologies being investigated. In addition, new position-error sensing algorithms must be developed to operate in this more precise environment. As demand continues for faster access to data, the servo will demand a wider bandwidth and therefore a larger portion of the storage capacity originally intended for the user. Obviously, one must make compromises.

Packaging. Finally, as drives shrink to smaller and smaller diameters, more functions must be packaged in less real estate, thus demanding a greater amount of integration. All of this must occur while reducing cost and power.

Magnetic tape issues

Tape storage densities are projected to increase 50-fold over the next ten years. Some of the key forces driving disk technology are also driving advances in magnetic tape. In particular, advances in magnetoresistive head technology are relevant to both types of storage. Development of ultrahigh-density magnetic disk technology will contribute to thin-film magnetic tape, although differences in cost sensitivity, substrates and tribological considerations will limit applicability. Data tape products serve a wide range of storage applications, from huge mass-storage libraries to small backup tape drives for personal computers, and are expected to play a large role in the rapidly expanding image storage and multimedia applications.

Unlike the disk storage business, where technology convergence is complete, two different hardware designs persist for tape storage. The data-storage and consumer audio businesses are dominated by fixed multitrack and stepped-head linear systems (which record tracks parallel

with the long dimension of the tape) with moderate- to high-speed tape transports. The consumer video storage business is dominated by rotating-head helical-scan systems, in which the recorded tracks are slanted across the width of the tape. These two recorder designs offer different trade-offs between density and performance, with the rotary design having much higher areal density. Systems based on consumer rotary technology are now making inroads into the data-storage business. These systems have about the same data rate as present low-end linear systems, but their capacity is much higher. Their data rate remains about an order of magnitude below mid-range and high-end data-storage requirements. The introduction of digital video recorders for standard and high-definition television will bring the data rates in high-volume consumer products up to a level that will meet the data-storage requirements of many other technologies.

The projected storage densities require recording media advances. Today, magnetic-particle tapes dominate the industry, but vacuum-deposited thin-film tapes have been introduced in some consumer applications. Achieving the projected densities will require improvements in either design, including thinner and smoother tape substrate materials and much smoother recording-surface finishes. Particulate tapes will require smaller particles. Thin-film tapes will require improved reliability and thinner protective overcoat and lubrication layers. Both types of media are advancing, and it is not clear when we will see a major shift to thin film, which will ultimately support the highest density. Most of the Japanese manufacturers are improving the reliability and performance of film media to target the markets for digital data storage. The higher output of thin-film media is particularly attractive

for rotary systems that have not yet been equipped with the more sensitive magnetoresistive heads.

In the home video and audio market, the demand is for high-density recording in low-cost products. The Far East dominates the development and manufacture of consumer recorders. No US companies are pursuing helical-scan consumer video recorders. The US dominates the development and manufacture of tape data-storage systems, predominantly based on linear tape systems, and has strong leadership in multichannel magnetoresistive heads. Storage density may increase rapidly in the next ten years, as table 1 indicates. Table 2 lists the key technologies required to support these projections.

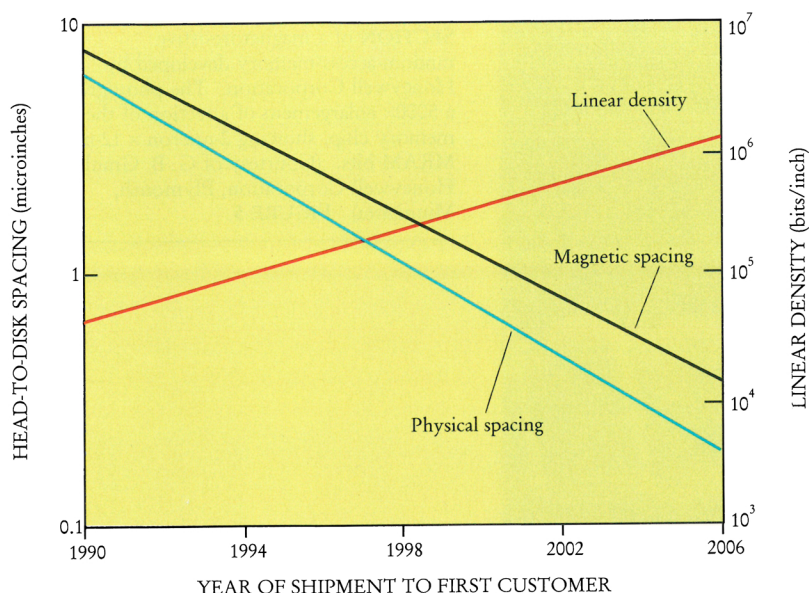
Reaching for the limit

Addressing the above issues will almost certainly result in areal densities on the order of 10 Gbits/in². Although a recording density of 10 Gbit/in² is possible with longitudinal recording, achieving another factor of ten will be difficult, because at the higher densities, thermal effects and internal demagnetizing fields cause longitudinal magnetizations to decay with time. (See the article by David Awschalom and David Vincenzo, page 43.)

