Laying out a field-effect transistor to be fabricated in silicon on a magnetic garnet substrate. Carnegie–Mellon University graduate student Paul R. Rasky works beneath a red photographic safe light. The National Aeronautics and Space Administration is supporting development of silicon-on-garnet technology. (Photograph by Bill Redic.) Figure 1

Magnetic information technology

Devices that can store tens of billions of characters of information in a few cubic feet, access blocks of that information in milliseconds and transfer it at the rate of tens of millions of characters per second are within our reach.

Mark H. Kryder and Alfred B. Bortz

Important advances in robotics, communications and information processing are awaiting the development of faster and more compact devices that store and handle information. Magnetic information technology could provide such devices in the near future, but to do so will require basic research on topics ranging from magnetic phenomena to unusual mechanical systems.

The market for magnetic information devices is already $25 billion per year, and the applications mentioned above are a major reason why sales are expected to maintain or exceed their current 20% annual growth for the remainder of this decade. When corporate executives see these figures, they strive mightily for a "piece of the action"; when researchers, including physicists, see the wealth of fundamental research opportunities in magnetic information technology, they react with characteristic enthusiasm. Yet somehow this critical growth industry has not attracted the attention of the nation's research community as a whole.

A National Science Foundation workshop on magnetic information technology concluded[1] that this perplexing lack of research interest in the subject is a serious national problem:

> [The] growth of magnetic information capacity will, in the near term, be limited not by the industrial capacity to manufacture equipment but by the availability of new basic and applied research data in all areas of magnetic information technology. Furthermore, growth in magnetic information technology will be limited by the absence of trained engineers, scientists, and faculty.

Our goal in this article is to describe magnetic information technology, not to try to remedy the critical shortage of workers in the field. However, to the extent that this shortage results simply from the research community's lack of awareness of magnetic information technology, the article may serve a dual purpose. We believe that research in the field is as exciting in its scientific aspects as it is in its technological possibilities (figure 1). The fundamental limits on magnetic information technology are orders of magnitude beyond the state of current technology—a state that many people already view as incredible. The technology includes storing information in microscopic magnetic domains, transferring information via the motion of domain walls and packing information into the twists of a Bloch wall. It offers the promise of erasable video disks and of single-chip silicon-on-garnet computers with magnetic bubble memories in the garnet and logical and control functions laid out on laser-annealed polysilicon by very-large-scale integration techniques.

The quest to store information at higher densities and to retrieve and transfer it at higher speeds offers research challenges to magnetics engineers, of course. However, it also involves studying the physical, chemical and rheological problems associated with laying out a smooth surface of fine, uniformly distributed magnetic particles suspended in an advanced polymeric fluid. It involves the tribology and aerodynamics of a magnetic head flying over the surface of a disk at a distance comparable to the mean free path of the air molecules between them. And it involves fascinating problems in mathematical modelling.

Magnetic information technology includes three major fields: magnetic recording, magneto-optic recording and

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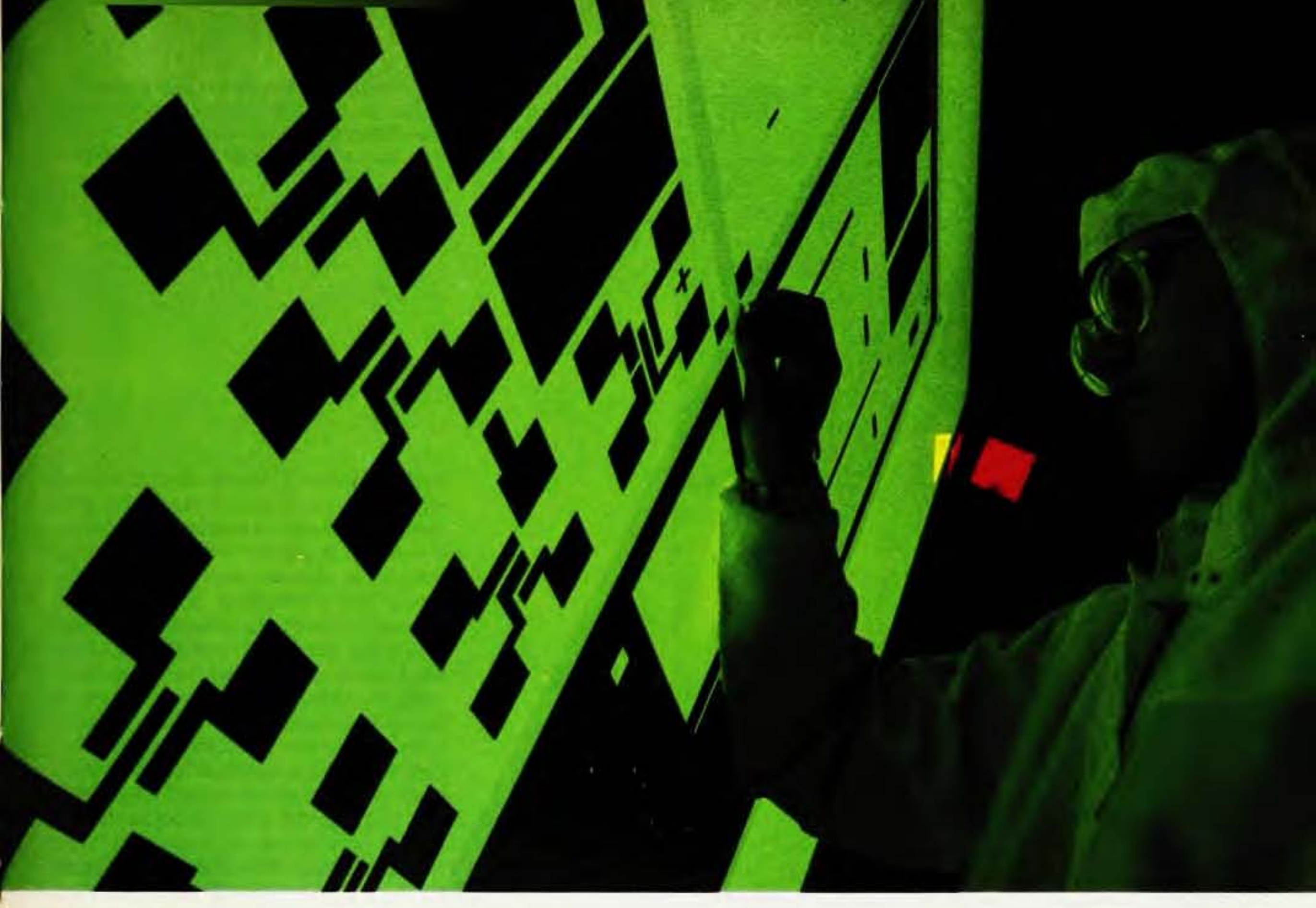


