INVITED PAPER

Magnetic Tape for Data Storage: An Enduring Technology

Tape provides long shelf life at low cost, and recording density continues to rapidly increase while robotic tape libraries reduce access times to data.

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ABSTRACT | Magnetic tape as used for data storage is reviewed. Attributes such as bit and track densities, tape cartridge capacities and data rates are discussed in terms of the growth seen over time together with future trends envisioned for tape. Tape has seen almost six orders of magnitude density increase since its introduction as a computer data storage device in the early 1950's with 1 Terabyte native capacity tape cartridges being introduced into the market. The recording methods and technologies used for tape data storage devices are outlined and tapes position in the storage landscape discussed. Most of the world's data is stored and archived on magnetic tape primarily because of its long shelf life and favorable cost factors.

KEYWORDS | Data storage; magnetic recording; magnetic tape

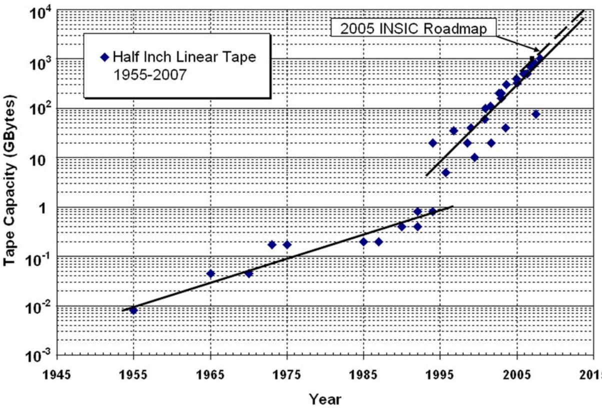

Fig. 1. *Tape capacity vs time for half inch wide tape using linear recording.*

I. INTRODUCTION

Magnetic tape recording for digital data storage has existed since the early 1950's when it became the first magnetic computer data storage device replacing the likes of paper tape and punch cards [1], [2]. The low cost (per Gigabyte) and high data reliability has made it the technology of choice for many applications where access times have not been an issue. Tape has tended to use mature technologies to assure reliability and thus has been behind the areal storage density growth curve seen in magnetic disk storage devices. This is compounded by the fact that tape is a removable medium (i.e. has to be read and written by many drives) and is based on a flexible substrate. Recently, capacities of single tape reels, cartridges or cassettes have accelerated from a few tens of Gigabytes (10^9 bytes) to a Terabyte (10^{12} bytes). Access times to data volumes have shrunk with the use of robotic tape libraries, which provide inexpensive, power miserly, huge data storage capacities: ~100 Petabytes (10^{15} bytes) and more.

The progression of tape reel/cartridge capacity is shown in Fig. 1. Five orders of magnitude gain in capacity over 50 yrs and almost 6 orders of magnitude in density [3]. Table 1 shows capacities and some recording details over time in 5 year increments with a projection for 2010. Fig. 2 shows the progress in areal density for 1/2″ wide linear data tape and helical scan tape the two primary architecture types. Fig. 3 illustrates these two methods of recording tracks on tape. Prior to 1995 linear tape filled the tape in one or two passes of the tape with tracks running parallel to the tape edge with a fixed head position. The jump in density and capacity seen in Figs. 1 and 2 is because of the introduction of track following servo allowing narrower tracks and multiple passes back and forth to fill the tape (so-called linear serpentine recording). In contrast, helical scan recording places the tracks at an angle to the tape edge using a head mounted on a rotating drum.

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Table 1 Capacity and Details of Magnetic Tape for Data Storage Over Time

	1955	1965	1975	1985	1995	2005	2010
Capacity (GB)	0.008	0.045	0.17	0.2	10	500	2000
No. of Tracks	7	9	9	18	128	760	1500
Areal Density (Mb/in^2)	0.001	0.029	0.11	0.76	24.9	400	1406
Linear Bit Density (kbpi)	0.10	1.6	6.25	21	86	214	370
Track Density (tpi)	14	18	18	36	289	1869	3800
Track Width (μm)	~1400	~1080	~1080	540	90	13	6
Data Rate (MB/s)	0.008	0.18	1.25	3.0	9	120	250
Media	γ-Fe_2O_3	γ-Fe_2O_3	γ-Fe_2O_3	CrO_2	MP	MP	MP
Coercivity, H_c (Oe)	300	300	350	550	1600	2400	2400
Media Thickness (μm)	64	50	50	38	9	7	7

The capacity and data rate from a tape drive is computed in bytes from basic parameters using the following simple equations [4]

$$\text{Capacity} = \frac{NbL\varepsilon}{8} \qquad \text{DataRate} = \frac{nbv\varepsilon}{8} \tag{1}$$

where $\boldsymbol{N}$ is the number of tracks, $\boldsymbol{b}$ is the linear bit density in bits/meter or bits/inch, $\boldsymbol{L}$ the length of the tape, $\boldsymbol{n}$ the number of parallel channels, $\boldsymbol{v}$ the tape speed and ε the efficiency of the recording format that takes into account any overhead due to the use of error correction codes and the like. A summary of today's tape product characteristics from various suppliers is shown in Table 2.

II. THE TECHNOLOGY

The tape media and recording heads have been key to the ongoing advancement of magnetic tape as a storage technology. Tape has been adopting the use of thinner magnetic coatings, narrow track stabilized magneto-resistive (MR) read devices and parallel arrays of thin film high moment pole write heads into the most recently available technologies. The most gain in areal density for tape lies in an accelerated increase in track density (tracks per inch, tpi) and linear bit density as seen in recent product trends (see Fig. 1, Table 2 and [5]). Gains in the linear density have been achieved by an improvement in the media (magnetic coating thickness and coercivity increase [4]) coupled with the introduction of advanced recording methods and channels as outlined below.

