Computers

# Higher densities for disk memories

## Despite rumors of their impending demise, disk memories are alive and well, and with good reason

Ten years ago, disk-memory technology was widely thought to be exhausted, with no promise of significant future increases in bit density, and bound to be obsoleted soon by the new semiconductor memories. Yet, disks have defied all efforts since then to dislodge them as the dominant computer mass-storage devices. Their bit density has increased several hundred times in the past decade—as fast a growth rate as the more publicized semiconductor memories of recent years—and it may increase almost as fast in the 1980s. However, disk technology today is indeed straining the limits of recording on particulate media—a coating of gamma type iron oxide—although the fundamental magnetic limits are still several orders of magnitude away. Further density increases require improvements in recording media, read/write heads, and encoding methods. Nevertheless, rigid disk memories will probably have at least $10^8$ bits per square inch by the late 1980s. The increased density will be obtained by further exploiting thin-film read/write heads, and particulate (iron oxide) recording media. Thin-film media or perpendicular recording may trigger new density increases by the late 1980s or the mid 1990s, depending largely on marketing considerations.

### Disks and tapes based on same principles

Disks and magnetic tapes use basically the same recording and playback principles (Fig. 1). A thin layer of iron oxide containing magnetic dipoles is drawn past a recording head—an electromagnet with a highly focused fringing field. This aligns the dipoles in one direction or the other along a track to represent 1's and 0's. Digital data is recorded more reliably when the medium is driven into magnet saturation; such recordings are less vulnerable to noise because all of the medium's response is exhausted, and they also make it easier to overwrite previously recorded data. Analog wave-forms, by contrast, are generally recorded below saturation level.

In playback, the medium is drawn past another electromagnet or magnetoresistive transducer, and the magnetic flux generates a voltage in the read head. The playback system interprets flux reversals as transitions between two magnetic states, or 1's and 0's, since the read heads only sense flux changes, not levels. The number of bits that can be written along a track is determined basically by the number of flux reversals per unit length that can be read out with an acceptable error rate. The output signal level decreases as the flux transitions occur closer together, and begin to mutually interfere. The signal amplitude is also proportional to track width, so that higher track densities also lead to lower signal levels. The signal level decreases with increasing density because of thickness, spacing, and gap-loss effects (Fig. 2). The output goes through zero at the density where the length of two oppositely magnetized regions is equal to the reading gap.

Errors may be caused by "dropouts" (missing bits) or "drop-ins" (extra bits). Dropouts occur when signal levels are lower than a specified threshold or pulses are shifted in time and are not synchronized with a clock pulse at reading time. Signals fall below threshold levels most often when the head spacing is increased by such disk surface defects as clumps of oxide or binding material, foreign matter or voids in the disk coating. Drop-ins may occur when interference between adjacent tracks or bits causes a shift in the peak signal or when voids or magnetic bumps of the disk cause discontinuities in the magnetization that may be interpreted as an extra 1 in a sequence of 0's. Peak shifts can also be caused by noise from the medium, preamplifier or read head. The practical limit on reducing the error rate in particulate media is probably one error in $10^8$ recorded bits at high densities, so that some form of error-correcting technique is needed in high-density disk systems.

Rigid disks with the highest density today have a bit length of about 2 micrometers, a packing density of about 2000/mm$^2$—about 10 times that of semiconductor memory of highest density and roughly equal to a magnetic bubble memory of highest density—and a read/write rate of about 30 million bits per second. Disk storage costs about 100 times less per bit than semiconductor storage. In addition, those costs are about 10 times less than bubble storage (Fig. 3).

Disk access times are about 100 000 times longer than rival solid-state memories, but they still allow real-time processing of vast data files through look-ahead data management. Although solid-state memories will continually increase in density, the demand for low-cost, on-line mass storage will increase faster, and thus disk storage will never be obsolete. Solid-state memories may displace some small disk systems—the so-called floppy disks—where lower entry costs are more important than cost per bit or total storage capacity. However, low-entry cost is also provided by the emerging 8-inch, 5¼-inch, and 3½-inch disks.

