TRENDS IN DIGITAL MAGNETIC RECORDING; THE APPLICATION OF THIN-FILM HEADS FOR TAPE RECORDING

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Abstract

Digital tape recording systems show the same trend as hard-disk drives: a large increase of storage density with time. The use of advanced media and highly sensitive thin-film heads with magnetoresistive (MR) readout will increase the storage density dramatically. Key improvements are narrower tracks, more sensitive MR elements attained by applying the giant magnetoresistance effect, high-saturation flux density pole materials, advanced metal powder tape, intimate head-to-tape contact, and accurate tracking. By increasing the number of channels in the multitrack thin-film head, high data rates can be obtained as well. The basics of digital magnetic recording are discussed and a short historical overview is given of the Philips activities on thin-film heads for tape recording. An outlook on future improvements is given.

Keywords: linear tape system, tape, bit density, read head, write head, thin-film head, magnetoresistance, giant magnetoresistance effect, digital, digital compact cassette, hard-disk drive, magnetic recording.

1. Introduction

Magnetic storage has been around for almost a hundred years. The first working apparatus in which the information was stored in a steel piano wire, was described by Poulsen [1] and demonstrated at the World Exhibition in Paris in 1900. Since then the performance of magnetic storage systems has increased tremendously because of improved technologies in conjunction with an improved understanding of the physics of the recording and playback process. After the Second World War, recording became generally accepted, especially
by the introduction of particulate tape and the invention of a.c.-bias recording. The magnetic head for recording and playback changed from a ring head with a discrete coil to a thin-film head with integrated coil. From 1970 on, thin-film playback heads with magnetoresistive (MR) readout elements attracted more and more attention [2].

Presently magnetic storage is very common in home products like audio recorders, video recorders and hard-disk drives (HDD) in personal computers (PC). The storage demand is increasing rapidly. Magnetic recording is perfectly suited to satisfy these future demands. Since the advent of the PC and the compact disk (CD) in the beginning of the 1980s the information became increasingly digital in nature. This tendency will continue. Therefore, future systems and their components have to be optimized for writing and reading digital information.

Philips Research has been involved in research on thin-film heads and related materials aspects for more than two decades. Publications in this field range from MR reading in the 1970s to the application of the highly sensitive giant magnetoresistance (GMR) materials in magnetic heads in 1994 [3–6]. Thin-film heads have been applied by Philips Electronics in the Communication Logging System (CLS) [7], a professional multi-channel speech recorder, and more recently in a consumer product, the Digital Compact Cassette (DCC) [8].

The main advantage of an MR read head as compared with an inductive (thin-film) head, is the high output which is independent of the head-to-medium speed. This makes the head highly suitable for the application in tape drives and hard-disk drives with a high storage density. For instance, current HDDs with a storage density around 150 Mb/cm² (see Sec. 3.)¹, apply track widths as small as 3 μm [9]. A second advantage is the possibility to manufacture multitrack heads quite easily. This feature allows the design of tape-storage systems with a high data rate at low head-to-tape speeds. In the professional data storage market this advantage was exploited by IBM in their 3480 tape system introduced in 1984 [10]. The DCC recorder is an example in the consumer market. In this system, digitized audio is stored using a thin-film head with eight data tracks and an auxiliary track [11]. The system is built around a sophisticated thin-film head and uses simple recorder mechanics and highly integrated (channel) electronics. It proves the feasibility of low-cost multitrack systems for mass production.

More applications of the multitrack thin-film head for low-cost high-density tape storage are expected. Digital storage of PC data and multimedia

¹) b stands for bit, the unit of digital information. B stands for Byte, a collection of 8 bits.
Fig. 1. The three-dimensional view of the layout of a multitrack thin-film head with reader and writer. Reading is carried out using a magnetoresistance element (MRE) in the yoke of the read head.