As mentioned there are two basic recording styles for tape in laying down tracks: helical scan, and linear. Helical drives typically have few recording elements but a high head to media speed whereas linear has many recording elements and a moderate head to tape speed. Older low tpi linear drives had used a single pass of the tape but the latest high capacity, higher tpi systems make multiple passes in both directions of tape in order to completely fill

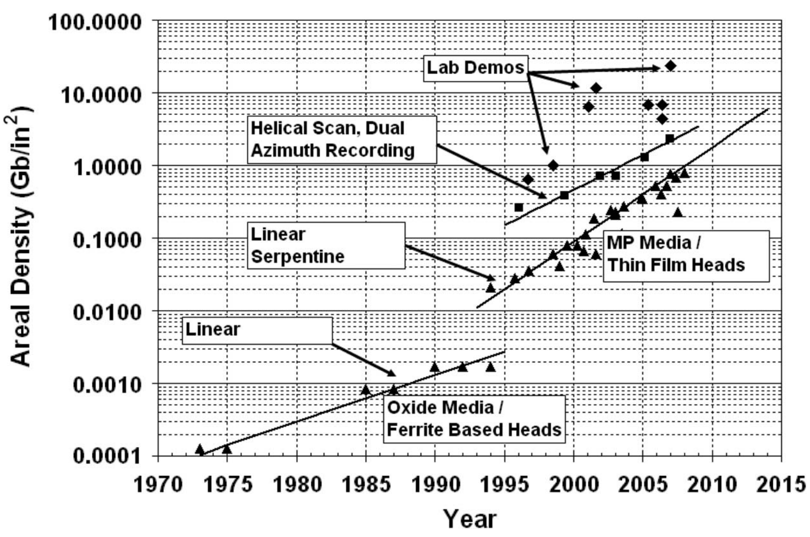

Fig. 2. *Tape areal density growth from the early 1970's to the present.*

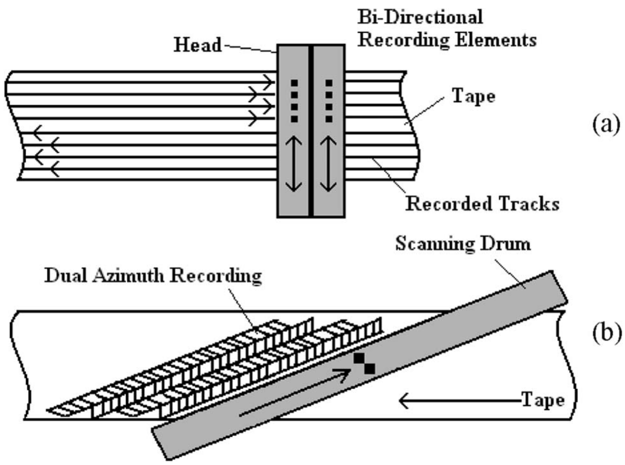

Fig. 3. ***Illustration of (a) linear serpentine and (b) helical scan recording.***

the tape with data. As the media structure is very thin and flexible, the read element width is driven to much narrower dimensions than the track pitch in order to stay on track, even with the implementation of track following servo control. This "write-wide/read-narrow" architecture is the norm in linear tape recording. The trend is such that the width of read elements are being quickly driven to very narrow dimensions and the use of advanced giant magneto-resistance (GMR) spin valve sensors will, as a result, probably appear in tape recording technology at much lower areal densities than that seen in magnetic disk drives.

In helical scan recording the use of two differing angles for the magnetic transitions on neighboring tracks (dual azimuth recording) allows a wider reader to be used as any excursion of the read head into an adjacent track does not reproduce the adjacent tracks recording due to azimuth losses [6]. This is the primary reason helical scan is ahead of linear recording in areal density as shown in Fig. 2.

III. TAPE MEDIA

Tape media is thin, flexible and comprises a polymer based substrate [7] coated with magnetic particles embedded in a polymer binder material or a magnetic film evaporated or sputtered on its surface. The tapes have become *very* thin ($< 10\ \mu$m, see Table 1) over time to satiate an increasing demand for capacity on a single reel or cartridge of tape of a given size (volume). Tape has exploited increasing the surface area to gain capacity with the constraints of moderate areal density gains and the need to retain interchangeable formats over long periods of time. The magnetic coating has properties such that in the direction of magnetic recording (longitudinal or helical) the hysteresis loop approximates a square shape, with a high enough coercivity (H_c) to support the density of recording desired (Fig. 4).

As the linear recording density (measured in kilo flux changes per inch, kfci) has increased over the years, the media coercivity has had to increase to support it [4]. Examples are γFe_2O_3 at 300 Oe and 6.25 kfci, CrO_2 at 550 Oe and 25 kfci and Metal Particle (MP) tape at 1600 Oe for 70 kfci and 2400 Oe for 120 kfci. The main features of today's typical tape media compared to magnetic disk are the substrate flexibility and the magnetic coating thickness. The coating thickness in tape has usually been much thicker leading to the recording only partially penetrating the magnetic layer. This in turn leads to significant spreading of