The floppy disk—a thin sheet of Mylar coated with iron oxide—spins in a record jacket, with the read and write heads contacting the disk through a long narrow slot in the jacket. The standard floppy has a diameter of 8 inches, and the "mini-floppy" has a 5¼-inch diameter. Full floppies contain up to 10 megabytes on 80 tracks. Double-sided minifloppies carry up to 2 megabytes. High-performance rigid disks—with 100 to 300 megabytes—have diameters of 8 or 14 inches. Typical hard disks revolve at 3000 r/min and floppies at 360 r/min.

### Writing limits digital recording

The main limit on high-density digital recording is in the writing process. The natural tendency of magnetized bodies is to demagnetize partly, and so the strength of the readout signal—and thus the error rate—depends on the strength of the residual

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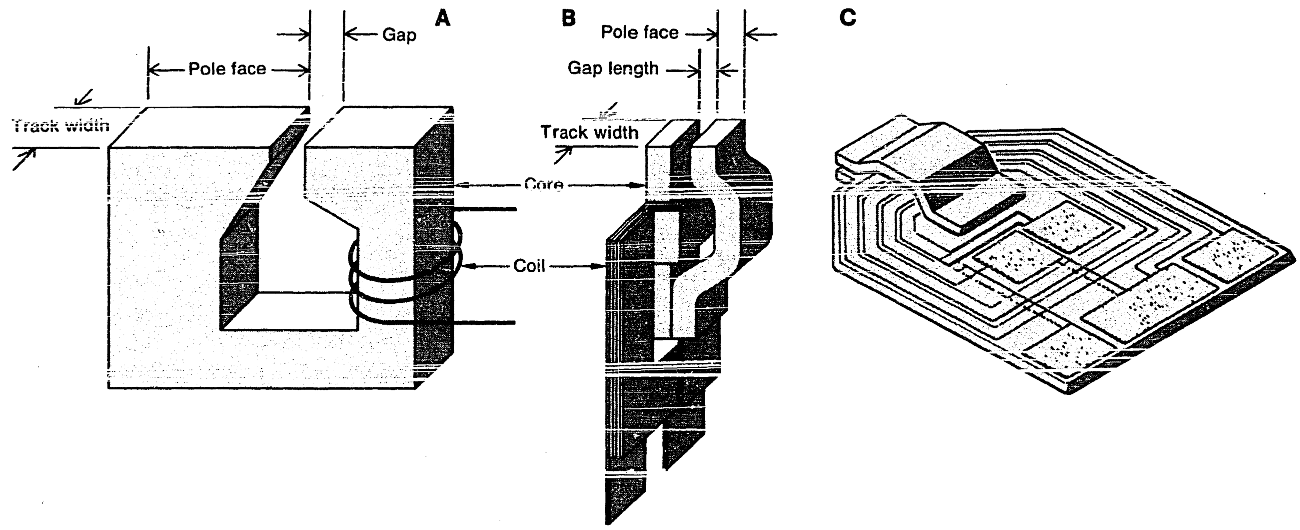
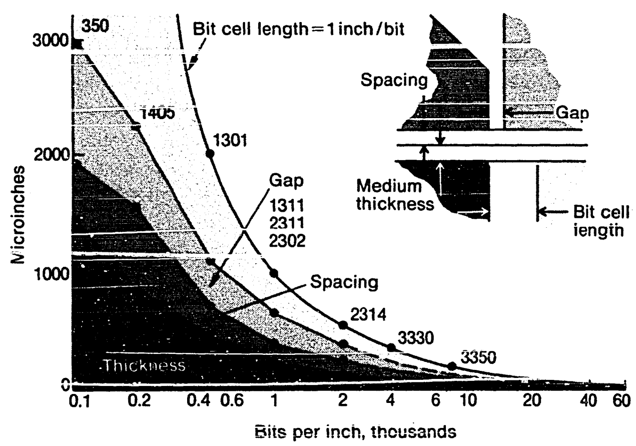



[1] Read/write heads are basically electromagnets (A), and conventional heads are made of a ferrite core (B). Much higher densities are achieved by thin-film heads (C), which are made through photolithographic processes, and have higher resolution, higher permeability, and less noise.