Information can be carried out conveniently with such systems, which will have high capacities and high data rates. An example is the DigaMax system recently announced by Philips. The first DigaMax generation has a native capacity of 15GB and a maximum data rate of 2 MB/s using an eight channel thin-film head and active tracking. Figure 1 shows the basic configuration of a read/write head used for the DigaMax tape storage system. The write head is used to write the data on the tape. Written information is recovered by the read head which has a yoke with a magnetoresistance element (MRE) to sense the flux from the tape. Eight of these heads are processed next to each other to obtain a multitrack head.

This paper deals with the application of thin-film heads for both reading and writing of digital information in storage systems. The principle of storage of digital information and the trends in recording density will be discussed in Secs 2. and 3. After describing the historical development and principles of the thin-film head in Sec. 4. we will discuss the requirements for thin-film heads for future high-density tape systems in Sec. 5. The conclusions are summarized in the last section.

2. Digital magnetic storage

Digital information is stored on a magnetic medium by writing small areas
with opposite directions of magnetization separated by a transition. This transition represents the digital information (the bit). The presence or absence of a transition corresponds to a one or zero, respectively. The parameters that are important in determining the performance are indicated in Fig. 2 which illustrates the process of writing and reading information using a thin-film write and read head [12 to 14]. The information is stored by energizing the coil in the write head. The magnetomotive force induced by the current in the coil causes a stray field $H_s$ near the gap. The magnitude of the stray field has to be a few times the coercivity $H_c$ of the medium to write the transitions. Upon readback the flux from the tape enters the yoke and flux is fed into the MR element. This gives rise to a change in the resistance of the MR element which is proportional to the flux and is used to obtain the readback signal. To realize a linear and stable response, appropriate biasing of the element is usually required (see Sec. 4.).

The parameters that have the largest influence on the output are the tape coercivity $H_c$ and remanence $M_r$, the transition length $a$, the head-to-tape distance $d$, the read head gap length $g_r$, the read track width $w_r$, and the read pole thicknesses $p_1$ and $p_2$. The write head gap is $g_w$ and $B_s$ is the saturation flux density of the yoke material which has to be sufficiently high to be able to write (and overwrite) high-coercivity media. All parameters are indicated in Fig. 2. The effects of these parameters will be discussed briefly. Tape coercivity $H_c$ and remanence $M_r$ are parameters which determine output and demagnetization effects. The output is proportional to $M_r$ as long as the MR element does not saturate. Demagnetization occurs when the internal field caused in the transition is larger than $H_c$. This happens more easily for a narrow transition, so that a broadening (demagnetization) occurs. In case no demagnetization occurs, the transition length is given by the Williams–Comstock expression
for thin media [15]:

\[ a = \sqrt{M_r \delta \left( d + \frac{\delta}{2} \right) / \pi H_c}, \]  

(1)

where \( \delta \) is the thickness of the medium. The smallest transition length \( a_s \) allowed in the case of the demagnetization limit is given by [16]:

\[ a_s = \frac{M_r \delta}{\pi H_c}. \]  

(2)

For thicker storage layers, like tape, this formula does not hold and \( \delta \) has to be considered as the penetration depth of the write field in the storage layer which can be approximated by:

\[ \delta = \frac{g_w / 2}{\tan \left( \frac{\pi H_c}{2H_g} \right)} - d, \]  

(3)

where \( H_g \) is the field in the gap of the write head. It is clear that thin storage layers with a high coercivity \( H_c \) are required for high density magnetic storage [17]. Typical values for \( d, a, \delta \) are 50, 200 and 200 nm, respectively. The transition length \( a \) and the head-to-layer distance \( d \) have a large effect on the output. The solution of the magnetostatic equations is an exponential decrease of the read output as a function of the frequency with increasing \( d \) and increasing \( a \). The output is proportional to \( 55d/\lambda dB^2 \), where \( \lambda \) is the wavelength on tape. For high densities the head-to-layer distance has to be small to achieve small \( a \) and \( d \). The output is proportional to the track width \( w_r \) of the read head. As the recorded wavelength approaches the gap length the sensitivity approaches zero. Therefore, shorter bits need a smaller read gap.

