Scaling tape-recording areal densities to 100 Gb/in^2

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We examine the issue of scaling magnetic tape-recording to higher areal densities, focusing on the challenges of achieving 100 Gb/in^2 in the linear tape format. The current highest achieved areal density demonstrations of 6.7 Gb/in^2 in the linear tape and 23.0 Gb/in^2 in the helical scan format provide a reference for this assessment. We argue that controlling the head–tape interaction is key to achieving high linear density, whereas track-following and reel-to-reel servomechanisms as well as transverse dimensional stability are key for achieving high track density. We envision that advancements in media, data-detection techniques, reel-to-reel control, and lateral motion control will enable much higher areal densities. An achievable goal is a linear density of 800 Kb/in and a track pitch of 0.2 μm, resulting in an areal density of 100 Gb/in^2.

Introduction

Historically, the cost and the size of the media recording area of both tape cartridges and disk drives have remained fairly constant. The areal recording density is the main factor determining the cost per gigabyte, which is fundamental to the commercial viability of these technologies. **Figure 1** compares the evolution of areal densities of laboratory demonstrations of linear tape technology and commercially available tape drives and hard-disk drives (HDDs). As can be seen, the previously wide gap in areal density values between helical scan and linear scan tapes has almost disappeared.

With an areal density two orders of magnitude lower than that of HDDs, tape drives maintain a lower cost per gigabyte only because tape media can be produced at a very low cost per area and because the media is removable, allowing the cost of the tape drive to be amortized over many cartridges. The cost-per-gigabyte difference is the key reason that tape technology has remained viable, even though the research and development investment in tape drives is far lower than that for HDDs. From another point of view, this difference presents a great opportunity for achieving a much lower cost per gigabyte for tape if the areal density can be brought closer to that of HDDs by skillful engineering.

In this paper, we analyze the feasibility and technologies required to achieve a target operating point of 100 Gb/in^2 in a linear magnetic tape drive. Previous demonstrations of record areal densities (including helical scan and linear tape technologies) and the state of current HDD technology provide important insight into key technological choices and highlight critical parameters that have to be considered for further advances in areal density [1–8].

Figure 2 illustrates the track density versus linear density of HDDs (square symbols) and tape drives (circles), where the linear density takes into account the rate loss due to modulation coding. The product of linear and track densities yields the areal density. The diagonal lines in Figure 2 thus indicate the points of constant areal density. Current tape drives, as specified by the Linear Tape-Open (LTO**) standard for generation 4 (LTO-4) [9], operate at a linear density of ~300 Kb/in, which is not very far from that of current HDDs. Today, although the gap in linear density between HDDs and tape drives is rather small, tape drives have much lower track density, indicating that there is room for significant improvements. Therefore, in order to reach the operating point of 100 Gb/in^2, the bit aspect ratio of tapes, usually defined as the ratio of linear density and track density, would need to approach that of current HDDs.

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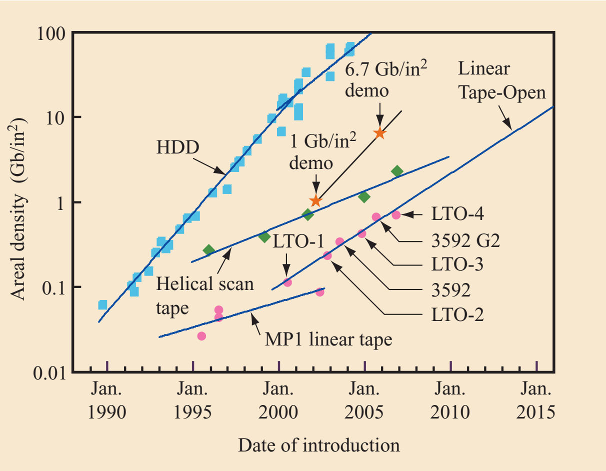

Figure 1

Areal density of tape drives and HDDs (reprinted with permission from [1]; ©2007 IEEE). Linear Tape-Open (LTO) is a magnetic tape data storage technology.

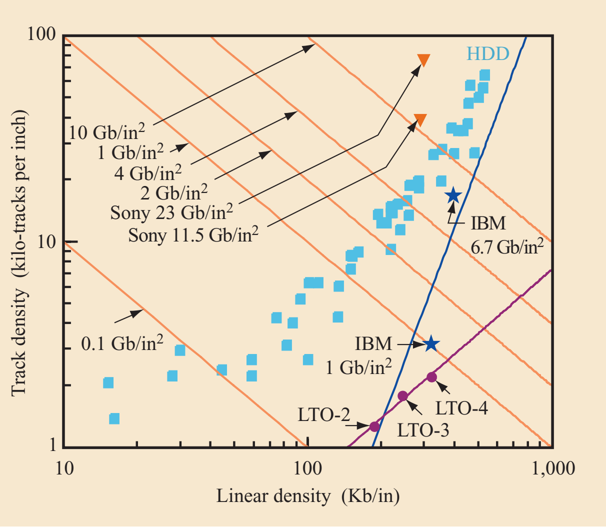

Figure 2

Linear density versus track density.

Media considerations

Areal recording density on tape is limited by medium magnetic stability, maximum achievable write-head fields, the minimum bit length that can be recorded in the medium, and the signal-to-noise ratio (SNR).

Broadband SNR varies with the number of magnetic particles per bit volume of the medium. Model calculations show that in order to achieve a reasonable SNR, about 100 particles per bit are required [10]; thus, as the areal density increases, particles must become smaller. However, in order to avoid thermally induced switching of the particles, the anisotropy energy $K_U V$ of each particle should be much larger than thermal energies, $k_B T$. Here, K_U is the uniaxial anisotropy energy density, V the volume of the particle, k_B the Boltzmann's constant, and T the absolute temperature. A widely used rule to facilitate data retention is $K_U V > 60\ k_B T$. Unfortunately, higher-anisotropy particles require larger magnetic fields for magnetization reversal, and head fields are limited by the saturation magnetization (B_s) of the head-pole materials. High-B_s materials allow about 20 kG saturation magnetization (e.g., 24 kG for $Co_{35}Fe_{65}$). Following the work in [11] and [12], the minimum bit length, $B_{\min}$, in a thin longitudinal medium is approximately

$$B_{\min} \cong \pi \sqrt{0.35 a_{WC}^2 + \left(\frac{D}{2}\right)^2},$$

where D is the particle diameter and a_{WC} is the Williams–Comstock transition width parameter. In SI units, a_{WC} can be expressed as [13, 14]

$$a_{WC} \approx \frac{(1-S^*)(d+t/2)}{\pi Q} + \sqrt{\left[\frac{(1-S^*)(d+t/2)}{\pi Q}\right]^2 + \frac{M_r t(d+t/2)}{\pi Q H_C}}.$$