[2] The thickness of the recording medium and the gap and spacing of the head are major factors determining the width of the readback pulse, and therefore the maximum potential recording density. Pulse width may be reduced by decreasing the gap or spacing of the head, or thickness of the medium.




magnetization. Demagnetization degrades the magnetic transition and reduces the signal-to-noise ratio (SNR). The noise spectrum is dominated by either the recording medium, the readout transducer or the read preamplifier. Noise may also enter from adjacent track interference, as well as from old information not completely overwritten. Adjacent track noise is especially hard to handle, because it has the same spectrum as the information signal. Demagnetization may be minimized by use of materials with higher coercivity and thinner coatings.

A major factor in reducing the signal strength is the separation between the head and the disk surface. The signal decreases as an exponential function of the ratio of the separation to the equivalent wavelength (2-bit lengths) of the recorded data. At a linear density of 2000 b/mm and a separation of about 0.1 micrometer, the signal amplitude decreases to about one-half what it would be in contact with the disk. At a separation of 0.75 micrometer, the signal is only one-hundredth the contact signal.

The readback pulse should have very narrow width, as well as maximum amplitude, so that flux transitions can be written close together without overlapping adjacent pulses (intersymbol interference). Pulse width may be reduced by a decrease in either the head-to-head medium separation, the head gap or the magnetic properties or thickness of the recording medium. Pulse slimming may be traded off for SNR through various methods for spectral equalization. (Equalization reshapes the spectral distribution, allowing the channel to pass the signal with minimal distortion or improved resolution.) These methods optimize the linear recording density by removing the intersymbol interference from the playback signal while minimizing noise enhancement. The magnetization transition should be narrow. This can be achieved with smaller, more highly oriented particles in the medium, with a more uniform size and shape.

## Improved coding techniques sought

The development of higher-density disks will require a reexamination of coding techniques and channel limitations. The ideal code should minimize the following quantities: (1) The number of transitions per recorded bit (and therefore the recording rate); (2) The dc component when the data has long strings of 1's or 0's; and (3) The time between transitions, to make reclocking easier (that is, the code's run length should be limited).

Whether particulate media technology will be displaced depends on the cost benefit of switching to thin-film media. Under study for the past decade, thin-film disks offer the potential of a much higher SNR than particulate coatings, as well as lower peak shifts (thus promoting higher densities).

The efforts to use more highly oriented and uniform particulated media, with higher coercivity and decreased thickness, has basically aimed at extending the limits of longitudinal magnetic recording (along the direction of the track). A fundamental limit of the longitudinal method, however, is that the demagnetizing field in the medium approaches $4\pi M$ as the wavelength approaches zero as density increases. At least one such form—perpendicular recording—has been proposed by Prof. Shun-ichi Iwasaki of Tohoku University (Fig. 4).

Whatever the hardware solutions to the problem of increasing density, the software problems associated with accessing larger memories will be difficult to solve. File access will become a major burden a decade from now, when processors are 1000 times faster than today's processors and there is 100 times more on-line storage.

An important requirement for high-density performance is an M-H curve with a high degree of squareness. The squareness is generally defined as the ratio of the remanence to the saturated magnetization. In particulate media, it is related to the degree of magnetic particle orientation along the easy direction. The more square the loop, the more sharply the magnetization changes with the applied field and the narrower the output pulse from the read head.

The demagnetizing field is $-GM$, where G is a geometric factor that is large for high densities and thick coatings. In a simplified picture, the operating point for the recording field, H, is at the intersection of the demagnetizing field and the magnetization curve. Higher coercivity materials reduce demagnetization losses because coercivity is proportional to remanence.

Thicknesses of about 0.5 micrometer are state-of-the-art for particulate coatings on rigid disks. The particles are aligned by exposure to a magnetic field while the coating is still fluid. However, floppy-disk coatings are unaligned, and they have a web-like structure (they are punched from a tape web). The practical limit on their thickness is about 1 micrometer.

## Bit density versus track density

Changes in bit density are generally traded against track density. The higher the track density, the narrower each track and the lower the SNR (other factors being equal). One may reduce adjacent track interference by placing guard bands between tracks and using special erase heads to sweep the bands clean before writing. This, of course, has the result of reducing the potential data track density.