During reading, the data written into the storage layer [16] have to be reconstructed from the readback waveform. A decision has to be taken about the presence of a transition in the readout signal. For a proper decision, it is necessary to restore the signal to a convenient form. This process, called equalization, is sketched in Fig. 3. The write current waveform is indicated on the left. Noise is introduced during readout. The equalizer reshapes the read waveform and the detector decides whether there is a transition present which represents a one. The equalizer function depends critically upon parameters like \( a, d, g_r \). The success of the decision at the detector is strongly influenced by the equalizer quality, the signal level, and the noise level at the detector. The signal-to-noise ratio

\[ \text{SNR} = 10 \log \left( \frac{V_1}{V_2} \right) \text{dB} \]

where \( V_1 \) and \( V_2 \) are output voltages at two conditions. As a consequence, 6 dB corresponds to a factor of 2.
has to be high enough to produce a low enough value of the Bit Error Rate (BER). The signal is a result of the write and read sequence and depends upon the quality of both the storage layer and the head. Noise is caused by the random nature of the magnetic units in the storage layer, thermal noise and Barkhausen noise in the MRE, and electronics noise from the read amplifier.

To achieve optimal reliability the user data is coded before the write process. The data sequence is transformed into a sequence that is more suitable for the properties of the magnetic recording process and, moreover, bits are added to correct for errors after the read process [12,14].

3. Trends in storage density

The performance of magnetic storage has increased tremendously in the hundred years of its existence. The performance is expressed in terms of the storage density, the number of bits stored per unit area. To calculate the storage density, the length and width of a bit have to be known. The width is given by the track pitch and the length by the minimum distance between transitions as written by the recorder. There are two transitions in one wavelength $\lambda$. The units often used for the track pitch and the minimum distance between transitions are $ktpi$ (kilo tracks per inch) and $kfc$ (kilo flux changes per inch). The storage density is often given in $b/in^2$ or $b/cm^2$ ($1 \text{ Gb/in}^2 = 154 \text{Mb/cm}^2$).

Three recording systems can be distinguished: hard-disk drives (HDD), linear recorders (like DCC), and helical scan systems (like the VHS video recorder). The first one has a storage layer on a rigid disk and the last two use a storage layer on a flexible tape. A lot of progress in storage density has been made in all these systems through improvement of head and storage layer properties.
The most striking example is the HDD. Figure 4 shows the storage density as a function of time since 1980 [18]. Many steps in the technology have been made to bring about this progress. All fundamental parameters have improved and there is no reason to doubt that they will continue to do so in the future to sustain the growth rate [15]. The storage layer in almost all disks is of the thin-film type. This type of layer was introduced in the mid-1980s and is manufactured by sputtering on the disk. A nucleation layer is used to obtain adequate decoupling of the magnetic grains for low noise media. The coercivity $H_c$ has continued to increase to reduce transition length $a$. Typical values of $H_c$ and the thickness $\delta$ are 1800–2000 Oe (141 to 156 kA/m) and 20–50 nm, respectively. Another important parameter is the flying height, which corresponds to the head-to-disk distance $d$. By adapting the shape of the slider and decreasing the roughness of the disk this parameter has lowered to values close to 30 to 50 nm. The thin-film head is one of the most important improvements. The combination of inductive thin-film heads and thin-film media led to the increase of 30% per year until 1990. Increasing the head sensitivity by incorporating an MR read head resulted in a growth rate of 60% per year during the first half of this decade. The MR head has a higher sensitivity, which allows narrower tracks. Typical values for the density in current products are a track pitch of 3.6 $\mu$m (7 ktpi) and a bit length of 0.16 $\mu$m (160 kfc), corresponding to 1 Gb/in$^2$ [9,15]. The signal-to-noise ratio is determined by the signal and noise of the storage layer in such a system. Values for track pitch and bit length as low as 0.7 and 0.1 $\mu$m (9.3 Gb/in$^2$) [19] are currently being investigated. The
density obtained in the HDD is comparable to the densities encountered in optical storage systems, the compact disk (CD) has a density of 0.65 Gb/in². The density used for DVD is 3.28 Gb/in² (data bits) in the case of the DVD-ROM single-layer disk.