Vertically oriented media appear to have the potential to overcome the thermal decay problem, because the media thickness can be made larger with higher-volume grains. This makes the thermal energy smaller compared to the total magnetic energy of the grain and less likely to destabilize it. Furthermore, in the vertical orientation the demagnetizing energy of a reverse domain generally helps to stabilize the domain rather than destabilize it, as in longitudinal recording. Amorphous exchange-coupled films, similar to those used in magneto-optic recording,

Table 2. Technologies to enable advances in magnetic tape recording

Magnetoresistive heads	
1 terabyte/in ³	5 terabytes/in ³
New tougher pole piece and insulator materials to reduce gap erosion and wear.	Corrosion-resistant GMR and/or spin valve materials and design to increase head output sensitivity by 3 to 5 times. Improved lithography for thick structures. Higher moment pole pieces.
Media	
1 terabyte/in ³	5 terabytes/in ³
~ 1-microinch magnetic spacing; smoother surface finish for particulate and thin media. Thinner protective layer and lube for film media. Smaller particles for particulate media. Improved media-limited signal-to-noise ratio: smaller particles for particulate media. Thinner substrate and magnetic coating. Improved substrate mechanical properties.	Higher moment and coercivity to provide higher output. Further reduction in magnetic spacing. Further improvement in media-limited signal-to-noise ratio: Smaller particles if particulate. 3- to 4-micron-thick substrates. Very thin coating.
Transport	
1 terabyte/in ³	5 terabytes/in ³
Head servo tracking to 0.2 microns. Handling of thin smooth tape.	Head servo tracking to 0.05 microns.
Channels	
1 terabyte/in ³	5 terabytes/in ³
Code to cope with 25 dB signal-to-noise ratio. Multilevel error correction coding to cope with 10 ⁻⁴ error rate.	Advanced multilevel codes



HEAD-TO-DISK SPACING AND LINEAR BIT DENSITY. As the number of bits per inch along the tracks increases, the physical spacing between the magnetic head and the recording medium decreases. (Courtesy of NBT Consulting.) **FIGURE 4**

could be used. Researchers using a near-field optical probe have already demonstrated⁴ recording domains at a density of 45 Gbits/in².

One can even envision arrays of scanning probes. In this approach, vertically oriented magnetic probe heads and near-field optical probes would run in contact or near contact on a fluid bearing above the media surface. Because the mechanical resonances of such probes would limit the data rate, one would have to build arrays of scanning probes.

Are we nearing the ultimate limit for magnetic recording? The theoretical answer is no, though a practical engineer would be reluctant to sign on to achieving this lofty limit in a commercial system. At the superparamagnetic limit, one might, for instance, envision an ordered array of single-domain particles, each about 8×8 nanometers in size. At present the technology to make such small, ordered arrays is not feasible. If by other techniques, such as those described above, we someday manage to reach a density of 100 Gbits/in², the effective recording cell would measure about 80 nanometers on a side, still much larger than the predicted ultimate limit.

Magnetic sensors and memories

Magnetic sensors play important roles in many commercial markets and scientific research activities. Areas of application include the automotive and aerospace industries, medicine, surveillance and manufacturing control. Magnetic sensor technologies are many and varied.⁵ They include search-coil magnetometers, flux-gate magnetometers, optically pumped magnetometers, nuclear precession magnetometers, SQUID magnetometers, Hall effect sensors, magnetoresistive magnetometers, magnetodiodes, magnetotransistors, fiber-optic magnetometers and magneto-optic sensors. Their sensitivities, power requirements and frequency limits vary considerably. SQUIDS can measure fields down to 10^{-10} gauss but require very-low-temperature operation; magnetoresistive sensors with flux collectors can be made to operate at up to 10^8 Hz and require only 100 milliwatts of power.

GMR materials have recently been used to construct⁶ low-cost magnetoresistive sensors with improved operation in the range of 0–200 gauss. They are Wheatstone bridge structures with field concentrators that can be made very