magnetic bubbles. In the sections that follow, we describe the current state and the projected developments in those fields, with emphasis on those areas where there are promising research opportunities for physicists.

Conventional magnetic recording

Today's magnetic recording technology, as applied to the storage of information, takes three familiar forms: magnetic tape, floppy disks and hard disks. In all of these forms, a recording head writes and reads information on the magnetic recording medium.

A conventional recording head consists of a C-shaped high-permeability magnetic material—typically a ferrite—around which a few turns of wire have been wound. When current is made to flow through the wire, the magnetic field emanating from the gap in the recording head intercepts a magnetic medium and magnetizes it in the direction of the field. By reversing the direction of current flow as the medium moves under the head, one can store information by magnetizing different regions of the medium in opposite directions. In the most commonly used encoding scheme, the presence or absence of a magnetic reversal is interpreted as a "1" or "0."

To read the magnetically encoded information, a mechanical system causes the medium and head to move relative to one another at high speed. The magnetic fields from the transition regions in the medium intercept the head and, by Lenz's law, induce current pulses in its windings.

In all recording systems, commerically important parameters are:

▶ Density of information. This is usually expressed in terms of bits per unit length along a track and tracks per unit length along a radius, or in terms of their product, bits per unit area.

▶ Access time. This is the time required to position the reading or writing head at a given place on the medium.

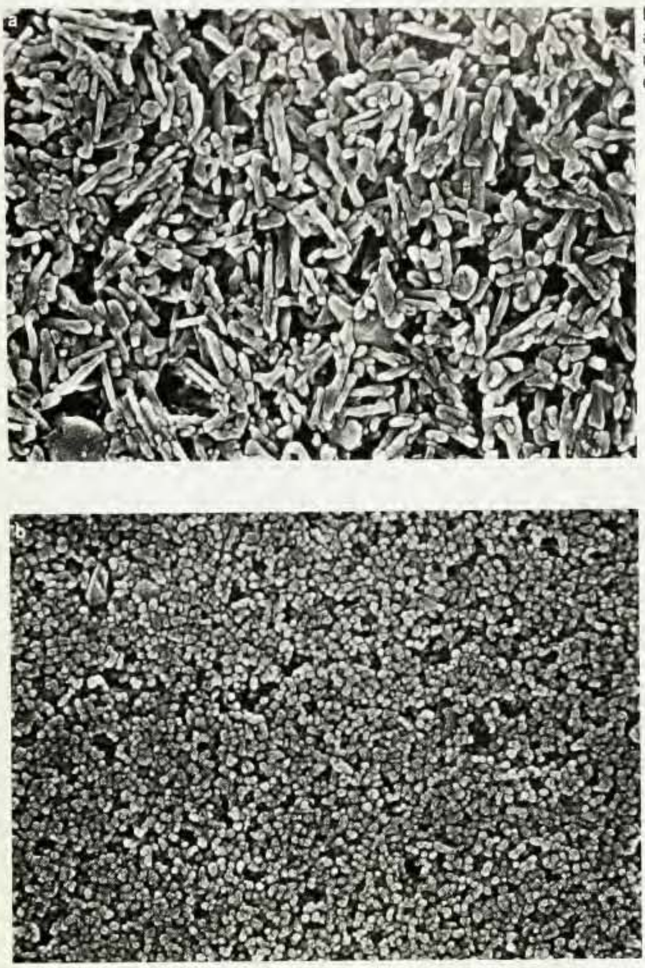
▶ Data transfer rate. This is the number of bits transferred per unit time after a block of data has been accessed.