Here, d is the head–media spacing, t the medium thickness, M_r the remanent magnetization, S^* the hysteresis squareness, Q the head-field gradient, and H_C the medium coercivity. H_C is proportional to the medium anisotropy field H_a and can be approximated for an imperfectly oriented medium at recording timescales by $0.5H_a$ or K_U/M_s, where M_s is the saturation magnetization [15].

Using the above equations, we can estimate the minimum bit length for longitudinal recording as a function of medium thickness, head–medium spacing, coercive field, and medium saturation magnetization. **Figure 3** presents the minimum bit length achievable, assuming a maximum coercive field of 5,300 Oe (corresponding to B_s of 20 kG, 80% usable deep gap field, and $H_C =$ one third of the deep gap field to account for head–medium spacing), and a saturation magnetization of 550 emu/cc. These values correspond to a required particle anisotropy constant of 2.9×10^6 erg/cc and a particle diameter of at least 12 nm. It also indicates that at a head–medium spacing of, for example, 20 nm, longitudinal media can sustain a linear density of 800 Kb/in if the medium is no thicker than 15 nm.

For such a linear density and a medium thickness of 15 nm, the minimum bit area is 32 nm × 380 nm, assuming 100 particles each of 12-nm diameter per bit with a 50% volume packing fraction. Adding a 50% margin to the track pitch to account for servoing error and dimensional stability yields a track density of 45 kilo-tracks/in, and a maximum areal density of 36 Gb/in^2, in agreement with earlier projections [16]. To achieve 100 Gb/in^2 areal density with a linear density of 800 Kb/in, the track density needs to be 125 kilo-tracks/in, corresponding to a minimum bit area of 32 nm × 135 nm (having removed 50% of the track width to account for track-following error) or $N = 36$ particles of 12-nm diameter with a 50% volume packing fraction. This corresponds to a loss in SNR of 4.5 dB compared to the $N=100$ particle case, in which SNR is defined as $20 \log(N^{1/2})$. This loss in SNR would need to be compensated for by improving signal processing. Other routes to an areal density of 100 Gb/in^2 with longitudinal media have been proposed, and these place even more constraints on track density or head–medium spacing [3, 10, 17].

Though theoretically possible, achieving a linear density of 800 Kb/in appears to be extremely challenging with longitudinal recording. In order to achieve such high linear densities, migration to perpendicular recording may be a more attractive alternative. In perpendicular recording, the magnetic orientation of the data bits is aligned vertically, that is, perpendicular to the tape. In this orientation, smaller particles can be used. Also, demagnetizing fields for perpendicular recording actually favor high linear densities, and thicker films could be used for thermal stability. For HDDs, 1,500-Kb/in linear densities have been demonstrated, using pole heads and perpendicular media with a soft underlayer [18].

Achieving 800-Kb/in linear density on tape will require very thin coatings, probably containing only a monolayer of particles. In order to achieve low noise for small bit sizes, the particles must be magnetically isolated but packed closely and uniformly with their neighbors. Uniformly sized spherical particles would enable the easiest packing, and recently there has been much success in synthesizing nanoparticles and arranging them uniformly on surfaces [19, 20]. Using these particles in magnetic tape will require inexpensive synthesis as well as a rapid method for coating them uniformly on the tape, which is now approaching 1 km in length. One alternative to particles requires the formation of thin magnetic films using vacuum deposition. Evaporated metal films have already been introduced in tape products [2] and have the advantage of being deposited at a high rate and of using inexpensive metals. Sputtered metal films have been successfully developed for HDD and have the potential for much larger areal density. Such technology would need to be transferred to tape media in an economically viable solution, which may be possible but remains challenging [21, 22]. In summary, sputtered magnetic films are a promising approach for tape, but optimized particulate and evaporated metal films may still have the potential to achieve a 100-Gb/in^2 areal density.

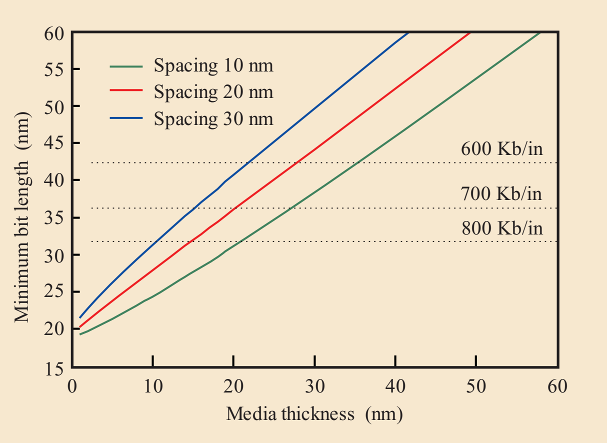

Figure 3

Minimum bit length versus medium thickness calculated for three different values of head–medium spacing. H_c = 5,300 Oe, M_s = 550 emu/cc, Q = 0.8, S^* = 0.8. With these values, the maximum particle anisotropy equals 2.9×10^6 erg/cc, and the minimum particle diameter for magnetic stability equals 12 nm.

Write and read heads

Unlike heads in disk drives, magnetic recording heads in modern tape drives employ arrays of transducers operating simultaneously to enable high-speed writing and reading. A multiplicity of transducers is needed because compared to disk drives, tapes move slower (3–6 m/s for tape versus >14 m/s for disk), and data is recorded to tape at 2 to 3 times fewer bits per inch due to the magnetic coating characteristics described in [23]. Multiple parallel transducers also facilitate writing or reading of an entire ½-inch tape cartridge within 2 to 3 hours. This has not changed significantly since tape cartridges were introduced more than 20 years ago. However, a paradigm in which the data rate does not scale with capacity necessarily increases fill times (i.e., time to write the full capacity of the cartridge) in the future. The large investment in cartridges and automation in modern tape libraries and the need to maintain a cost advantage over disk-drive libraries provide a strong incentive to preserve the existing ½-inch-wide tape and cartridge formats. Thus, a challenge involves increasing areal density and ½-inch tape cartridge capacity while preserving or molding customer expectations for backup and restore times.