It is clear that a tremendous effort is needed to improve the properties of the head and the storage layer, to lower the flying height, and to maintain adequate tribological properties and reliability all at the same time. This improvement cannot be achieved without the corresponding developments in tracking accuracy and servo strategy. In the future the introduction of an MR element based on the giant magnetoresistance (GMR) effect (see Sec. 3.) will be a key step to maintain the present growth rate in storage density.

A similar trend is observed in tape-based linear and helical scan systems. For these systems, the storage layer is still mostly particulate in nature. However, particle size has decreased and the coercivity has increased in going from \(\gamma-\text{Fe}_2\text{O}_3\) to metal powder (MP) tapes [20]. In addition tape based on thin-film storage layers, called Metal Evaporated tape (ME-tape), has been introduced for helical scan systems [20,21]. The Digital Video (DV) system [22] is designed for ME-tape and has a track pitch and bit length of 10 \(\mu\text{m}\) (2.5 ktpi) and 0.25 \(\mu\text{m}\) (100 kfc), respectively.

It is expected that these improvements will also be incorporated in linear! (multitrack) systems. Figure 5 shows the density as a function of time for some linear tape recorders. The existing linear recorders are based on the Quarter Inch Cartridge (QIC) technology [23]. The product of 1988 conforms
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to the QIC80 standard. The densities beyond 1996 are based on expected density improvements (see below). Systems based on the QIC technology are popular for backup of computer data. These systems are in a transition from using Co-doped $\gamma$-Fe$_2$O$_3$ media with $H_c = 900$ Oe (72 kA/m) to using MP-tape with $H_c = 1650$ Oe (131 kA/m). In addition, MR thin-film heads and advanced MP-tapes is expected to increase the density by a factor of 5–10 from a track pitch of 99 $\mu$m (TR4 system) to a track pitch of 10–20 $\mu$m (2.5–1.25 ktpi) and a bit length of 0.35–0.25 $\mu$m (72–100 kfc1) in the next five years. A crucial element in such a linear system with narrow tracks will be the servo system (servo signal and actuator for the head), which has to provide accurate positioning of the heads for access of information and tracking during write and read operations. The introduction of multitrack heads will increase the data rate correspondingly.

Multitrack heads and active servo tracking are already incorporated in the first generation DigaMax system recently announced by Philips. The first DigaMax generation has a track pitch of 37.5 $\mu$m (0.66 ktpi) and a bit length of 0.35 $\mu$m (72 kfc1) which leads to an (uncompressed) capacity for the user of 15GB using 1150 ft (345 m) 8 mm wide Co-doped $\gamma$-Fe$_2$O$_3$ tape ($H_c = 900$ Oe, 72 kA/m). Active tracking is applied and a data rate of 2 MB/s is obtained at a velocity of 44 in/s (1.1m/s) using an eight channel thin-film head. Such a digital recorder will be an interesting option for the storage of vast amounts of digital data which can either be audio, real time video or multimedia information.

4. Thin-film heads for tape recording

MR heads exploit the anisotropic-magnetoresistance (AMR) effect in thin permalloy (NiFe) films to convert flux changes into resistance changes. The resistance of this material decreases when the magnetization direction changes from parallel with (or anti-parallel to) the current direction to perpendicular to the current direction. For sputter-deposited NiFe films the total resistance change is typically 2%. In the MR heads according to the Philips concept as shown in Fig. 1, the MRE bridges a gap in the yoke of the thin-film head. Other manufacturers concentrated on MREs in close proximity of the medium, with soft-magnetic shields to suppress the long-wavelength response of the MR head (therefore called 'shielded head'). The output of these latter heads is larger because the MRE is closer to the medium. But in the case of tape applications, there is also more rubbing of the MRE and therefore more noise, wear, corrosion and a higher sensitivity to electrostatic
discharge damage. For disk applications the shielded heads are undoubtedly advantageous.