▶ Cost.

The total number of bits per drive, and the weight and volume of the drive system are also important in certain applications. These factors are related to information density because higher information density means that smaller systems can be used for a given application.

Limiting factors in heads and media. The recording medium in conventional magnetic recording systems typically consists of fine particles of γ-Fe_2O_3 bound to a disk substrate by a glue-like polymer. Figure 2a shows an electron micrograph of particles in a floppy disk. The particles are variable in size and shape, but they are generally acicular, or needle-like. The quality of the medium depends on the size of the particles, the uniformity of their distribution on the substrate, the smoothness of the deposited surface, the anisotropy of the particles, their remanent magnetization and their magnetic coercivity, that is, the field necessary to reverse their magnetization. Other factors affecting quality are the alignment of the particle axes, whether they have single or multiple magnetic domains, and the distribution of coercivities and magnetizations, which is related to the distribution of shapes and sizes of individual particles.

Among the many factors limiting the rate of progress toward higher recording densities, the most critical problems involve the interaction of the head and the recording medium. Because one cannot focus magnetic fields, unlike light, the only means of achieving higher recording density with an inductive recording head is to use a narrower gap and a smaller head-to-medium spacing. The latter causes severe wear problems at the head–medium inter-



Magnetic tape particles. The electron micrograph in **a** shows acicular, or needle-like, particles of γ-Fe_2O_3 in a floppy disk. The micrograph in **b** shows isotropic magnetic particles in a tape. (Images courtesy of James U. Lemke, Eastman Technology.) Figure 2

face. These problems are especially pronounced in tape and floppy-disk drives where, to achieve satisfactory head-to-medium spacing, the head and medium are in actual physical contact with each other.

With hard disks, where the relative velocity between the disk and the head is a few hundred miles per hour, the head floats on an air bearing about 2000 angstroms above the surface of the medium—a distance approximately equal to the mean free path of molecules in the air. On this length scale, surface roughness of the medium increases the effective head-to-medium spacing and leads to wear problems of both the head and the medium. Additionally, isolated rough spots on the disk can cause the head to crash into the medium, quickly destroying a portion of the disk and rendering inaccessible all the data recorded on the entire disk.

Alternative head technologies

With bulk ferrite heads, conventional particulate media and high-quality mechanical elements, Winchester hard-disk drives are available with information densities of about one million bits/cm^2, "seek" or access times of 15 milliseconds and data transfer rates of about 10 million bits per second. However, these devices are meeting stiff competition from new disk products with higher density and equal or greater capacity and speed. Even greater speeds and information densities are on the near horizon. These new-generation products are the result of the commercialization of new head and media technologies. The disks and their components are, in many cases, products of or prototypes from start-up "high-tech" companies, although established companies in the magnetic information business are also aggressively pursuing new ideas.

Among the many new head technologies under investigation, thin-film inductive heads have shown the most commercial promise and have already appeared in products. Thin-film heads are built on ceramic or other suitable substrates using microfabrication techniques similar to those used in the manufacture of semiconductor devices.[2] Figure 3a shows a schematic diagram of a single-turn thin-film head. Such heads are made by depositing and etching succeeding layers of high-permeability nickel–iron alloys, insulating layers and conductors. The head in its final form consists of upper and lower layers of NiFe shorted together at the top, but open in the center where the conductor forms a turn through the head, and at the bottom where the insulator thickness forms the recording gap width. Figure 3b is a photograph of a thin-film head like those used in the IBM 3380 Winchester disk drive. This head uses an eight-turn spiral coil. The top layer of the NiFe yoke is clearly visible.

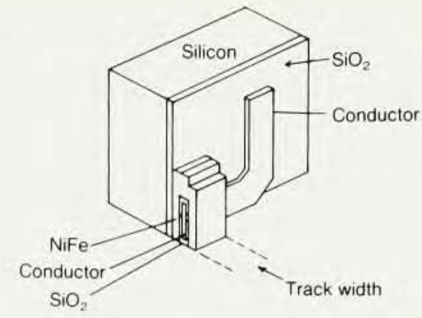
Thin-film heads exhibit high sensitivity and, because of their small size, have low inductance, making possible high data rates. The microfabrication technique permits excellent control of gapwidth and trackwidth, both of which can be made almost arbitrarily small, permitting high data density.

Alternative recording media. To overcome the limitations of particulate γ-Fe_2O_3, a number of alternative recording media are commercially available or under development. Doping the γ-Fe_2O_3 with cobalt or other materials increases the coercivity and remanence, which are necessary for higher data density. Other potential media under investigation include sputtered oxide films,[3] metallic particles,[4] and continuous metallic thin films made by vacuum deposition[5] or plating.[6]

Media made of isotropic particles rather than acicular ones also have great potential for increased information density.[7] Such media respond to both the horizontal and vertical components of the magnetic field from a recording head, producing a three-dimensional rather than two dimensional magnetization pattern. There is less self-demagnetization in such media than in media that are magnetized only in the plane of the film. Figure 2b shows an electron micrograph of isotropic particles in a tape. The regular size and shape of the particles produces a relatively uniform distribution of particles, reducing noise from the magnetic medium itself.