A cartridge containing a 1,000-m-long tape, recorded at 100 Gb/in^2 has a capacity of more than 100 TB, more than 100 times that of LTO-4 tapes. Given 32 active write heads, which is the current maximum in a drive (Sun

Figure 4

Schematic of a magnetic write head, showing 2 of 16 write transducers. The yokes are sectioned to show front and back gaps, yoke length, and coils. The spacing between transducers in this exemplary view is less than the LTO spacing of 166.5 μm, which would permit only one device to be displayed in this figure. (Coils are red, and yokes are in green, blue, and purple. The back gap occurs where the green and purple meet inside the coil. The front gap occurs where the green and purple meet in front of the coil.)

Microsystems T10K tape drive), and 60,000 data tracks, a simple calculation shows that 1,875 one-way passes (i.e., moving the tape from beginning to the end) would be required to fill this cartridge. A tape speed of 5 m/s corresponds to more than 100 hours. This challenge could force a change in backup management strategy. Doubling both tape speed and the number of channels reduces this time to 25 hours, still outside what is acceptable today. Increasing the tape speed has its own challenges, the most serious of which may be the burgeoning per-channel data rate. There is still an ongoing need to increase the number of active channels regardless of tape speed. However, simply increasing the number of active transducers is not sufficient for scaling to 100 Gb/in^2. As explained below, transducer dimensions must shrink to enable writing smaller tracks and higher linear densities. In addition, the span occupied by the transducers must shrink to accommodate transverse dimensional stability, which may improve only to about 400 ppm from 800 ppm today. Thus, more transducers will have to fit into a smaller span. The "span" is the distance from the read element at one end of the head array to the read element at the other end of the head array.

Consider the span of transducers in an LTO head, which is composed of two symmetrical halves called *modules* (two modules are needed for read-verifying data in real time as it is written, see [23]). Each module contains 16 write, 16 read, plus 2 or more dedicated servo-track read transducers. The write and read transducers are piggybacked (i.e., the write transducer is on top of the read transducer), as in disk heads, and the pitch (i.e., the space between adjacent write–read pairs) is 166.5 μm. The span between outermost pairs is $(16 - 1) \times$ 166.5 μm, or ~2,500 μm. A cross-section schematic of a pair of write transducers is shown in **Figure 4**. A transducer-to-transducer spacing that is closer than the spacing in LTO was chosen for this figure in order to display more than one writer and thus emphasize a key difference between tape and HDD heads, which have only a single write transducer (*transducer* and *writer* are used interchangeably in this context). A 400-ppm environmentally induced change in tape width between writing and subsequent read back could produce up to 0.5-μm misregistration between an ideal head and the tape, or ~2.5 times the track spacing projected for 100-Gb/in^2 areal densities. Thus, a threefold active-elements span reduction will be needed. Since at least 64 active channels will be required, transducer centerline spacing must decrease to ~14 μm, as shown schematically in **Figures 5(a)** and **5(b)**. **Figure 5(c)** shows an exemplary LTO write transducer. At this spacing, writers may interfere, or produce *crosstalk*, a phenomenon in which current in one write transducer alters the current in its nearest neighbors. A design requirement should ensure that writer yokes must not saturate, particularly in the portion wound by the coils (called the *back-gap region*), as this can divert stray flux into neighboring write gaps. Thus, high-B_s pole materials and wide back gaps (wider than top pole) are preferred. Writer poles in the range of 0.5–1.0 μm may be used to *shingle-write* a 0.2-μm residual track. With a shingle-write, the final written track width is not determined by the writer width but by the slight overlap of the adjacent written track. A 1.0-μm-wide write pole would have approximately a 2-μm back gap. This leaves a space between neighboring write yokes of ~12 μm, enough to accommodate two coil turns on a 1.75-μm pitch, which is within the capabilities of current thin-film microfabrication technology [see Figures 5(a) and 5(b)]. Crosstalk effects due to coil proximity may be tolerable. In any case, traditional design methodology would suggest that coils in heads at this pitch will be limited to between two (one-layer) turns and six (three-layer) turns.

To help orient the reader in studying Figure 5, note that the current channel pitch shown in Figure 5(c) is 166.5 μm, as compared to 14 μm for future heads. The current write width of 12 μm is contrasted with 1 μm for future heads. The current yoke length of 25 μm is reduced significantly to 8 μm in future heads. The back-gap width of 24 μm in current heads is contrasted with 2 μm in future heads.

Restricting tape-head coils to two to six turns poses challenges. Whereas disk heads may have only 3 to 5 coil turns, tape heads typically have 8 to 14 turns. The reason for this is as follows. In disk drives, current-mode write drivers are mounted on the actuator arm in close proximity to the head. Cable impedance is not critical, and more than 100 mA can be supplied to the head, enabling fewer turns (the writing field is proportional to the number of turns times the current). In tape systems, write driver chips are located at the stationary end of the cables, that is, on the circuit boards with other drive electronics, due to heat, space, row-access-strobe latency, and other restrictions. Cables must be sufficiently long to allow heads to access the entire tape, and so cable impedance becomes critical. As a result, a voltage mode must be used, reducing the maximum write current and raising the minimum number of coil turns. Operating in the lowest possible write driver voltage range helps. This enables use of smaller series write resistors but requires lower cable impedance, which ultimately affects the minimum acceptable turns count. Impedance matching also helps, and while a 10 to 90 rise time is smallest in this case, up to 50% overshoot has been used in tape and disk products, even though the reasons for overshoot are different. The relationship between overshoot and error rates, especially for thinner and nonoriented tapes, is a subject of active discussion [24]. Another consideration is that lower write voltage enables lower power dissipation, especially important for 32 or more active write transducers. This lowering of write voltages is a likely future trend, regardless of the number of coil turns. In summary, six coil turns is an aggressive lower bound for the turn number. Accordingly, though challenging for technologists, the 14-μm scaled transducer pitch is still possible. Writer crosstalk may affect minimum achievable pitch. Another factor that could affect write-head coil turns is electromigration, which places a limit on maximum acceptable current. Over time, higher media coercivity will demand larger head fields, which for a given design demands larger magnetomotive force, usually specified in units of amp-turns. However, media coatings will become thinner, enabling the use of smaller write gaps, thus resulting in higher head efficiency and helping to alleviate the current demands.