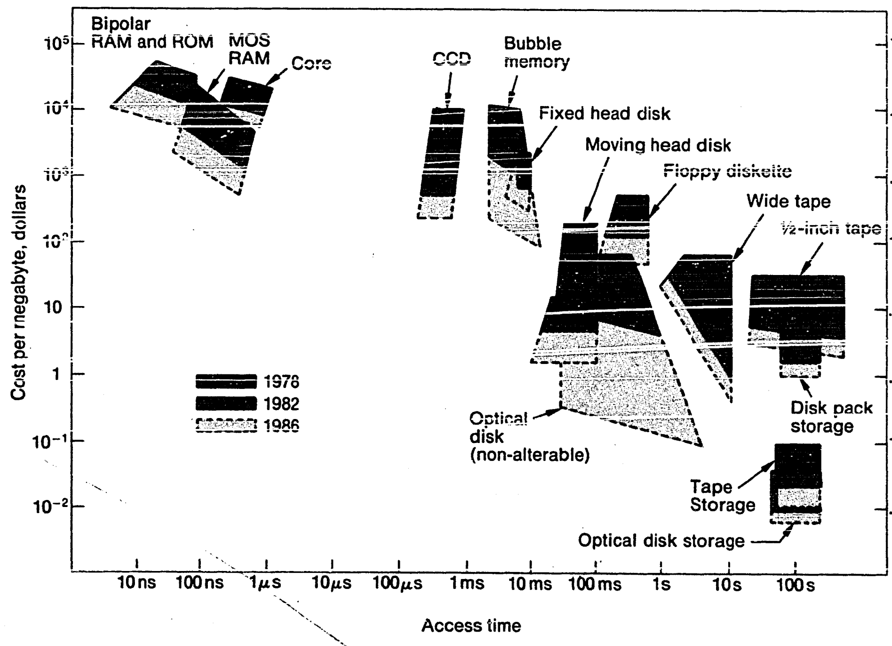
As track density increases, however, it becomes increasingly difficult both to position the head on the proper track and to keep it there. The track may be displaced by such factors as deviation between the axis of the drive spindle and the true center of the disk, as well as by the eccentricity of the disk and the failure to lock the disk securely in the drive. The head actuator may also introduce vibrations. For many years, rigid disks have had track-following servos to maintain proper head position through special information recorded on a separate group of tracks. Such servos were recently introduced in floppy disks.

Two basic methods are available for correcting errors in track position through referencing information recorded near the information track: (1) Comparison of the amplitudes of reference signals, and (2) Comparison of the arrival times of reference signals. One type of amplitude method—the tri-bit technique— derives the track position error from the difference in amplitude of two bits that are displaced from the reference position. An arrival time method is based on diagonally recorded reference tracks on either side of the data track. Here, the track position error is proportional to the difference in arrival times of the displaced bits. The percentage position error due to random noise is inversely proportional to the SNR. A number of reference samples must be averaged to reduce the error caused by random noise.

Disk playback systems generally use a peak detection circuit, in which the signal is time-differentiated and then analyzed in a zero-crossing circuit to detect flux reversals in the presence of noise. The characteristics of the isolated reversals do not shed light, however, on the ultimate density that can be achieved for a given head-disk interface. The ultimate density depends on two types of distortion: (1) A linear part, resulting in inter-symbol interference, and (2) A nonlinear part that depends on the recorded pattern of 1's and 0's and is inherent in the record-demagnetization process.

The linear part of the distortion can be corrected by linear equalization, since it can be described, and it is pattern independent. Nonlinear distortion, by contrast, is not predictable by linear methods. The nonlinear distortion, then, is the key factor limiting density. Various methods have been developed for characterizing it by removal of the intersymbol interference through linear equalization. However, peak detection systems still operate without precise equalization, and so nonlinear effects may often cause distortion.

A major problem in designing disk memories, therefore, is selecting a digital recording code for trading available SNR against areal density for a given head-disk separation, head inductance, oxide thickness, and magnetic properties. The efficiency of a code is generally measured by the density ratio—the number of data bits per flux reversal, which is equivalent to the ratio of the minimum time interval between transitions to data-bit period. The higher the ratio that can be attained, the less crowded are the pulses.