Perpendicular or vertical recording

Thin-film recording heads. The schematic diagram in **a** depicts a single-turn thin-film head. The silica insulator forms the recording gap width. The photograph in **b** shows a thin-film head like those used in the IBM 3380 Winchester disk drive. Figure 3



is the subject of considerable interest among manufacturers of recording systems.[8] Perpendicular recording media have their magnetization oriented normal to the plane of the substrate, rather than in the plane as in conventional recording. Longitudinal recording heads produce fields with perpendicular components, but there is considerable research into heads specifically designed for perpendicular recording. Perpendicular recording has the potential to increase the density of data significantly, because it does even more to reduce self-demagnetization than does use of an isotropic recording medium. In perpendicular recording, the transition regions between adjacent magnetic domains of opposite orientation do not tend to increase in size, as they do in longitudinal recording. Because this demagnetization is less of a problem than in longitudinal recording, one may use thicker media in perpendicular or isotropic recording. Many recording industry experts believe that using thicker media will lead to improved manufacturability and reduced sensitivity to substrate defects.

The most popular perpendicular recording medium is a sputter-deposited film of CoCr, which exhibits hexagonal crystal structure with the c-axis perpendicular to the film plane. An interesting alternative to CoCr is particulate barium ferrite.[9] Barium ferrite particles are typically in the form of platelets whose preferred direction of magnetization is perpendicular to the platelet plane. Barium ferrite recording media would be resistant to wear and corrosion, and their manufacture would make use of the existing capital investment in coating facilities.

Other challenges in recording. High-density storage of information on magnetic media, and the head technologies that make such storage possible, are not by themselves sufficient for advances in data density and transfer rate. The mechanical system that positions the head for reading and writing also has a major role in determining what is possible. It must be able to operate accurately, repeatably and rapidly. The major components of the mechanical system on a disk are the spindle, a radial positioning device and the head suspension. The precision and accuracy of these components, as well as the mechanical stability of the disk itself with respect to changes in environmental conditions, are critical limiting factors in track and bit density.

As information densities and data rates increase, and as flying heights decrease, the design of the air-bearing to support the head becomes an increasingly formidable research problem. A favorite analogy of many in the recording business is that current head positioning control, if scaled up to the size of an aircraft, is like flying a jumbo jet at 500 miles per hour 0.1 inch off the ground. As astounding as that seems, the mechanical control requirements will undoubtedly become even more demanding in the future.

Problems in manufacturing recording media bring with them a set of research opportunities. To make particulate media, magnetic particles are put on a disk substrate in a polymeric fluid slurry and bonded in place. To get a more uniform distribution of particles, rapid bonding and a smooth surface, manufacturers are actively interested in the physical, chemical and rheological properties of existing polymers and in the synthesis of new ones.

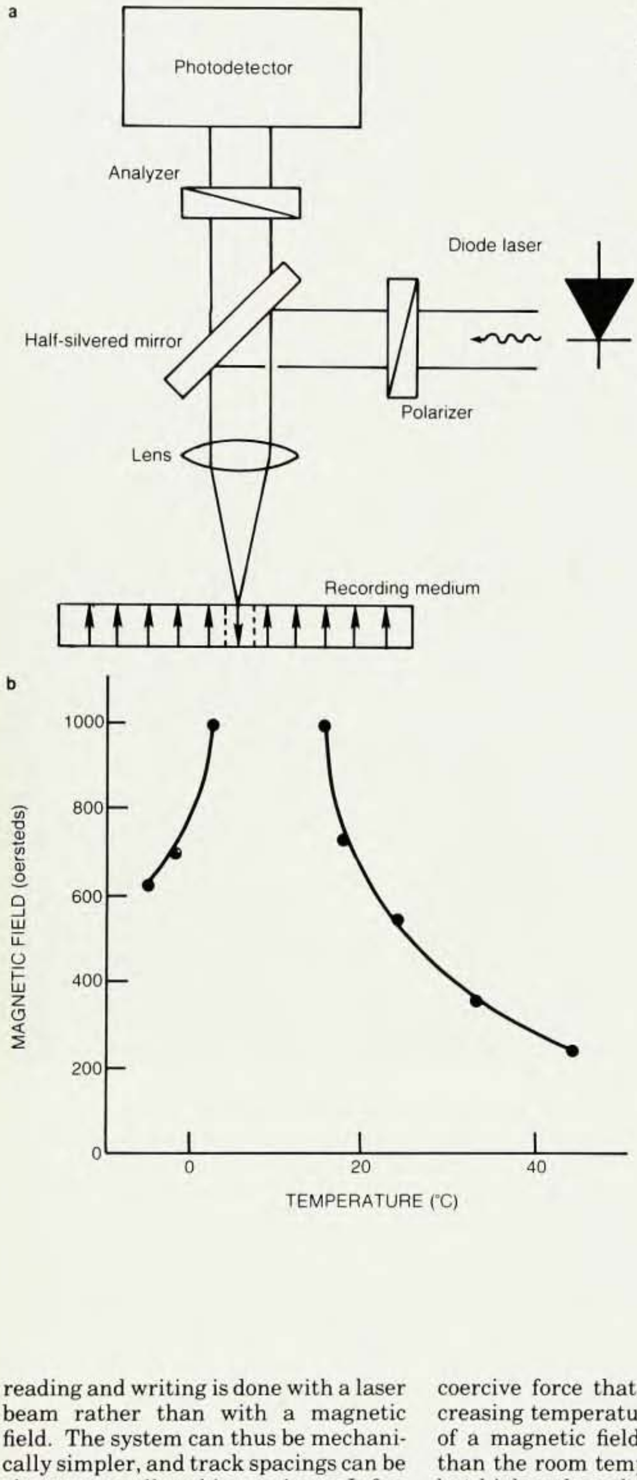
Signal processing can also limit the speed of a recording system. Thus, electromechanical advances that lead to higher disk data rates also generate a need for faster electronic and mathematical data-handling techniques.