A trend in write-head design has been the reduction of writer yoke length. Scaling the present 25-μm yoke length to less than 10 μm will be required. Pancake coil heads (i.e., with coils having the shape of a pancake, with the turns arranged in the form of a flat spiral) have the advantage of coil-turns stacking, but as described above, a 14-μm pitch would accommodate at most two coil turns per layer. Thus, an eight-turn head would require at least four layers, which would be complex to fabricate and could still have a longer than desired yoke because of the height of the coils stack. An alternative approach is to build tiers of writers on two or more planes. Two tiers enable the building of writers in each tier on double the pitch otherwise required. However, this approach has device yield and tier-to-tier alignment challenges. Further, tiers are associated with a wider mechanical gap, that is, the gap of thin films residing between the hard ceramic portions of the head [23], leading to greater susceptibility to wear-induced gap recession. Alternatively, helical ("barber pole") coil transducers have a spacing advantage, but a 1.8-μm coil pitch would accommodate only five helical coil turns with a 10-μm yoke. This is problematic for the reasons cited above.

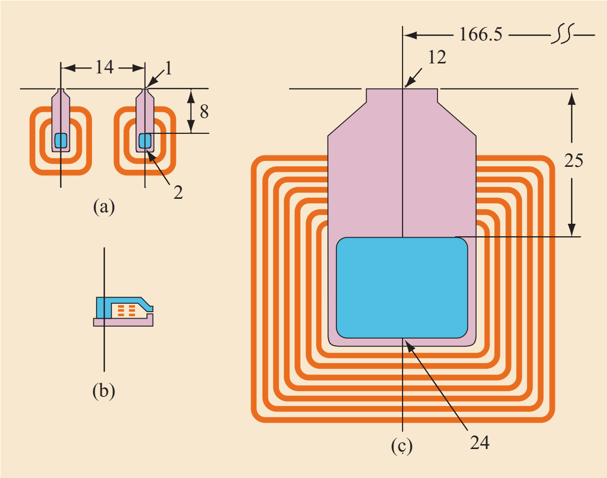

Figure 5

Future and current write heads compared. Channel pitch, write-pole width, yoke length, and back-gap width are shown in microns. (a) A depiction of a future write head at the same scale having three layers of coils, with two turns in each layer. The pitch between transducers is only 14 μm, thus enabling 64 writers (four times the number of writers in LTO drives) to fit in one-third the LTO span. (b) Cross-section of (a). (c) Schematic drawing of an exemplary LTO write transducer, having two layers (one shown) of coils, with seven turns in each layer. The pitch between transducers is 166.5 μm; thus, only one transducer fits in this figure.

Scaling read heads for 100-Gb/in^2 areal densities is less about achieving small centerline pitches, which have been successfully demonstrated as small as ~15 μm, than it is about maintaining sufficient output signal. Read-head output is preferably at least 1 mV, or about ten times above any non-medium-related electronic noise, including the Johnson noise voltage in the sensor itself ($V_n \sim [4k_B TR\Delta f]^{1/2}$, where T is temperature, R is resistance, and Δf is the frequency bandwidth over which the noise is measured). At 100 Gb/in^2, the width of the read heads approaches 0.1 μm or less, and the read heads have an even smaller shield-to-shield spacing. For anisotropic magnetoresistive (AMR) heads, sensing layer resistance change, measured as $\delta R/R$, is ~0.023. R is proportional to $W_{\mathrm{MR}}/(t_{\mathrm{MR}}h_{\mathrm{MR}})$, where W_{MR} denotes the sensor width, t_{MR} the thickness, and h_{MR} the height, and thus the decline of W_{MR} may be opposed by reducing the sensor-free layer thickness t_{MR}. However, for thickness less than ~13 nm, the output no longer rises inversely with thickness, because of the relative contribution of electron scattering at the free layer surfaces; resistance increases, but δR does not by the same proportion. Thinner media (even assuming we can overcome the challenge of making $M_r t$ small) and reduced shield-to-shield spacing, which is required for reading shorter tape wavelengths that accompany high linear density, lead to reduced signal amplitude. Increasing sensor bias current to offset declining amplitude raises temperature. As temperature increases, tape asperity cooling noise also increases. Also, the ratio of signal to sensor Johnson noise becomes reduced. Giant magnetoresistive (GMR) sensors have about five times higher sensitivity and are required for reader widths of less than ~4 μm for the reasons cited. GMR sensors are expected to appear in the first terabyte cartridge products. However, GMR sensors do not have enough sensitivity for scaling to 100 Gb/in^2. Tunneling magnetoresistive sensors, currently in use in HDDs, will be required for maintaining 1-mV output for 0.1-μm-wide read heads.

Planar head technology, in which transducers are fabricated with the critical recording gaps orthogonal to the wafer surface, is promising. Accordingly, planar magnetic heads are not sliced and lapped like conventional disk heads. Planar technology enables staggering writer arrays for reducing the effective pitch between elements. This may lead to fabricating adjacent track bundle writing arrays, which is not feasible with conventional processes. In the absence of dynamic tape skewing, adjacent track bundle writing does not experience an unwanted wavy track effect, in which residual shingled track widths vary down the length of the tape. To date, planar write heads have been successfully fabricated, but planar read-head fabrication processes have yet to be developed. This relates to another challenge. A requirement for high-density recording is accurate track placement. Ideally, this is achieved using servo readers proximate to the writing transducers. For example, servo tracking via readers in the writing module was first implemented in the IBM LTO-2 product and is referred to as the "same-gap servo," as the servo readers are in the same physical gap as the active writers. Since there are no planar readers, this writing mode is not possible yet. Another challenge for writing using staggered arrays is detecting and controlling tape dynamic skewing during writing. Again, planar readers will be needed.