Table 2 Summary of Parameters for Tape Storage Devices

System	SUN T9840C	SUN T9940B	IBM 3592JA	QTM SDLT600	HP/IBM/QTM LTO-3	SONY SAIT	IBM TS1120JA	SUN T10000A	IBM TS1120JB	HP/IBM/QTM LTO-4	QTM S4	SUN T10000B
Capacity (GB)	40	200	300	300	400	500	500	500	700	800	800	1000
Data Rate (MB/s)	30	30	40	36	80	30	104	120	104	120	60	>120
No. of // Data Channels	16	16	8	16	16	6	16	32	16	16	16	32
No. of Tracks	288	576	512	640	704	-	896	768	896	896	1280	1152
Bit Density (kbpi)	163	157	282	233	245	155	282	214	282	328	256	284
Track Density (tpi)	705	1411	1233	1567	1776	4618	2025	1869	2025	2009	3135	2804
Tape Speed (m/s)	3.3	3.4	4.0	2.7	5.5	-	6.0	5.0	6.0	6.3	3.9	5.0
Tape Length (m)	249	648	610	630	680	595	610	855	820	824	640	855
Tape Width (mm)	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7
Areal Density (Gb/in^2)	0.11	0.22	0.33	0.37	0.44	0.72	0.54	0.40	0.75	0.65	0.87	0.80
Volumetric Density (Tb/in^3)	0.25	0.48	0.82	0.84	1.05	2.08	1.43	1.20	2.00	1.90	2.20	2.40

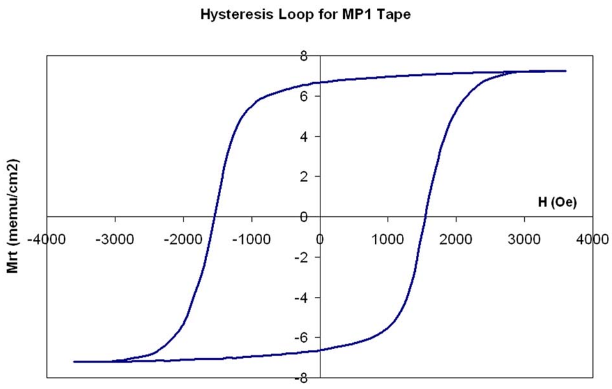

Fig. 4. ***Magnetic hysteresis loop of 1600 Oe coercivity metal particle tape.***

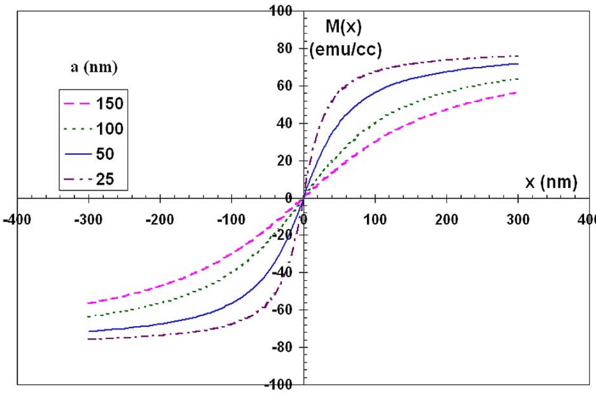

Fig. 6. ***Arctangent transition shape for various values of the 'a' parameter.***

the transition from one direction of magnetization to the opposite direction. This spreading, caused by demagnetization and the transition arcing deep upstream in the media [8], makes it difficult to place transitions very close together (the definition of high density recording) unless the coercivity is high, moment thickness product of the magnetic layer is low and the recording method/channel design is set up to deal with this crowding. In advancing up the areal density growth curve the magnetic thickness of the tape media coating has been reduced to levels approaching those used in disk. Fig. 5 shows the progression using a dual coating method that allows an under layer to smooth the substrate roughness and allow a thin magnetic coating [9], [10].

The physics behind this is best summarized the Williams Comstock model [11], [12] of the magnetic transition for thin magnetic coatings. This uses an arctangent function to model the transition width from which a characteristic transition length, $\boldsymbol{a}$, can be calculated according to following:

$$M(x) = \frac{2M_r}{\pi}\tan^{-1}\left(\frac{x}{a}\right) \quad \text{where}$$
$$a = 2\left[\left(\frac{2}{\sqrt{3}}\right)\left(\frac{M_r\delta}{H_c}\right)\left(d+\frac{\delta}{2}\right)\right]^{1/2}. \qquad (2)$$

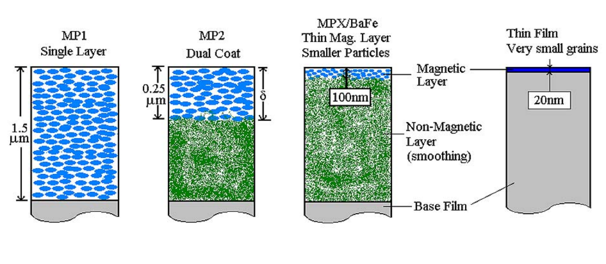

Fig. 5. ***Progression of particulate magnetic tape coating.***

The ratio $\boldsymbol{M_r\delta/H_c}$, sometimes referred to as the demagnetization ratio, is the key to scaling down the parameter '$\boldsymbol{a}$' for a narrower transition length and resultant higher linear recording density. Reducing $\boldsymbol{M_r\delta}$ (the cause of the spreading) and increasing $\boldsymbol{H_c}$ (which inhibits the spreading) results in a reduced '$\boldsymbol{a}$' parameter. Fig. 6 illustrates the arctangent function for various values of $\boldsymbol{a}$.