The recording process itself is, in many ways, still poorly understood. Modeling the behavior of individual components and modeling the recording process as a whole is full of interesting mathematical and computational challenges.

Magneto-optic recording

Magneto-optic recording is related to, but distinct from, magnetic recording. In the broadest view, the former differs from the latter in that the

Magneto-optic recording. The recording scheme shown in **a** takes advantage of the fact that magnetic coercivity is a function of temperature as shown in **b**. Figure 4



reading and writing is done with a laser beam rather than with a magnetic field. The system can thus be mechanically simpler, and track spacings can be about as small as bit spacings. Information density is limited by the wavelength of the laser beam and the capabilities of the optical system. Advocates of magneto-optic recording emphasize[10] that it offers the data density of optical recording with the erasibility of magnetic recording.

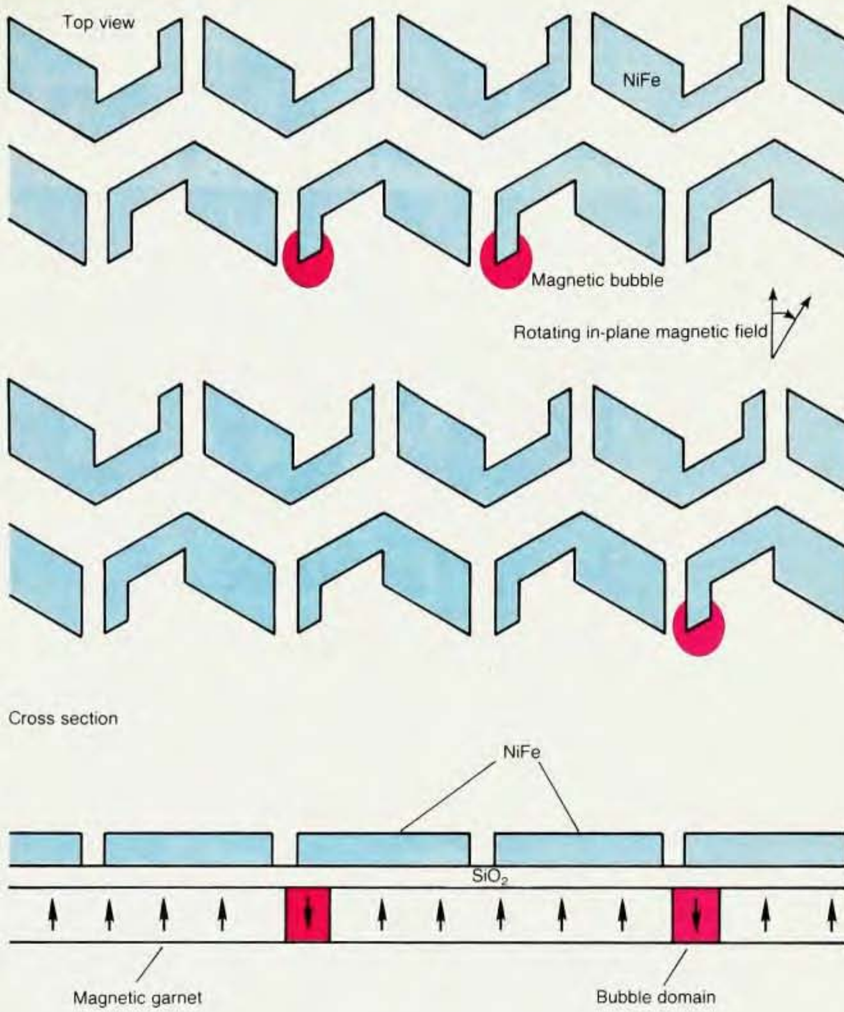
Figure 4 shows a schematic diagram of a magneto-optical recording system. A pulsed beam of light from a diode laser focuses on a thin film of magnetic material. The thin film has a magnetic coercive force that decreases with increasing temperature. In the presence of a magnetic field that is much less than the room temperature coercivity, but higher than that at high temperatures, a laser pulse can heat a one-micron region sufficiently to align its magnetic moment with the applied field, thereby writing or erasing a flux change at that spot in the material. In our laboratory, using an AlGaAs diode laser with 0.82-micron wavelength, we have written one-micron domains on two-micron centers. A single laser can write at rates as high as 20 million bits per second.