**[3] Disk storage is about 100 times cheaper than semiconductor storage, and 10 times cheaper than bubble storage. Although disks have far longer access times, vast data files can still be processed in real time by look-ahead software.**

The simplest code is the NRZ (non-return-to-zero) type, which offers the most efficient use of available bandwidth and is the easiest to implement (Fig. 5). The data to be recorded is sent to the head, with a 1 represented by positive saturation and a 0 by negative saturation. The NRZ code has a substantial dc component, since it is not limited in run-length, and no safeguards are built-in to prevent the recorded data from having uninterrupted strings of 1's or 0's. Such long strings cannot be recorded without distortion at high and low frequencies, inasmuch as the recorder cannot operate close to dc. Uninterrupted strings of 1's or 0's, moreover, may not allow enough time to ensure lock-on by the timing oscillator.

Another shortcoming of NRZ is that, in playback, a flip-flop toggles between 1 and 0 every time it detects a change in magnetic saturation. A single-bit error, therefore, corrupts all of the following data, since the flip-flop will be out of phase with the recorded data.

## Developing improved codes

Many codes limited by run length have been developed, such as NRZ-Inverted (NRZI). Instead of a change in saturation direction on all transitions between 1 and 0, the saturation changes only when a 1 is to be recorded. When data is retrieved, a transition change indicates that the data is 1; if no change occurs, it is 0. This code also eliminates the problem of error propagation. A dropped 1 will be misread as 0, but subsequent bits may still be read correctly.

NRZ has a density ratio of 1. A code with a density ratio of 1.5 was developed recently, however, by George Jacoby of the ISS Division of Sperry Univac in Cupertino, Calif. Termed 3PM (three-position modulation), the code converts a group of three data bits into six code bits that are represented by the presence of signal transitions. At least two 0's are maintained between consecutive 1's, so that a minimum distance of three bit positions occurs between flux reversals. This code was used to achieve a 50 per cent density increase in an ISS-Univac disk storage system with 2500 b/cm, a 10 Mb/s data rate, and error rate of 1 per $10^{10}$ bits.

Progress toward higher densities is also linked to the development of new recording heads, as well as to media. Conventional read/write heads are made of an electromagnet with a ferrite core—a ceramic made of iron oxide particles mixed with nickel and zinc. However, ferrite cores have three disadvantages for high-density disks: (1) Their permeability exhibits poor frequency response in recording regions about 10 MHz; (2) The head dimensions are difficult to control accurately as track widths and magnetic gaps decrease to less than 35 micrometers and 1 micrometer, respectively; and (3) The high inductance causes high impedance noise and low head resonance.

## Impact of photolithographic techniques

Photolithographic techniques have been used in recent years, however, to make thin permalloy film heads, which can be more accurately aligned than ferrite heads and have high permeability at frequencies up to 100 MHz (Fig. 1). The greatly reduced volume of magnetic material results in lower susceptibility to electromagnetic noise, while the thinner pole tips allow finer resolution. The inductive circuit in the thin-film head is not a coil of wire, but a thin-film conductor deposited as a spiral on the surface of a silicon substrate. New disk systems using thin-film heads, such as the IBM 3081, have almost tripled previously available density and capacity per spindle.

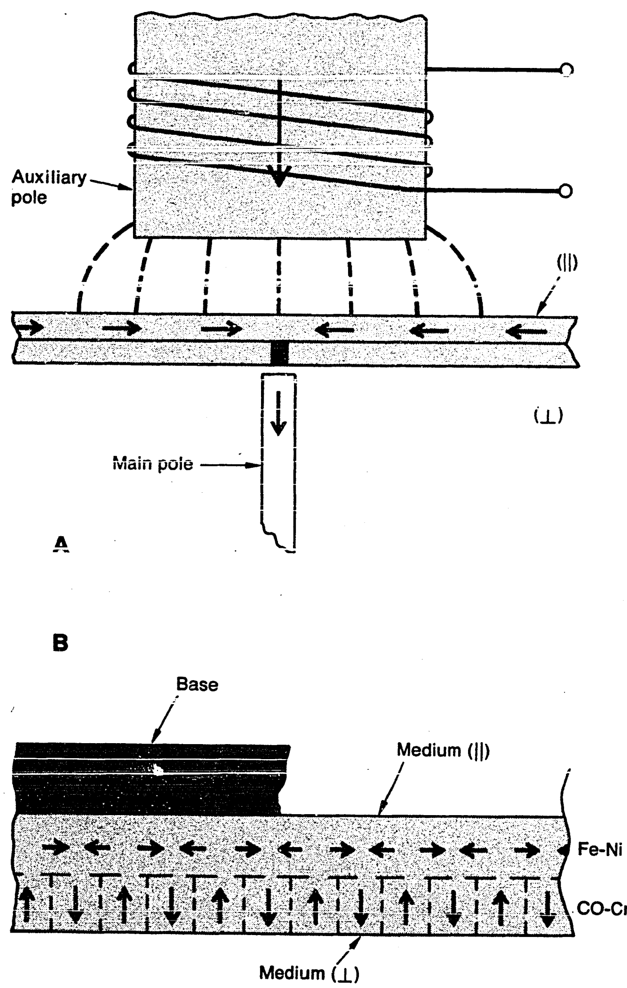
Thin-film head technology combines semiconductor processing with magnetic circuit design. The fabrication of core, coil, and all the geometries is done through precision masks, plating, and vacuum deposition. Several hundred layers are commonly put in place to form the desired pole geometry, coil, and gap. The process complexity here may indeed exceed that in conventional integrated circuits. This complexity has slowed progress in thin-film head technology. The major development today is concentrated on structural refinements to allow larger write currents without saturation, as well as to refine process technology.