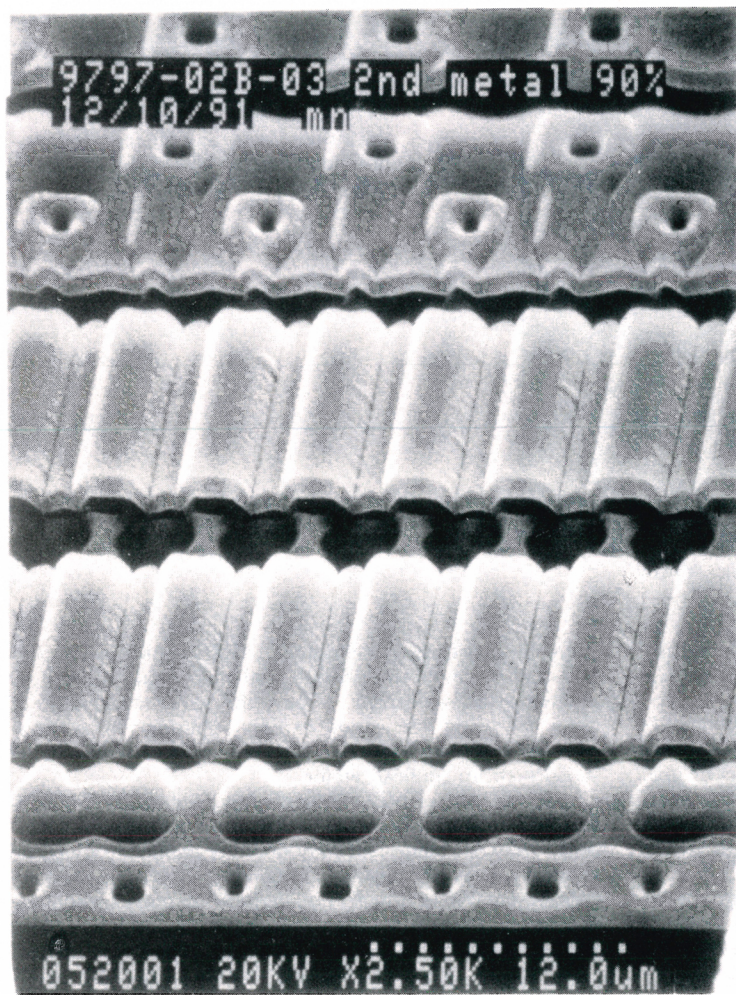
small by integration techniques. GMR sensors offer signals that are 3–20 times those of a traditional (Permalloy) magnetoresistive sensor. They are linear over most of their operating range and exhibit superior temperature stability.⁷ Figure 1 shows a top view of three GMR bridge sensors on an undiced wafer.

Advances in GMR materials have led to the development of memory elements that are now finding applications and that some feel may one day challenge dynamic random-access memories. Magnetoresistive random-access memory is an integrated magnetic memory technology that uses magnetic storage and magnetoresistive reading with semiconductor support circuits.⁸ The basic MRAM cell configuration is a magnetic sensing line and an orthogonal and insulated word line. The magnetic sense line consists of a pair of thin magnetic films with their easy axes across the sense line and with an interlayer sandwiched between to break the exchange coupling between the magnetic layers. A current in the sense line produces a magnetic field across the line in opposite directions in the top and bottom films. The storage states are a clockwise or counterclockwise orientation of the magnetizations in the sandwich layers about the sense current. A one or zero can be written into a two-dimensional array of these cells by a word current in combination with a sense current of appropriate polarity.

MRAM chips with up to 16 kilobits of storage have already been demonstrated. (See figure 5 and the figure on page 25.) Designs of chips with up to a million bits are now in progress. MRAM devices might possibly be competitive with DRAM technologies because of their inherent simplicity of processing, nonvolatility, static storage and nondestructive readout.

Some good science, too

All of this technology development rests on continuing fundamental magnetics studies at a number of university and industrial centers (as Awschalom and Vincenzo describe in their article). New measurement techniques include the magnetic force microscope, an atomic force microscope in which the force is not mechanical but is generated by the magnetic attraction or repulsion of the sample and a magnetic probe tip. An example of this microscope's utility is in work being done at the University



SECTION of a magnetoresistive random-access memory developed by Honeywell Corporation. The photograph is a 5000 $\times$ enlargement of a section of the memory chip, showing 2-micron $\times$ 12-micron MRAM bits. (Courtesy of G. B. Granley, Honeywell Corporation, Plymouth, Minnesota) **FIGURE 5**

of California, San Diego, and Yokohama City University.⁹ Scientists at those institutions have been studying the probability of the spontaneous thermal reversal of magnetization of single domains of $\gamma\text{-Fe}_2\text{O}_3$ that were deposited on the grid of a transmission electron microscope. Their studies point to magnetization reversals that depend on magnetization nucleation sites within the domains. The understanding that will emerge from this fundamental work is of value not only in ultrahigh-density magnetic recording but also in paleontology, where one studies the magnetizations of rocks to determine Earth's magnetic history.¹⁰

Magnetics and the industry

Magnetics is fueling a major growth industry and enjoying a revitalization of university research that is both fundamental and, as never before, coupled with industry programs leading to new products and services for recording, sensing, memory and control systems.

The US recording industry itself recognizes the value of cooperative research and has banded together in a major consortium. The National Storage Industry Consortium now has over 80 member organizations from industry, universities, national laboratories and supercomputer centers. It sponsors and manages "pre-competitive" joint research in magnetics for recording. Hardware and software programs are either in progress or are being devel-

oped with the support of the National Institute of Standards and Technology and the Advanced Research Projects Agency. These programs provide a unique focus for university research and offer the US storage industry enhanced chances for worldwide competitiveness.

The articles that follow in this special issue give a view into some of the advanced research that is continuing to provide vitality in magnetics technologies. Had Mark Twain and Yogi Berra known each other, they might have issued the following retort to those who like to believe that magnetics is mature: "Reports of its death are premature, because it ain't over until it's over."

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