To read magneto-optic information, one uses laser light of lower intensity than is used for writing. When that light passes through or reflects from the magneto-optic material, its plane of polarization rotates due to the Faraday or Kerr magneto-optic effects. The direction of rotation depends upon the direction of magnetization in the material. By using a polarizer as an analyzer, one can transform rotations in opposite directions into intensity differences. Unfortunately, the angle of rotation is typically on the order of only 0.25 degree, so the signal is weak. Improving the signal-to-noise ratio is thus one problem in magneto-optic recording.

The materials used for magneto-optic recording are typically amorphous alloys of rare earth and transition metal elements, and may be classified into two groups: compensation-point materials and Curie-point materials. In compensation-point materials, the rare earth atoms are antiferromagnetically coupled to the transition metal atoms, so that the net magnetization is the difference between the magnetization of the transition metal and that of the rare earth. Because the properties of the rare earth and transition metal sublattices depend differently on temperature, there is a temperature at which the net magnetization of the alloy is zero. At this "compensation temperature," the coercivity tends toward infinity. For magneto-optic recording in compensation-point materials, the composition of the alloy is chosen such that the compensation temperature is slightly below room temperature.

At room temperature, the alloy exhibits a very high coercivity of, say, 1000 oersteds. But when the temperature is raised 100 to 200 degrees above room temperature, the coercive force

Permalloy structures that propagate magnetic bubbles. In the presence of a rotating magnetic field, microfabricated asymmetric chevrons of nickel–iron alloy cause magnetic bubbles to move in thin garnet films. Figure 5



drops to less than 100 oersteds, and a small externally applied field can then switch the film.

For Curie-point writing, one chooses a material with a Curie temperature—the temperature at which ferromagnetic order is lost—that is 100 to 200 °C above room temperature. As the Curie temperature is approached, coercivity decreases and the material can again be easily magnetized by a small magnetic field.

The amorphous materials being used are new and not well understood, nor are the magnetic or magneto-optic phenomena that take place in them. Thus physicsts and materials scientists have excellent research opportunities in the search for materials with large magneto-optic Kerr or Faraday rotation, with the desired temperature dependence of magnetic coercivity, with stability against annealing and with resistance to corrosion.

Magnetic-bubble technology

Magnetic-bubble memories were patented in 1967, brought to market in 1975 and today are being manufactured by several US, European and Japanese firms. The standard chip capacity today is one megabit, although four-megabit devices have been announced. Bubble technology was initially regarded as an area of high technological promise. As noted below, that promise remains, but there is also now the spectre of missed technological opportunities in the United States.

A magnetic bubble can be thought of as a small mobile domain whose polarity is reversed relative to its surroundings. The presence or absence of a bubble can be interpreted as a binary "1" or "0." Magnetic-bubble memories offer nonvolatile storage of information in a highly reliable solid-state package that is resistant to harsh environments with temperature extremes, vibration or radiation. They offer shorter access times than floppy disks or Winchester disks. Magnetic-bubble memories are therefore advantageous where considerations of reliability, access time, or cost per bit for a small number of bits are critical.[11]

Today's bubble memories are microfabricated structures of permalloy (a nickel–iron alloy), produced lithographically on films of garnet. A rotating magnetic field applied in the plane of the film induces magnetic poles on asymetric chevrons made of permalloy, causing the bubble domains to propagate. (See figure 5.) Similar permalloy structures generate bubbles, replicate them, detect them and carry out other functions. The minimum feature size in mass-produced bubble memories is about one micron.

Many scientists and engineers involved in bubble technology believe that ion-implanted devices, such as the one shown schematically in figure 6, will eventually replace permalloy devices. The cell size in this technology is, in the best case, a factor of sixteen smaller than in present technology. As the figure shows, stress created by ion implantation induces an in-plane anisotropy in the surface layer of the bubble garnet. Domain walls with magnetic poles on them, which form near the pattern boundaries when an in-plane magnetic field is applied, attract the bubbles. When the in-plane field rotates, the bubbles propagate.

This ion-implantation technology was invented in the United States. IBM and Bell Laboratories pursued it aggressively for a number of years, but they recently decided to terminate research and development of bubble memories. In Japan, Hitachi, Fujitsu and the Nippon Electric Company picked up the technology and are pursuing it vigorously. In the United States, even companies that have bubble-memory products have thus far failed to set aside research funds for this promising technology.