The progression towards smaller particles and higher particle densities has also transpired in order to maintain adequate signal to noise ratios (SNR) for reliable bit detection. The SNR is related to the number of particles contained in each bit as described by Mallinson [13]. In order to achieve linear bit densities anywhere close to that seen in magnetic disk, the reduction in coating thickness required along with the associated required reduction in particle size, may require a shift from the "particles in a binder" concept to thin film sputtered coatings that are used in disk drives [5], [14] (Fig. 5). When the particles become too small to remain thermally stable this switch in technology will have to happen for tape to remain viable. Thermal stability in small volume magnetic particles or thin film grains is related to the magnetic anisotropy energy as compared to the thermal energy ($\boldsymbol{K_u V/kT}$) and has been an issue in magnetic disk recording recently [15], [16].

The particles used in tape have long relied on shape anisotropy [17]–[19] (elongated particles) but as the size approaches 30 nm and less, maintaining this provides a challenge. Materials with intrinsic crystalline anisotropy are being researched (such as barium ferrite [18], [20], [21] and iron nitride [22]) to enable the ongoing scaling of the particles to continue to leverage the large infrastructure that exists for polymer binder based media.

IV. RECORDING HEADS

In order to record sharp transitions on the tape, the writing devices have to provide two things. Firstly, a high enough magnetic field to overcome the media coercivity, and secondly, a steep gradient in the field, such that the space

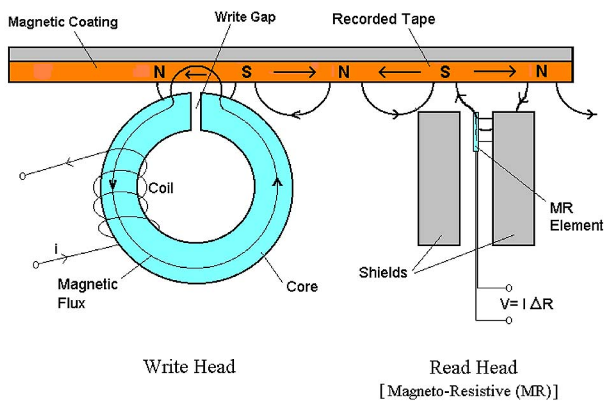

Fig. 7. ***Writing and reading magnetic recordings on magnetic tape.***

occupied by the distribution of coercivities presented by the particle orientation distribution in the tape is short compared to the wavelength of the recording [8]. If this were not so then the opposing field of a subsequent intended transition would overlap the previous recording and partially erase it.

Write devices are simple in concept. A ring of permeable material with a high saturation flux density, $\boldsymbol{B_s}$, is coupled to a coil having $\boldsymbol{N}$ turns as shown in Fig. 7. The field generated by a current, $\boldsymbol{I}$, in the coil couples to the permeable core. A small gap placed near the medium allows magnetic flux to fringe out and the local field magnetizes the tape. Rapid reversals in current as the tape moves by will record transitions between two magnetized states. The field, $\boldsymbol{H_g}$, appearing deep in the gap, $\boldsymbol{g}$, is derived from Ampere's Law and is given by [23], [24]:

$$H_g = \frac{4\pi N I \varepsilon}{10g} \tag{3}$$

where, ε is the efficiency of the device containing the frequency dependent permeability of the core material, $\boldsymbol{H_g}$ is in Oersteds, $\boldsymbol{I}$ is in amperes and $\boldsymbol{g}$ in cm. In order to provide a sufficient record level, this field has to be approximately 3–4 times the tape coercivity, $\boldsymbol{H_c}$ [25]. Thus for high coercivity metal particle (MP) tape ($\boldsymbol{H_c} \cong 2400$ Oe) this field has to be near 7500 Oe. In order to have a sharp field gradient the permeability at the core tip near the media must not be degraded such as might happen if the magnetic material here were to approach saturation. Thus the saturation flux density, $\boldsymbol{B_s}$, of the tip region has to be much higher than the gap field in order to prevent the onset of saturation. A typical rule of thumb is to have $\boldsymbol{B_s} \cong \boldsymbol{2H_g}$ giving a core material requirement of $\boldsymbol{B_s} > 12\text{-}14$ kGauss to ensure the recording of crisp transitions and a high recording density on MP tape [23]. Today's thin film write head used in many tape drives use sputtered Cobalt Zirconium Tantalum (CZT) alloy which meets these needs. The construction of write heads in the past was primarily by using stacks of wire wound permalloy or ferrite cores but the multiple track thin film head is now found in virtually every tape drive.

In order to have a high data transfer rate to the tape (bytes/second) the tape speed is high e.g. 2–6 m/s. This puts the frequency of the required recording in the 1–30 MHz range for linear densities 50–200 kfci. In addition, a common method for counteracting the effects of large low density recordings in thick media, called write equalization [26], also puts an additional high frequency requirement on the write head by using short duration (5–10 nSec) opposing polarity pulses after the main transitions. The rise times required to transmit these pulses through the write device are of the order 1–2 nSec, increasing the flux transmission bandwidth considerably. Again the CZT amorphous alloy has been found to provide a high enough frequency permeability to support this.

Although tapes have traditionally (first 25 years at least) been read with inductive devices, which use Faraday's law of induction ($\boldsymbol{V_{out}} = \boldsymbol{N d\phi/dt}$), the magneto-resistive (MR) sensor has taken over all tape applications [27]. The relatively simple geometries required for MR devices, lends itself to multi-element linear tape applications and to scaling for the future. One of the first products was the IBM3480 18 track tape system that used 18 parallel differentially biased and sensed MR elements. Since then, other parallel track tape heads and systems have routinely used MR technology.