The first application of MR heads in a commercial tape system was the Philips PCQR system (Pulse Code Quick Refind) introduced in 1980 for the automatic search of music passages in compact cassette recorders. The PCQR system is based on a 5 Hz code signal which is written superimposed on the audio R and L signals. The signal is read out by an unshielded double MR sensor. To linearize the parabolic AMR sensor output for small fields [3,12,14] a 'barber pole' metallization structure is applied on top of the MRE [2]. The name barber pole is due to the conductor stripes that are applied under 45 with the length direction of the element. The current in the MRE flows almost perpendicularly from one conductor stripe to the other. Since the magnetization, at zero applied field, is in the length direction, the angle between the current and magnetization varies around 45 and maximum linearity is obtained.

The Philips CLS recording system (Communication Logging System) [7] applied multitrack MR heads for the first time. The CLS is a professional system for multi-channel speech recording on 1/2 inch tape, used for instance in air traffic control centres. The CLS recorders were produced from 1987 and applied thin-film heads with 32 channels. The signal frequencies involved are from 300 to 3400 Hz and the tape velocity is very low: 6.6 mm/s. The recorder can function unattended for 24 h. The CLS has separate write and read thin-film heads. In order to achieve high resolution and linearity the read heads are yoke-type MR heads with a barber pole.

The Digital Compact Cassette (DCC) audio system was launched in 1992 by Philips and Matsushita. The DCC head is the first multitrack thin-film tape head for consumer use. It can handle the digital multitrack format, but can also play back standard analogue compact cassette tapes [7]. The total digital audio bit rate is 768 kb/s, including bits for error correction. The DCC heads contain 18 parallel tracks for recording (185 μm wide) and playback (70 μm wide). Depending on the tape direction the upper or lower nine channels are connected to the channel electronics. Eight tracks are used for audio data and one auxiliary track for text data and search information. The analogue playback function is performed by adding the output of two digital read channels per analogue track on tape. Magnetic feedback (sometimes called servo-bias) is used during playback of analogue tapes, in order to increase linearity and to obtain HiFi specifications. Like the CLS head, the DCC playback head is a yoke-type MR head with barber pole. In Fig. 6 a photograph of a cross-section of a DCC head is shown. The MRE is fabricated first and is on the bottom of the structure. The MRE is very thin and is barely visible in this.
cross-section. A conductor, which is used to provide a bias for the MRE during readout and for testing the structure in the fabrication process, is shared by several channels. The write yoke is processed directly on top of the read yoke. They have a common ‘shared’ pole. The ceramic substrate is made of a composition of $\text{Al}_2\text{O}_3$ and TiC. The fluxguides are made of electrodeposited NiFe. The bias conductor is 40 $\mu$m wide and the write conductor is 20 $\mu$m. Polymer structures are used to increase the distance between the fluxguides in the head and thereby the efficiency of the yokes.

The MRE in a DCC head is made of 35 nm thick NiFe with an element height of 10 $\mu$m and a sensitive width of 70 $\mu$m. To ensure a stable operation of the MRE under all operating conditions, i.e. without Barkhausen noise caused by jumps in domain wall positions, a stabilizing longitudinal magnetic field is required. A single-domain MR configuration can be obtained by magnetostatic biasing with two small integrated CoPt thin-film permanent magnetic structures besides the MRE sensing area. A disadvantage of a longitudinal magnetic field is loss of sensitivity. For sufficient stabilization
and a minimum loss of sensitivity a field strength of about 0.1 kA/m (1 Oe) is required. It has been found that the application of CoPt internal magnets in this way results in magnetically stable heads with good field immunity against disturbing external fields.

Some compact cassette tapes are known to accelerate corrosion effects in a high-humidity atmosphere. A bare DCC head would suffer from too short a lifetime against these analogue tapes, as the effective head-to-tape distance could increase rapidly during operation due to NiFe corrosion. Therefore, a coating is applied on the tape-bearing surface of DCC heads. This coating consists of a 55nm wear-resistant Super Protective Layer (SPL). It has been shown from accelerated lifetime tests that in this way the reliability of the heads is ensured [24]. The coated thin-film head is fixed into a housing which has tape guides on either side to control the tape travel over the head.