In the quest for scaling to 100 Gb/in^2, there is opportunity for improving the reading process itself. For example, arrays of readers may be configured for electronic track following, in which readers may bridge into neighboring tracks during read back. Note that by having several readers per track, such that a few bridge into the neighboring tracks, the signal may be deconvoluted electronically rather than requiring precise mechanical control over the path of the reader. Another opportunity relates to the separation between head modules [23]. This spacing enables isolating writers from downstream readers, which are on for read verification during writing. However, similar to the case of staggered arrays, this spacing increases susceptibility to tape-skew-induced mis-tracking between readers and writers. Simply reducing module separation does not work well, not only because of the isolation requirement but also because of head-building constraints. Thus, some form of dynamic skew compensation will be required for achieving 100-Gb/in^2 areal density.

Head–tape interaction

The head–tape interface must be designed to achieve a small magnetic spacing while minimizing head–tape forces, wear, and chemical degradation of the magnetic elements.

In tape recording, a critical problem is signal degradation due to spacing loss as the magnetic elements wear down as much as 40 nm below the plane of the bearing surface. This is unacceptable for 100-Gb/in^2 areal density. A protective diamond-like carbon (DLC) coating is used on HDDs and metal-evaporated tapes, but not on metal-particle tapes or linear tape drive heads, where the coating would be worn away. Because head material choices are limited by magnetic, chemical, and physical requirements, designing for wear resistance has largely been unfruitful. Perhaps smoother future media will lead to less head recession. Reducing the head closure gap can further reduce head recession.

If head recession can be reduced to 10 nm, the 20-nm magnetic spacing required for 800-Kb/in linear density can be achieved only if the tape roughness is less than 10 nm. Decreasing surface roughness increases real contact area, leading to higher adhesion and frictional forces [25]. The static friction to start the tape, called *stiction*, is often much higher than the friction during operation. When the tape is stopped, stiction increases as the tape deforms into local contact with the head, and liquids condense or migrate to the contact. Of course, stiction cannot be so high that it damages the tape or stalls the tape drive. More fundamentally, variations in a high running frictional force can distort the tape laterally, impairing tracking and distorting the track spacing, or longitudinally, distorting the signal timing. To improve volumetric storage density for a given areal density, the thickness of the tape should be reduced, which further increases its sensitivity to these problems. Thus, there is a fundamental conflict between the requirements of high linear density and unperturbed tape motion.

In tape drives, air bearings are not used at the read and write elements, because the head–tape interface cannot be controlled as well as the head–disk interface. The tape surface cannot be made as smooth as a disk, and the fast-moving tape generates many particles that can clog the air bearing. In modern tape drives, the tape is in partial contact with the head, supported by the tips of the asperities associated with the tape roughness. The sharp leading corner of the head keeps particles from the interface. Loose particles are brushed from the head during tape loading. A mildly abrasive cleaning tape occasionally removes any adherent debris. Excess mobile lubricant is absorbed in the tape underlayer, forming a reservoir for replenishing the tape surface. On the smooth flexible tape surface, the friction can become large even at zero-applied normal load, because the surface energy of the interface pulls the head and tape into contact. Protruding asperities tend to hold most of the tape surface away from the head, but the overall attraction of the tape surface partially flattens these asperities, in turn leading to greater attraction. Thus, adhesion and attraction increase quite rapidly as the roughness is decreased to maintain a small spacing between the head and the tape.

Mobile liquids on the tape surface also contribute to attraction and increased friction. Liquids with contact angles less than 90 degrees tend to wet the area around an asperity contact, bridging the several-nanometer-wide gap between the head and tape near the asperity. The tape is attracted to the head because the total surface energy decreases as the surfaces move closer and wetting increases. Mobile lubricants contribute to this problem, as does water condensed from the atmosphere. Between surfaces wet by water, at 80% humidity, condensation can fill a 4.6-nm gap. This humidity sensitivity can be prevented by selecting tape, head, and lubricant systems having water contact angles more than 90 degrees.

Friction thus becomes problematic with increasing areal density. The fundamental problem is that as the surface profile is scaled down to decrease the magnetic spacing, the energy required (per nominal surface area) to deform the surface to flatness and to increase friction decreases, whereas the energy available from surface interactions remains constant.

One strategy to reduce the head–surface contact and resulting friction is to minimize the size of the head. For example, for the head design used by IBM, the entire length of tape contact is only 1.2 mm [26]. However, this length cannot be reduced much further while maintaining close head–tape spacing. Careful microscopic design of the head–tape interface is thus essential. For example, to ensure that the valleys of the tape surface are no further than the 10 nm (specified above) from the contacting tape peaks, the RMS roughness of the tape surface must be no larger than 1.7 nm. The bulk Young's modulus of a particulate tape coating is about 10^{10} N/m^2, which makes the tape sufficiently flexible for the surface topology to deform completely into contact with the head, even for small surface energies, in the absence of liquids.

This problem can be avoided by incorporating hard (e.g., alumina) particles, which are $\sim$0.2 μm, into the medium. These particles protrude from an otherwise flat medium to support local head contact. Until recently, the main role of such particles was to clean debris from the head. The sharp particle radius ensures a weak attraction to the head, but the particles are sufficiently large to distribute a large head force over the surrounding medium. An average spacing between contacting asperities of 10 μm imposes a low enough load/particle to prevent plastic deformation of the medium around the head. The protrusion heights of the particles need to be uniform so that a high fraction of the particles support the head. Otherwise, the required high particle density will cause many local magnetic dropouts. This scheme can successfully support the magnetic media within 10 nm of the head without generating strong attraction and friction.

We conclude that it is feasible to design a head–tape interface that will support 100-Gb/in^2 areal density.

Data detection

Achieving the areal recording densities discussed in this paper poses significant challenges in terms of read-channel design. The main challenge is to ensure highly reliable operation of all front-end analog and digital signal-processing functions, including adaptive equalization and gain and timing control, despite significant reductions in the available SNR values.