The major advantage of thin-film recording media over particulate coatings is that they can be made thinner. Their coercivity can also be increased more easily. The coercivity of gamma-iron oxide particles can be increased if they are coated with a layer of metallic cobalt. This is done by heating a solution containing both the particles and cobalt ions. This type of medium is being used in some high-density magnetic tapes, but it has not yet been proved durable enough for disk applications.

## Limits of longitudinal recording

At some future date, however, the limits of longitudinal recording will be reached, even with metallic thin films. This limit is imposed by a fundamental property of longitudinal magnetization: The demagnetization at the transition boundary ap-

**[4] Perpendicular magnetic recording can potentially triple the recording density possible with conventional longitudinal magnetization. Readback may be performed by standard ring heads, but the single pole head (A) offers ideal conditions for creating perpendicular magnetization (B).**



proaches $4\pi M$ as the bit density increases. Experiments by Tu Chen and Richard M. Martin of the Xerox Palo Alto Research Center in California indicate that the physical limit of high density recording in metallic media is actually the size of the magnetic clusters in the film. The magnetization direction of each cluster can deviate significantly from the net magnetization direction of the medium. At the magnetization transition boundary, these clusters group to form sawtooth figures. At sufficiently high densities—perhaps 10 000 flux reversals per centimeter—the recording process breaks down.

The density of thin films may be increased by a factor of 3, however, by perpendicular recording. In theory, perpendicular recording allows the ideal step change in magnetization, since the demagnetization approaches zero as the recorded wavelength approaches zero. Interest in this technique has been spurred by the preparation by sputtering of cobalt-chromium films that exhibit columnar growth structure, with perpendicular anisotropy favoring vertical magnetization.

The original idea, as proposed by Prof. Iwasaki, required a special recording head with a main pole of magnetic thin-film in contact with the recording medium (Fig. 5). However, this head requires a much higher recording current than the conventional core, or ring-shaped head. This is because the perpendicular head has a large air gap between the main and auxiliary poles. To decrease the current, Prof. Iwasaki developed a composite recording medium made of cobalt-chromium film sputtered onto an iron-nickel film—which is, in turn, sputtered onto the base material. The recording current needed to saturate the double film is one-tenth that for the single anisotropic film.

The iron-nickel film decreases the magnetic reluctance of the head by providing a low energy path from the bottom surface of the cobalt-chromium film to the auxiliary head, according to Prof. Iwasaki. In the remanent state, moreover, the iron-nickel film rotates the magnetic vector so that it forms a horseshoe-shaped magnetization mode—thus increasing the remanent magnetization and decreasing the demagnetization field.

## For further reading

*IEEE Transactions on Magnetics*, Vol. MAG-15, no. 6, November 1979, special issue: Second Joint INTERMAG-MMM Conference. The conference combined the 24th International Magnetics Conference and the 25th Conference on Magnetism and Magnetic Materials. The papers of highest interest for the newcomer appear on pages 1444 to 1469, in a symposium titled, "Recording—Mostly Theory." Especially notable are the discussions of spectral equalization for high density recording (by Dr. Chi), and perpendicular recording by S. Iwasaki.