The MR read head in its simplest form is a rectangular shaped thin (10–40 nm) permalloy ($Ni_{81}Fe_{19}$) film sandwiched between permeable shields. The shields provide the necessary resolution of closely spaced transitions by shielding the element from the fields from upstream and downstream bits. The shields have been made from magnetically soft but physically hard materials such as NiZn ferrite onto which the MR device is deposited or thin film ferromagnetic metals, vacuum deposited. The latter is the norm today for the future as they allow cleaner crisper and yet smaller gaps. As the MR device has a quadratic response function, a DC bias field is required to linearize the device [23]. Many methods and designs have been used for this but more recently the soft adjacent layer self bias technique has been dominant [23], [27] and is shown in Fig. 8. Here the magnetic field generated by the sense current in the MR element magnetizes the soft magnetic layer next to the MR layer and the field from this magnetized layer couples to the sense layer and rotates the magnetization to about 45° which puts the device on a quasi-linear portion of the MR response curve. In addition to avoid the effects of domain wall movement as the flux conduction mechanism for these devices, an additional DC field is applied along the length of the device to keep the sense layer close to a single domain state. A view of an actual device as seen looking at the head surface is shown in Fig. 9. Today's tape drives use the shared shield read/write head where the read and write head are fabricated on

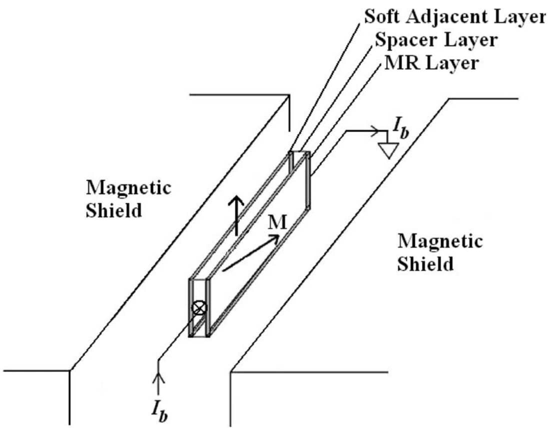

Fig. 8. ***Diagram of a soft-adjacent-layer (SAL) biased MR element.***

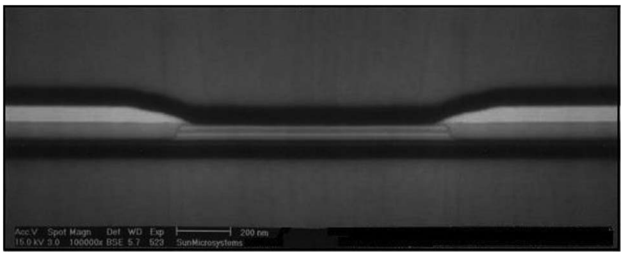

Fig. 9. ***Photograph of a SAL biased MR element showing magnetic shields, sensing element and permanent magnets at each end integral with electrical leads.***

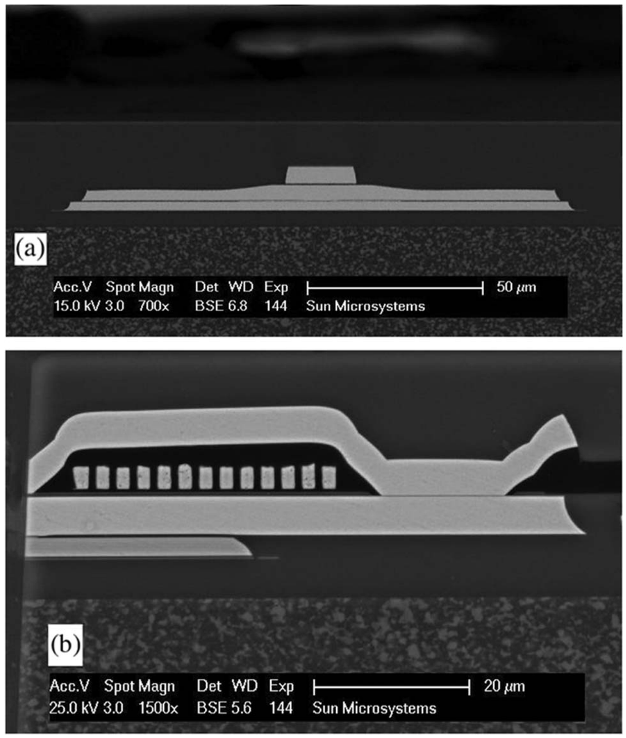

Fig. 10. ***(a) Top and (b) cross-section views of a shared shield read/write head structure.***

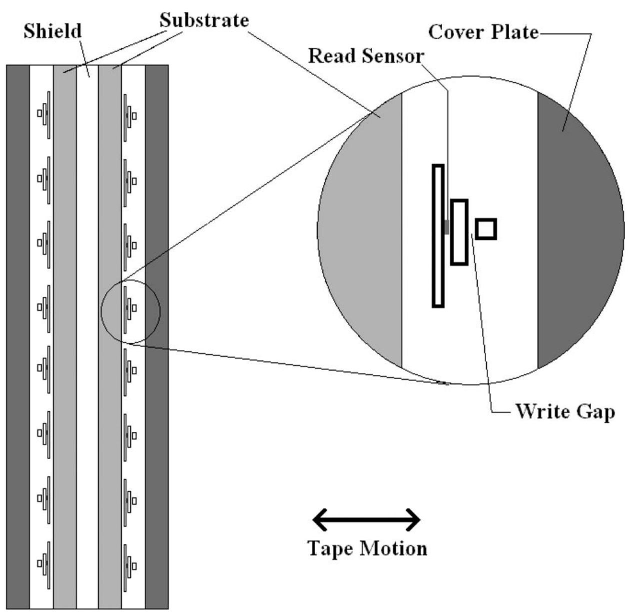

Fig. 11. ***Read/write head layout showing multiple elements for simultaneous bi-directional writing and reading.***

top of one another to form one thin film structure similar to those use in magnetic disk drives (see Fig. 10). They are set out in multi-channel arrays typically using two head modules to allow writing and reading in both directions of tape motion (Fig. 11). Linear tape systems perform an immediate, simultaneous verification of the written data using the read devices on the opposing downstream head module. The arrangement shown allows this "read-while-write" mode for forward and reverse passes of the tape. Other arragements have been used in the past including the use of interleaved/side-by-side read and write elements or three head modules with read-write-read or write-read-write combinations as described in reference [24]. The number of parallel channels used depends on the system design. Examples are 16 for an LTO (Linear Tape Open) drive and 32 for a Sun T10000 drive (Table 2).