At high areal densities, read channels also need to rely on powerful data-detection methods to guarantee post-detection symbol error rates that are sufficiently low. Noise-predictive maximum-likelihood (NPML) sequence detection [27] is well suited to address these performance requirements. For example, the class of NPML detectors, with target polynomials $(1 - D^2)W(D)$, where $W(D)$ represents a noise whitening filter and D a delay operator, has been implemented successfully in HDDs and is also attractive for tape systems. At high linear densities, NPML schemes achieve a better match between the detector target and physical channel characteristics than, for example, extended partial-response class 4 (EPR4) schemes. Moreover, the NPML schemes whiten the noise process (i.e., make the noise have a flatter frequency spectrum) at the detector input and also reduce its power. Another important aspect of tape systems is the inherent variability of the recording channel, which is due to cartridge exchange, variations in the read- and write-head characteristics, nonstationary noise processes, and other factors. This aspect can best be dealt with by employing a detector target that automatically adapts itself to the current channel characteristics. Such a feature is enabled by the class of NPML targets mentioned above.

NPML detection can be extended further to take into account the data-dependent nature of the noise process. It is, for example, well known that surface roughness in tape media introduces a type of noise that is colored (i.e., with a non-flat frequency spectrum) and data dependent. Data-dependent NPML detection allows one to achieve the best detection performance in the presence of such noise processes, which can be the predominant contributors to the total channel noise. In conjunction with advanced coding, these techniques could provide the additional 4.5-dB noise margin that is needed to achieve the 100-Gb/in^2 operating point.

Format efficiency

To make efficient use of the magnetic recording channel and thus achieve reliable read-back operation of the user data, the bit stream written onto the magnetic medium includes redundancy and synchronization patterns. The specification of this overhead data is referred to as *formatting* or *data format*. The goal of an efficient format is to introduce as little overhead as possible while ensuring proper operation of the data acquisition and timing loops and meeting the 10^{-17} bit error rate requirement of tape recording systems. Clearly, improvements in format efficiency directly lead to higher cartridge capacity.

The format efficiency of current tape-recording systems such as LTO-4 is about 71.6% [9]. The 28.4% overhead of LTO-4 can be broken down into about 17% for error-correction coding (ECC), 5.5% for modulation coding, and about 5.9% for sync patterns and encoded data headers. There are several ways to improve format efficiency. One approach is based on using longer ECC codes of higher rates, resulting in about 4% gain without sacrificing error-correction performance. Higher efficiency, however, is achieved by another approach, which relies on reverse concatenation (RC), and has already been effectively implemented in HDD products.

In a standard forward-concatenation scheme, user data is first ECC encoded and then passed through a modulation encoder to enforce predetermined modulation constraints for timing and efficient data-detection purposes. In an RC scheme, the order of the ECC encoder and modulation encoder is reversed [28]. This reversal of the encoding order provides three major benefits: 1) There is no error propagation through the modulation decoder; 2) because error propagation is not a concern, the first modulation code can be taken to be very long, allowing the use of capacity-efficient and high-rate modulation codes and thereby resulting in code rate gains; 3) in the read-back path, the ECC decoding block comes immediately after the channel-detection block, which can readily pass tentative decisions to the decoder on a bit-by-bit basis. The placement of the ECC decoding block creates the appropriate framework for using novel ECC techniques, which are based on turbo and low-density parity-check (LDPC) codes and may provide significant performance improvements [29].

These three benefits can also be exploited in the framework of tape recording. However, the ECC used in HDDs has a different structure from that used in tape recording. Previously, RC has been proposed for one-dimensional ECC architectures, for which the ECC typically consists of a single code such as a Reed–Solomon or an LDPC code [30, 31]. These RC architectures cannot be directly applied to two-dimensional ECC in tape systems, which are based on Reed–Solomon product codes with a C1 code along rows and a C2 code along columns. To overcome this problem, a novel RC scheme is proposed, which is illustrated in **Figure 6**. The main steps in the write path are as follows: 1) user data is reorganized into a stream of N_2 rows by the serial-to-parallel function (represented by the S/P block), 2) modulation encoding of each row is accomplished by the first modulation encoder ME-1, 3) formatting is performed for partial symbol interleaving, 4) C2-column-dependent encoding is performed, 5) C1 encoding is performed along rows, and 6) modulation coding of the C1 parity is performed by a systematic modulation encoder ME-2.

A key component in the proposed RC scheme is the first modulation code, for which one may select a very high-rate $n/(n+1)$ Fibonacci code, typically $n > 200$ [31]. These codes involve simple enumerative encoders and achieve very restrictive modulation constraints, which are comparable to those of the LTO-4 standard. Modulation constraints avoid the writing of sequences for which the overall detection process would be less reliable (i.e., they avoid unfavorable timing patterns, reduce path-memory length in sequence detectors, and avoid quasi-catastrophic error propagation). Another specific feature of the RC scheme is the formatting block, which transforms the modulated user data array into an array with "empty" components in each column, which are the locations in which the parity symbols of the C2 code will be introduced.

The new RC scheme has a modulation method with less than 1% redundancy while maintaining essentially unaltered modulation constraints. This improvement in rate is more than 5% above the rate-16/17 code of the LTO-4 standard and, together with the 4% potential gain from longer C2 codes, leads to an overall format with an overhead of about 18% rather than the 27% of LTO-4. This represents a substantial reduction in redundancy. Furthermore, by using an LDPC code or turbo code for C1, the new format supports novel ECC techniques based on iterative decoding. The C1/C2-based ECC structure is an ideal setting for LDPC or turbo codes because the typical error floor issue (in which the correctable error rate is not sufficiently low) of these codes is resolved by the C2 Reed–Solomon code, which can reduce the error rates to the desired 10^{-17} level.

Track density limits

Track misregistration

Track misregistration (TMR) limits the allowable track pitch that can be written on tape. To achieve 100 Gb/in^2 with a linear density limited to 800 Kb/in will require a track density of 125 kilo-tracks per inch or 0.2-μm written tracks. To a first-order approximation, if we assume the reader width to be 0.13 μm, the TMR, which is defined here as the difference between the track pitch and the reader width, must be less than 70 nm. Various factors contribute to TMR, including the dimensional variability of the head, track-following fidelity, and the transverse dimensional stability (TDS) of the tape.