5. Heads for high-density tape recording

Higher bit rates and higher storage capacities are the two main issues to be considered in the development of thin-film heads for future linear tape drives. Systems with higher bit rates bring about larger tape speeds, typically around 1 m/s. In a later stage the number of parallel tracks might be increased above eight to enable a further increase in bit rate. The first generation DigaMax has already shown to be capable of 2 MB/s at 1.1 m/s using eight tracks. A coating of the tape-bearing surface (TBS) as applied for DCC is not expected to be necessary for these high-density recording systems because improved tapes can be applied which induce less wear and corrosion of the head. Furthermore, by the incorporation of fluxguides of amorphous Co-alloys or nanocrystalline Fe-alloys, the heads can be made more wear-tolerant and corrosion-resistant than heads with NiFe fluxguides.

To obtain higher storage densities, tape media need to be applied with an increased coercivity compared to, e.g. the Co-doped γ-Fe₂O₃ media. Replacing the NiFe fluxguides in the heads by materials with an increased saturation flux density, like the aforementioned amorphous Co-alloys and nanocrystalline Fe-alloys, will be necessary to write on high-coercivity media without saturation of the yoke in the head. These fluxguide materials have saturation flux densities of 1.0–1.9 T, which should be compared to 0.9 T for permalloy.

In principle the signal-to-noise ratio of the MR readout head should be kept at the same level as at lower densities in spite of the density increase that results from smaller values for bit length and track width. At a fixed distance between the head and the magnetic recording layer, the magnetic flux detected by the read head is reduced for smaller bits. Intimate head-to-tape contact is essential.
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at these high densities. Smaller track widths will lead to proportionally smaller signal levels. Medium-noise levels will be reduced as well (but less) for small bit areas which makes it more difficult to obtain a medium-noise limited signal-to-noise ratio. Thus, read heads should be improved in magnetic efficiency and stability to increase their signal level and reduce their Barkhausen-noise level as far as possible. Additionally, MR-sensor elements with a higher sensitivity will be required. Efficiency and stability of yoke-type heads can be improved by applying small throat heights, reducing the height of the fluxguide in front of the MRE and increasing the flux transfer between read fluxguide and MRE by reducing the thickness of the separation oxide in between. Optimized yoke-head designs will have an efficiency around 30%, which should be compared to 10% for the barber pole DCC heads described before.

An interesting class of MR materials with improved sensitivities are the giant magnetoresistance (GMR) materials. These are metallic multilayers that consist of alternating ferromagnetic and non-magnetic layers. An interesting high-sensitivity GMR material is the Ta/NiFe/Cu/NiFe/FeMn spin-valve multilayer [25]. The sensitivity of optimized spin-valve structures is about four times higher than that of a normal AMR material. A second advantage is that GMR materials can be made with an intrinsically linear MR curve [26].

6. Conclusions

The increase of the storage density for magnetic storage has been very large during the last decade, as is quite clear for hard-disk drives. Digital tape recording systems follow the same trend. The DCC audio system proves that multitrack recorders for digital data storage for the consumer market are feasible. The key factors for the increased density will be narrower tracks, more sensitive read heads attained by applying a giant magnetoresistance (GMR) sensor element, high-saturation pole materials, advanced Metal Powder (MP) tape, intimate head-to-tape contact, and accurate tracking. In the next five years the track pitch can be expected to decrease down to 10 μm and the bit length to 0.25 μm, which allows 60GB of capacity on a 1150ft QIC cartridge of 8mm wide tape. With eight or even more channels in the thin-film head high data rates (2 to 4 MB/s) can be obtained at tape speeds of around 1 m/s. A first step in this direction is illustrated by the DigaMax system as announced by Philips.

The challenge for the thin-film head technology is the use of high-saturation flux density amorphous Co-alloys and nanocrystalline Fe-alloys to write on high-coercivity media. Advanced fluxguide materials have a saturation flux
density of 1.0 to 1.9T. Sensitivity can be gained by using GMR-type of materials. In addition, the geometry of the yoke-type head can be improved, which could lead to a factor of three higher sensitivity with respect to DCC MR-heads. These are promising options for new linear tape recording systems with high capacity and high data rate. Such a data recorder will be an interesting option for the storage of vast amounts of multimedia information by the consumer.

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