The MR response, media and spatial issues for magnetic tape recording are summarized in the following readback equation using self biased MR read head similar to that given in Mallinson [28]

$$\text{Output} = 2\varepsilon\gamma\left(\frac{\rho}{t}\right)\left(\frac{W}{h}\right)\left(\frac{dR}{R}\right)I_b^2\left(\frac{4\pi M_r\delta W}{B_s^2 tW}\right)f(k) \quad (4)$$

where the first terms relate to the MR element response, the latter the medium input and $\boldsymbol{f(k)}$ the spatial wavelength dependent loss functions. The variables here are: ε the efficiency of the device, for the MR element γ is the change in flux density per unit bias current, ρ is the resistivity, t the thickness, W the width, h the height dR/R the MR ratio, I_b the bias current, B_s the saturation flux density. $M_r\delta$ is the moment thickness product for the media and $f(k)$ is given by

$$f(k) = \left(\frac{1-e^{-k\delta}}{k\delta}\right) e^{-k(d+a)} \left(\frac{SIN\left(\frac{kg}{2}\right)}{\frac{kg}{2}}\right) \times 2jSIN\left(\frac{k(g+t)}{2}\right) \tag{5}$$

where k is the wave number $(2\pi/\lambda)$, d the head to tape magnetic spacing, a the transition parameter, and g the distance from the shield to MR element. The main purpose of including the above equation is to highlight the following observations. With the media having to become thinner for higher linear recording density along with narrower tracks the total amount of magnetic flux available for detection goes down dramatically. This means that for adequate raw signal, the sensitivity of the read device will have to improve by reducing the thickness of the sensor, t, and increasing the MR ratio, dR/R. Simply increasing the bias current, I_b, is limited by the onset of unwanted thermal effects as the sensor heats up [29], [30]. The spin valve GMR sensor currently used in many disk drives is clearly a candidate to deliver what's needed for the future here with the value of t approximately 5 nm and $dR/R \sim 10\%$ [31]–[34]. The effect of spacing with the term $e^{-k(d+a)}$ is clearly extremely important for high density recording. It has many implications for improvements to the smoothness of tapes to reduce d with the resulting issues that may arise with more intimate physical contact with the head surface. Most notably this would be the tape sticking to the head and intermittent or long term separations cause by debris, asperities or stain build up on the head surface.

V. THE CHANNEL

The recording channel is composed of several stages in order to transfer the data to be stored from the computer onto the storage medium and back. Fig. 12 shows a simplified diagram of a tape recording channel similar to that described by Schneider [35]. On one side, the channel transforms the data into a write current waveform to accommodate the write head response and the interaction of the write head field with the media. On the other side, the channel takes the analog readback waveform from the read head and transforms the signal shape, with the use of a read equalizer, into a uniform signal from which ONEs and ZEROs can be identified (detected). This detection is often done by identifying peaks in the equalized readback waveform above some threshold. If the peak is above the threshold a ONE is detected and if the signal is below the threshold during the data clock cycle the channel reports a ZERO. The equalization both on the write and read side is to ensure that the amplitude and phase of the recording, from which data bits are to be detected, is uniform and of equal magnitude regardless of the spacing between flux transitions on tape.

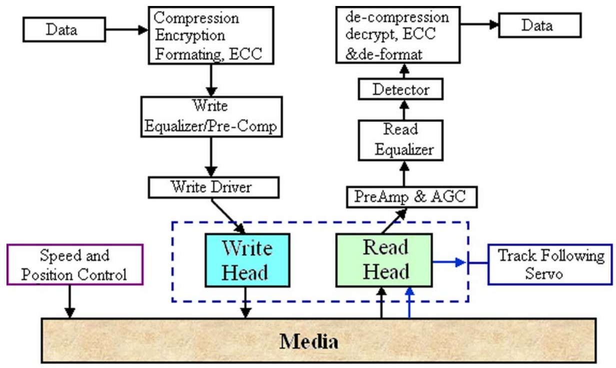

Fig. 12. *High level block diagram of a magnetic recording channel.*

Peak detectors such as these were replaced a few years ago by Partial Response Maximum Likelihood (PRML) detection channels that enable higher logical bit densities than are derived from a peak detecting system. This advance enabled higher capacities using similar magnetic recordings with Extended PR4 (EPR4) channels being pervasive in tape drives today [36], [37]. The encoding, formatting, error detection and correction coding (ECC) are ways used by the channel to prepare the data for recording and provide redundancy such that if data bits were to be unrecoverable or incorrectly recovered (e.g. a ONE mistakenly detected as a ZERO or vice versa or media defect etc.) the data can be restored with high reliability. This aspect is particularly exploited in tape storage. As the data is spread over multiple parallel channels across the tape and interleaved down the length of the tape forming a two dimensional data array, intermittent defects in the tape media or head to media contact can be corrected on the fly with impunity. Fig. 13 illustrates this for a 32 channel tape system utilizing two 16 channels heads spaced up to 40 mm apart down tape and 2 data bands across tape. The user data is assembled into a codeword with added ECC bytes that is then interleaved with similar codewords that are spatially distributed down and across the tape. With the data bit length being only around 100 nm for these systems, related bits and bytes in the assembled codeword are so far apart that local anomalies are easily corrected.