Because multiple heads are used in parallel, lateral expansion and contraction of the tape contributes to TMR. Achieving 100-Gb/in^2 areal density, or equivalently 100 TB in a tape cartridge, will require a tape that can be written in one environment, appended to in a second environment, and read in a third environment. This imposes severe dimensional-stability constraints. Currently, the substrate is stretched in the machine direction and transverse direction to thin the tape to facilitate high volumetric density and to increase its modulus for easier coating and better performance. However, this process complicates and degrades the TDS. Current media exhibit a lateral dimensional change of 750–800 ppm over the full environmental variation, and improvement beyond 500 ppm is unlikely. At this level, dimensional stability can be accommodated by reducing the head span by a factor of 3, as discussed above.

Tape paths for high track density

Lateral tape motion (LTM) must be significantly improved to achieve higher track densities. In high-performance drives, rolling elements transport the tape between reels and limit LTM. Continued use of rollers requires the prevention of debris accumulation on the roller flanges, which strikes the tape edges, causing LTM. This LTM disturbance often exceeds the bandwidth and slewing capability of the track-following actuator. Debris accumulates because the spacing between the two reel flanges is much larger than the roller flange spacing. Tape tends to stack against the reel flanges, so that when it is transported from a reel to the first roller, a large force develops between the tape edge and the roller flange, causing wear and debris accumulation.

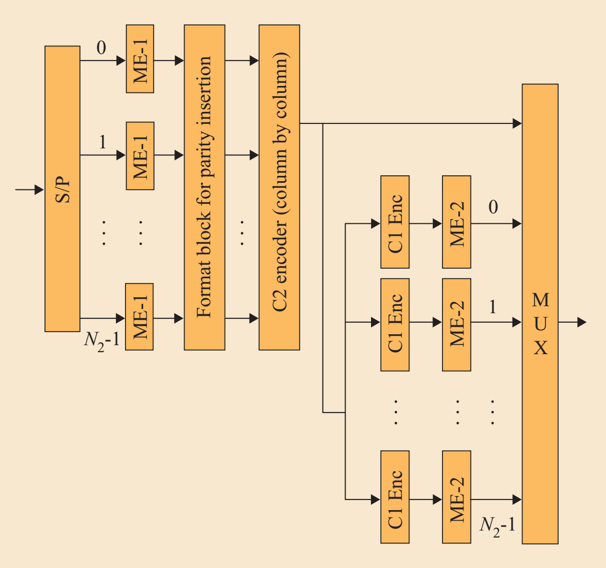

Figure 6

Reverse concatenation architecture. (S/P: serial to parallel; Enc: encoder; MUX: multiplexer.)

One obvious solution to this problem is to remove the flanges, but this introduces other challenges. First, without the constraint of the flanges, LTM increases as the tape moves up or down between the widely spaced reel flanges. Second, the angle of the tape with respect to the head can become skewed. These additional challenges can be addressed by constructing a more advanced actuator, capable of following a larger LTM and of servoing its rotation angle to keep the head perpendicular to the tape. In addition, actively controlled tilting elements elsewhere in the path may be used to reduce skew and lateral excursion.

By implementing these and other advancements, track-following can be improved significantly. Experimental paths incorporating flangeless grooved rollers have achieved a position error signal (PES) with a standard deviation σ_{PES} as low as 61 nm, using a legacy servo channel. Although this represents a substantial improvement, we anticipate that an even larger reduction of σ_{PES} will result from improved detection of the position and velocity information, larger actuator bandwidth, and improved control of the reel-to-reel servomechanism.

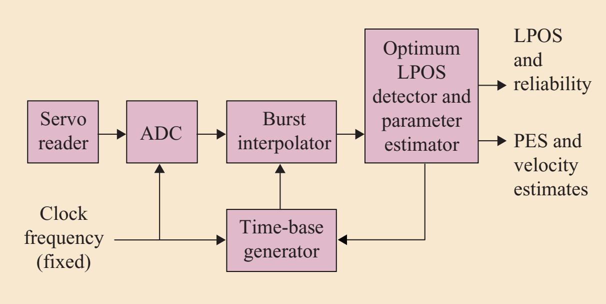

Figure 7

Block diagram of a synchronous servo channel. (ADC: analog-to-digital converter; LPOS: longitudinal position; PES: position error signal.)

Synchronous servo channel

Timing-based servoing (TBS) is a technology developed specifically for linear tape drives in the mid 1990s [32], and it has been adopted as an LTO standard. In TBS systems, recorded patterns to aid track-following servo consist of transitions with two different azimuthal slopes. The lateral position is derived from the relative timing of pulses generated by a narrow head reading the pattern. TBS patterns also enable the encoding of additional longitudinal position (LPOS) information without affecting the generation of the transversal PES. This encoding is obtained by properly shifting transitions from their nominal pattern position, using pulse-position modulation (PPM). In tape systems, two dedicated servo channels are normally available, from which LPOS information and PES can be derived. To achieve small σ_{PES} values, advances in the servo-channel architecture are required that include the following three main functions: 1) optimal matched-filter detection of servo bursts, 2) optimal demodulation of LPOS symbols, and 3) generation of a fixed number of signal samples per unit of length of tape, irrespective of tape velocity. An experimental fully synchronous servo channel [33], which implements the aforementioned functions, has been realized in a prototype drive system.

Figure 7 shows a block diagram of a synchronous servo channel that relies on a digital interpolator to generate a fixed number of signal samples per unit of length of tape, independent of velocity. A digital dibit correlator approach is employed for optimal detection of PPM signals in the presence of noise and for the computation of estimates of tape velocity and lateral position. In addition, a reliability measure is assigned to the detector output to monitor the quality of the servo channel.

The synchronous servo-channel concept was implemented in a field-programmable gate array (FPGA) and tested in a prototype environment. The performance of the system has been evaluated during real-time operation with servo-channel output samples taken directly from a tape drive. With this experimental setup, a σ_{PES} significantly lower than that obtained with a legacy servo channel has been measured, using the servo patterns with azimuthal slopes of 6 degrees, as specified in LTO-4. The measured σ_{PES} can be further decreased to a projected value of 10 nm by jointly optimizing the azimuth and spacing of the written transitions in the servo patterns as well as the width of the servo reader.