Both permalloy and ion-implanted devices are "field-accessed"—a rotating in-plane magnetic field propagates the bubbles. An alternative means of propagating bubbles is "current-access." Two conductor sheets with aper-

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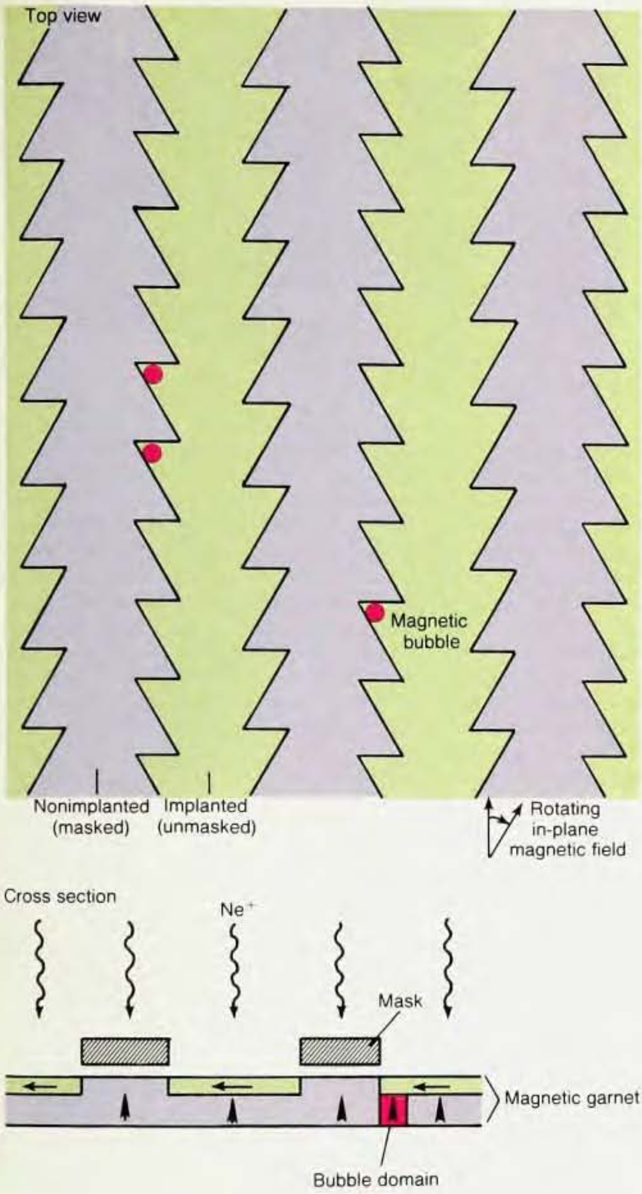


Shift register. As this schematic diagram indicates, ion implantation can produce intricate magnetic bubble devices. Figure 6

tures etched into them carry currents that flow around the apertures, producing in-plane magnetic fields that induce magnetic poles on permalloy bars. The poles attract the bubbles, which propagate as the current changes. Current-access devices store information four times more densely than do the permalloy devices now being manufactured, and one-fourth as densely as the highest-density ion-implanted devices.

Current-access technology makes possible higher data rates than field-access technology. Field-access data rates are limited by the inductance of the coils that generate the rotating field. The conductor sheets of current-access devices on the other hand, present low inductance and can be driven by high-frequency pulses. This should allow a ten- to one-hundred-fold improvement in the present 100 kHz data rate.

The current-access technique also gives us a means of implementing logical functions in bubble devices. Figure 7 shows an example of a bubble logic gate built with current-access technology. At Carnegie–Mellon, a wide variety of gates like this have been designed, built and shown to operate.

There is a need for research in several areas of current-access technology. For example, the technique's high power dissipation limits its use to small portions of a bubble chip. The development of ultra-low coercivity materials could lower the drive requirements and reduce the generation of heat.

Susumu Konishi of Kyushu University in Japan recently suggested[12] a novel ultra-high-density device based on bubble-memory materials, and the Nippon Electric Company is now pursuing the idea. This memory device uses vertical Bloch lines, which are twists in the domain wall of stripe domains in bubble materials, to store information. Depending on the density of Bloch lines along a stripe domain, information densities of 100 megabits/cm^2 to 1 gigabit/cm^2 are possible with this technique.

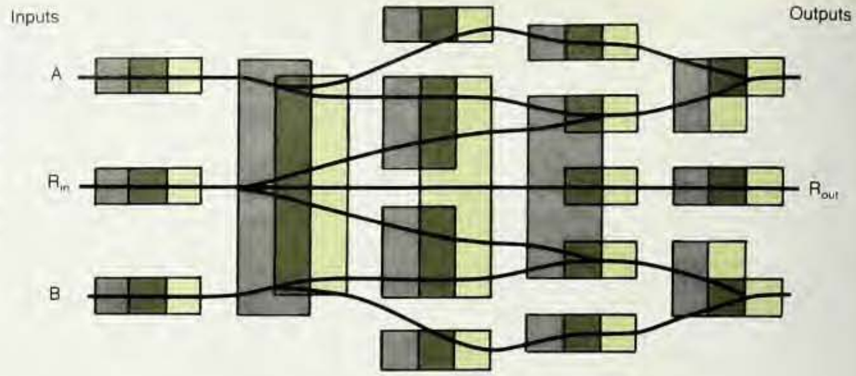
The concept of Bloch-line memories grew out of studies of the dynamics of domain walls, and, if it is to be successful, requires substantially more research by physicists. Considerable work is required on understanding the stability and dynamic properties of the Bloch lines and relating them to materials properties. The promise of a solid-state memory device with an information density approaching a billion bits per square centimeter makes the research effort very worthwhile.