The channel in a tape system also provides for data compression and encryption. The former has allowed many users to store over 1 Terabyte of data on tapes with native capacities 2 to 5 (or more) times lower than this

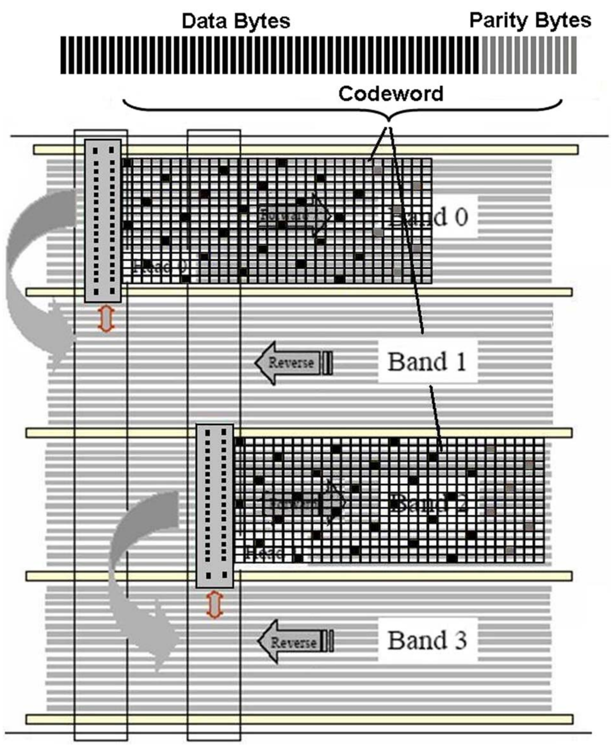

Fig. 13. ***Diagram of byte layout as written onto tape for 2 dimensional error correction.***

together with supporting two to three times the device native data rate at the interface (300–400 MBytes/sec). The introduction of AES-256 encryption algorithms into the data path prior to recording provides security for inadvertent loss or theft of tapes as the data is unreadable without possession of the encryption keys.

In the future it is highly likely that advanced channels codes such as Noise Predictive Maximum Likelihood (NPML) [38] or Low Density Parity Check Codes (LDPC) [39] will be incorporated to handle the lower SNR operating points that result at higher areal densities (5 Gb/in^2 and up). Even though these methods can be complex and introduce delays in the data detection, tape systems typically operate with many parallel channels allowing high overall data rates even with modest data rates per channel.

VI. THE MECHANICS

As the medium is thin and flexible, tape guiding and tracking technology is key to future advances in areal density for linear tape. The changeover from a guided tape with a static head to active track following servo systems for linear serpentine recording occurred at about 288 tpi. 18 and 36 track tape products used a fixed position head and physically guided tape. This was possible because the track width was still relatively wide (100's of μm) and a large guard band between the read and write width could be used ($\sim$40 μm). With written track widths plummeting to <15 μm this luxury is no longer available to write wide/read narrow systems. The even narrower read widths required to allow for track alignment between tapes and drives becomes a key issue in determining the raw signal amplitude and SNR in future systems.

Track following servo systems used for tape that significantly reduce the off-track contribution of lateral tape motion (LTM) have been implemented in several ways: amplitude based [40], timing based [41] or optical [42] with spatially separate or buried servo signals. The important aspects of either method depend greatly on the servo writing or the cross track amplitude linearity of the MR servo reader [43], [44].

For a timing based system [41] the cross track reader amplitude characteristics are de-emphasized in exchange for servo pattern writing accuracy. An example timing based servo pattern is shown by way of the ferrofluid image in Fig. 14(a) where multiple magnetic transitions (dark lines) are recorded at opposing angles so that the time between groups of transitions, as the tape moves by a servo reading element, varies with the cross tape position. For amplitude based systems the cross track linearity is important in determining the position error signal (PES). Fig. 14(b) shows another ferrofluid image of an amplitude based servo pattern where there are erased zones in a uniform recorded area such that a servo reader straddling the pattern will yield an output signal that is proportional to the cross tape position in alternating bursts. Other

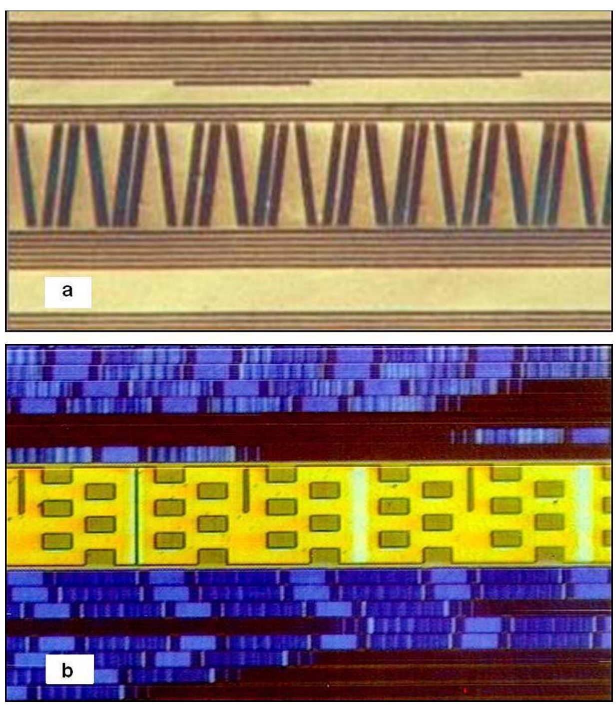

Fig. 14. ***Magnetically recorded servo patterns for track following. (a) Timing based (b) Amplitude based.***

features seen in this pattern are for synchronization and servo track identification and data tracks written above and below the servo pattern. MR read heads have been shown to have an asymmetric cross track profile when they become sufficiently narrow [45]. This is due to the magnetization and bias current in the element being unidirectional. However, this can be reduced if the servo read width is wide compared to the data track, which would also deliver reasonable range for the servo off-track sensing. Of these options the most widely used technique in today's tape drives is the timing based system.