Reel-to-reel control

One of the main advantages of tape-based storage systems is their ability to achieve a very high volumetric density by winding a very long tape on a single reel. To further increase the tape cartridge capacity, both areal and volumetric storage densities must be improved. High areal densities require excellent tape motion and tension control because the quality of the tape transport directly affects the data write and read performance. Moreover, higher volumetric densities require thinner magnetic coating and tape substrate, which in turn may lead to reduced TDS and a larger susceptibility to tape damage. In order to counteract these effects, an adequate design of the reel-to-reel servo system for tape velocity and tension control becomes increasingly important.

For the tape transport system mentioned above, which requires simultaneous control of tape velocity and tension, a departure from standard proportional-integral-derivative (PID) controllers and the introduction of state-space-based methods are required. The main advantage of a state-space-based control system is its suitability for the design of a multi-input multi-output (MIMO) control system. A MIMO control design allows multiple inputs as required if information from multiple sensors and several estimated parameters need to be utilized. Another important feature of a state-space-based system is its capability of handling designs in which the rate of measurements from the sensors is not commensurate with the sampling frequency of the digital controller. The notion of a MIMO control system for tape transport was introduced in [34] and has been applied to a prototype tape-transport system in [35]. A MIMO architecture enables simultaneous control of tension and velocity, which in conjunction with an optimized tape path can substantially reduce LTM.

Important steps in defining the reel-to-reel control architecture include accurate characterization of the mechanical performance of the reel motor system, as well as the proper design of controller and estimator. One of the main challenges in using a MIMO system is the provision of reliable sensor measurements to determine the state of the system. There are various approaches that include embedded sensors as well as signal-processing

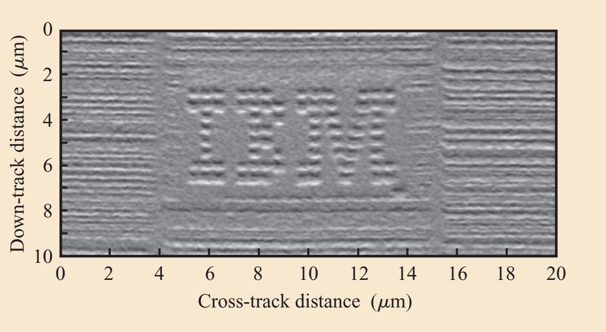

Figure 8

IBM logo written by high-density tape recording.

techniques to gather the necessary information to provide feedback of tension and velocity.

Example of high-areal-density recording

To demonstrate the potential extendibility of tape technology density, we have constructed an experimental apparatus for measuring the recording properties of tape media at high areal density. This apparatus precisely positions an HDD head with a narrow writer and reader to probe tape media at extremely small dimensions. As the head is moved along the tape, the bearing surface of the head is in contact with the tape surface, with the magnetic spacing being limited only by the tape surface roughness. Positioning is achieved with a Physik Instrumente (PI) P-587 six-axis piezoelectric nanopositioning stage, which achieves sub-10-nm accuracy, so that we have precise control over all degrees of freedom of the head–tape interface. The head writer width is 0.3 μm, and the giant magnetoresistive (GMR) reader width is 0.15 μm. In the example below, the tape particle length is on the order of 35 nm, resulting in a reader width of approximately five particles, so that we can probe the magnetic recording properties to the level of a few particles. To demonstrate the relative difference between HDD density and the large potential for improvement in tape technology, we have used a piece of LTO-4 tape in an experiment in this setup. The tape was prewritten in an LTO tape drive with a standard LTO-4 track width of 11.3 μm. **Figure 8** shows a grayscale image of the read-back signal from the GMR head on our high-density recording apparatus. White stripes correspond to positive transitions, and dark stripes correspond to negative transitions. A section of this tape was overwritten by the HDD write head in our high-density recording system to spell out the letters *IBM* and to fit them into a single tape track. Each letter consists of tracks parallel to the tape track direction, with transitions positioned to correspond to the horizontal stripes in the IBM logo. The tracks in the letters are written at a pitch of 0.5 μm, and the positive transitions are positioned at a period of 0.5 μm. Thus, for example, the letter *I* in "IBM," which consists of three parallel tracks, is 1.5 μm wide and, as there are eight horizontal stripes, is 4 μm long. The ratio of the track pitch of the LTO-4 tape to the track pitch of this HDD head on-tape example is greater than 22. In this experiment, the density of the letters is limited by the tape surface roughness.

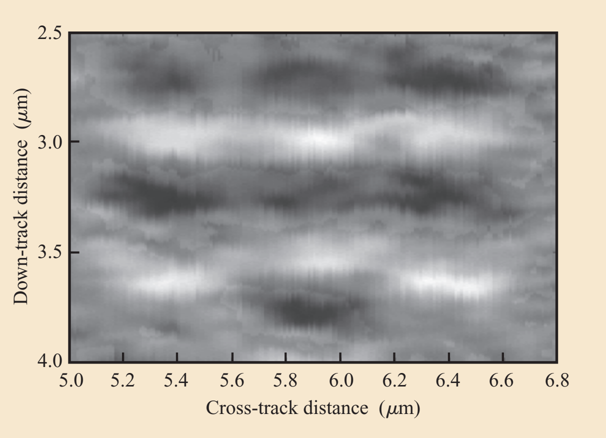

Figure 9

Large magnification image of the top of the letter *I* in "IBM."

Figure 9 shows a high-magnification image of the top of the letter *I* in the IBM logo, revealing that the transition position and shape are heavily modulated by the characteristics of the medium particles. The orientation, shape, packing, and even coupling between particles all affect the transition shape.

Conclusions

While it is clear that there will be significant challenges in scaling linear magnetic tape technology to areal densities comparable to current HDD technology, there appears to be a viable path toward this goal. Controlling the tape–head interaction will be key to achieving high linear density, while improvements in track-following and reel-to-reel servomechanisms as well as improvements in TDS and reduced-span heads will be key to achieving high track densities. In addition, advanced head- and data-detection technologies as well as improved LTM control will have an impact on both linear density and track pitch and, therefore, will be key enablers to achieving ultrahigh areal densities in a linear magnetic tape system. Through the combination of these technologies, a linear density of 800 Kb/in and a track pitch of 0.2 μm appears feasible, leading to an areal density of 100 Gb/in^2.

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