Future generations

Industry experts expect the next generation of hard-disk recording systems to have information densities of 3 to 5 megabits per square centimeter, access times of 10 to 25 milliseconds and data transfer rates of 20 to 30 megabits per second. These systems will probably make use of thin-film heads, particulate media (although thin-film media will be available) and flying heights on the order of 1000 angstroms. The first generation of magneto-optical recording devices is expected within three years. These devices will most likely offer information densities of about 50 megabits/cm^2, access times of about 50 nsec and data transfer rates of 20 to 30 megabits/sec. The next mass-production bubble-memory chips will have capacities of four megabits and cell sizes of about four microns. Data will flow at about 400 megabits/sec using multiple detectors on a chip.

As remarkable as these capabilities may seem, the fundamental limits are still orders of magnitude away. Laboratory experiments on magnetic recording media have achieved densities in excess of 100 000 bits/cm at low track densities. Similarly, track densities of 5000/cm have been observed.

Logic gate based on the repulsive interaction between magnetic bubbles. A bubble enters at the point labeled R_{in} in this schematic diagram, while bubbles may simultaneously enter at A and B. Bubble–bubble repulsion causes the input bubbles to follow one of the indicated paths. A bubble reaches R_{out} only if the inputs to A and B were the same. In FORTRAN terminology, the gate performs the logical function, R_{out} = (A.EQ.B). Figure 7



Whether it is possible to achieve this high linear bit density and this high track density simultaneously in a practical system is unknown. However, estimates of the bandwidth and signal-to-noise ratio of a recording channel[13] indicate that it is possible to achieve much higher recording densities than those in the best present systems.

Magneto-optical recording density limits are set by the laws governing the diffraction of light. Domains smaller than $0.61\,\lambda/N$, where λ is the wavelength of light and N is the numerical aperture of the objective lens, cannot be resolved individually. With AlGaAs diode lasers and high-quality optics, the wavelength λ is 0.82 microns and the numerical aperture N is about 1, so that domain densities of $10^8/\mathrm{cm}^2$ are possible. With sophisticated encoding techniques, such systems could provide bit densities of $3\times10^8/\mathrm{cm}^2$. To achieve higher bit densities, one would have to use lasers with shorter wavelengths. An argon laser, for example, has half the wavelength of an AlGaAs laser, and potentially offers a bit density exceeding $10^9/\mathrm{cm}^2$.

Magnetic-bubble technology, too, will not approach fundamental limits until far in the future. Garnet bubble materials can support[14] bubble domains only down to about 0.3 microns. However, amorphous bubble materials have supported[15] bubbles as small as 0.03 microns, and the ultimate size limit is unknown. It is conceivable that Bloch-line memory devices built of those materials could reach bit densities in excess of $10^9/\mathrm{cm}^2$.

Thus, the fundamental limits of all magnetic information technologies are still orders of magnitude away from what we can achieve today. Practical limits, rather than fundamental ones, dominate current research. And practical considerations, such as the need for more investment in magnetic information technology research and the need to train more scientists and engineers for the field, may be the most serious obstacles to progress.

Opportunities for physicists. Magnetic information technology is an area of great opportunity for physicists. Industry and government are looking to unversity research programs to alleviate the shortage of trained researchers, practitioners and faculty. Professors who understand the needs of the field should be able to attract funding from industry and from government agencies for research in a number of areas: understanding, developing and characterizing new magnetic materials and devices; modeling magnetic materials, devices and systems; designing and developing high-speed, high-precision electromechanical devices; understanding the tribology and lubrication at the head–disk interface; developing improved optical and electronic signal processing techniques; and understanding the rheology of the polymeric fluids in which the magnetic particles are suspended.

Likewise, graduate students who choose thesis topics relevant to magnetic information technology will be improving their marketability in the academic, industrial and government sectors without compromising their intellectual integrity or their opportunity to do creative, original research. Practicing physicists, looking for new opportunities, can find them in this field. The demand for fresh graduates far exceeds the supply, so proven researchers who can quickly climb the "learning curve" in the magnetic information industry will be valuable in industrial and government laboratories.

Large established companies and a great many new companies are aggressively pursuing magnetic information technology. In the last few years, there have been nearly 100 start-ups in the field. The dynamics of the magnetics information industry and the challenge of putting new technology into practice in demanding applications, combine to produce opportunities for creative physicists to do interesting work.

Some people say that the United States in moving toward a service-based economy. Our assessment is somewhat different. We believe that it is moving toward an information-based economy, and that the most interesting opportunities for careers and research lie in the information industry. Magnetics, a field as ancient as the lodestone compass, is also as modern as the gigabit memory. In our view, magnetic information technology offers greater challenges and opportunities to today's physicists than any previous application of magnetism ever has. We invite our colleagues to have a look at it.

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