Introductory papers by Dr. Iwasaki on perpendicular recording were published in *IEEE Transactions on Magnetics*, Vol. MAG-13, no. 5, September 1977, and Vol. MAG-14, no. 5, September 1978.

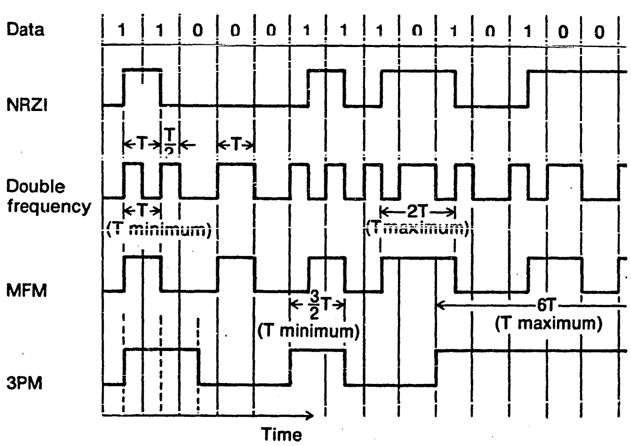
"Position sensing for high density recording" is analyzed by H. Ragle *et al* in *IEEE Transactions on Magnetics*, Vol. MAG-14, no. 5, September 1978, p. 327.

Floppy disk technology is described at considerable length in "Improvements in Flexible Disk Media," by Geoffrey Bate, published in Session 7 of the *Electro '80 Professional Program*. The paper discusses the most important performance factors generally governing disk technology, including: storage capacity, access time, data rate, error rate, durability, and cost.

*IBM Disk Storage Technology*, a booklet, is available from IBM (Technical Communication, 5600 Cottle Rd., San Jose, Calif. 95193). This promotional literature provides excellent background for thin-film technology beginning with the 3370. The IBM 3370 film head represents a major change in processing and geometry from those used on previous disk files.

Another excellent piece of promotional literature is *Parallel Mode High Density Digital Recording—Technical Fundamentals*, published by Bell and Howell, Datatape Division, 300 Sierra Madre Villa, Pasadena, Calif. 91109. This booklet does assume that readers have some familiarity with the principles of magnetic recording, but no previous experience with high-density recording techniques. It summarizes, at any rate, the various encoding schemes and discusses criteria of code efficiency, bandwidth sensitivity, error rates, spectral sensitivity, and the like. In addition, the booklet contains a lengthy discussion of error detection and correction methods. The discussion indicates that the choice of a recording code is a far more complex problem than could be elaborated in the *Spectrum* article. In parallel mode, high-density recording, for example, not all bits recorded are actual user bits. Those that are not include the bits used for synchronizing playback, and for parity (an error-checking provision). The added bits are called "overhead". The overhead for various encoding methods varies from about 5 percent to 22 percent of the recording space that is available. However, low overhead does not necessarily make one code better than another. That is, a code with lower overhead may actually require more tracks than one with higher overhead. A more meaningful criterion of performance that is brought out is the ration between usable, per-track bit rate and the maximum theoretical rate (Nyquist rate).

**[5] A major task in designing disk systems is to choose recording codes that optimize signal-to-noise ratio, area density for a given head, and the thickness and magnetic properties of the medium. Such codes as Non-Return-to-Zero-Inverted (NRZI), Miller FM (MFM), and 3-position modulation (3PM) eliminate problems caused by long runs of 1's or 0's.**




## About the author

Chao S. Chi (M) has been with Sperry Research Center since 1977 as principal investigator and manager of the Magnetic Recording Laboratory. He was born in Nanking, China, in 1938. He received the B.S. degree from National Chengkung University in Taiwan, and the M.S. and Ph.D. degrees from Worcester Polytechnic Institute, Worcester, Mass., all in electrical engineering. Dr. Chi joined Digital Equipment Corp. in Maynard, Mass., in 1971, and was a principal designer of the RSJ03/04 thin-film disk drives, and he later had project responsibility for the LSI-11 microcomputer. Dr. Chi is a member of the IEEE Magnetic and Computer Societies and is a registered professional engineer in Connecticut and New Jersey. ◆