An alternate to the write wide/read narrow philosophy is the use of dual azimuth recording long used in video cassette recorders (VCRs) [46]. As mentioned earlier, here the in-band noise picked up when a read head goes off-track is reduced by azimuth loss in the readback process. Helical scan data tape systems use both dual azimuth and an integral servo system (in this case based on the data) to both stay on track and allow greater off-track margin. This has resulted in track densities for helical recorders being much higher than linear systems.

As tape is often viewed as, and used as, a back-up and/or archiving medium, the mechanical stability of the tape over time has to be figured in to any tracking budget. As the tape will expand or contract under temperature and humidity excursions, recovering data reliably on widely spread tracks of the same data group becomes impacted [47]–[49]. Thus tape format and architectures are changing to operate with reduced side-by-side spans of parallel tracks rather than interleaved sets. Direct adjacent track writing and over sampled reading techniques have been suggested as ways to eliminate the effect of tape dimensional change upon long term storage [50], [51]. To maintain a high degree of parallelism for high data rate, systems will likely move to multiple heads or other novel architectures to mitigate this issue [52]. Today's systems allow margin between the read and write widths to account for this to ensure reliable data recovery from archived tapes.

VII. AUTOMATION AND ECONOMICS

The early stigma of tape being really slow offline storage only was changed in the mid 1980s with the introduction of automation in the form of the large robotic tape library (Sun/STK). This introduced the concept of "Nearline" storage where the tapes could be accessed in 10's of seconds rather than hours or days. These libraries or silos allowed large data stores with very favorable data center metrics including

- Low cost of storage as measured in terms of \$/Gbyte;
- Small footprint (Gbytes/sq.ft.);
- Low power consumption (Gbytes/watt);
- Easy scale up both in capacity and throughput with little impact to data center infrastructure and access times to any tape.

All of the above are improved further with the use of data compression which has been used in tape drives as normal operation for many years meaning that the fabled terabyte tape has actually been around for sometime (at least as far as the user is concerned). The libraries now come in many sizes to suit a variety of needs from a few 10's of tapes with one or two drives to a few 100 000 tapes and hundreds of tape drives with multiple redundant robots (e.g. the Sun SL8500 Fig. 15) for multi-petabyte installations with highly parallel data streams. Tape being removable storage and an interchange medium also allows for the physical transfer of data in massive quantities to offsite storage repositories for disaster recovery or other purposes rather than electronic transfer. At the petabyte scale physical transportation is much quicker than electronic transfer. Security of the data is now routinely assured with the introduction of encryption at the device level in the tape drives. This delivers the concept of security of data at rest if the tape were to be stolen or lost [53]. In addition to this with the use of virtual technology and disk buffering the efficiency of tape usage and the ability to migrate data to newer tape technologies can be done automatically with little impact to the main computer system or network. It is clear that removable storage such as tape has all the attributes you need for data storage except one—fast access to the first byte of data on a read. However, when streaming large data sets involving multiple gigabyte transfers the initial access time becomes much less significant with data transfer completion time being more important.

Fig. 15. ***A Sun Microsystems/StorageTek SL8500 automated tape library.***

VIII. SUMMARY AND CONCLUSIONS

Tape drives are no longer lumbering great boxes moving relatively low capacity large reels of tape. High performance (capacity, data rate and reliability) is the expectation and is being delivered with leading edge thin film technology, high capacity tape media and cartridges. The recording channel and head design is driven primarily by the media characteristics as is the case for other storage technologies. As a result, tape heads carry a complexity to rival any of the more newsworthy devices in the industry due to their tightly compact multi-element read-while-write architecture including high moment poled thin film writes and complex magneto-resistive reads. The time scales required for magnetic tape storage are 10^{-9} seconds to initiate a recording that lasts 30 years (10^9 seconds), a span of 18 orders of magnitude. Similarly in spatial terms with thin films down to 10^{-9} m thick (or thin) used in read sensors traversing 10^4 m of tape length to store a terabyte of data, a span of 13 orders of magnitude. In general the tape recording environment appears decidedly hostile to microscopic entities such as ultra thin films and resolution of nano-scale recordings. Yet the technology keeps on improving and delivers reliable recording systems with secure encrypted data and powerful error correcting codes. No problem to date has been insurmountable and it appears that this will remain the case for some time. Demonstrations of more than ten times today's areal density [54], [55] (see Fig. 2) indicate an ongoing growth in this metric.

It is clear that over time, tape as a storage medium has certainly proven to be incredibly sustainable and still shows promise of another order of magnitude gain over the next 5 years as envisioned by the 2005 INSIC industry derived tape roadmap (see Fig. 1) [52]. Tape has endured throughout our lifetime with the space needed to store a terabyte shrinking from the size of a room down to a single cartridge. In a world concerned about environmental issues, the lower space and power levels required for data storage technologies along with longer term archive characteristics (exemplified by magnetic tape) will become increasingly in demand. ■

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