DESIGN OF THIN-FILM TAPE HEADS

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Abstract
In this paper tools to handle the magnetostatic aspects of thin-film tape head design are reviewed. Some illustrative results from transmission-line calculations on inductive write heads and yoke-type magnetoresistive read heads are shown. New is the application to nonlinear saturation effects in write heads. The design of an emboss head for writing servo tracks on tape is described. Finally, a new type of read head is discussed that utilizes anisotropy of the permeability instead of structuring of the fluxguides for obtaining very small track widths.

Keywords: magnetoresistive head, transmission-line model, tracking, inductive head, saturation, nonlinear, anisotropy, design tools.

1. Introduction

During the design of a head for a certain application, many aspects have to be taken into account. The most important of these are classified as technological, application-dependent and magnetic aspects. The application-dependent specification of a head is only briefly discussed. The practical design of a head is always a compromise between the ideal design for a given application, technological possibilities and price. In this paper the main tools for handling the magnetostatic design of heads are discussed. We will show a number of results, illustrating the application of these tools. Most of the results were obtained with tools developed for thin-film head designs.

In Sec. 2. we start with a short review of the progress that has been made in tools to handle the magnetostatic aspects of magnetic devices, especially heads. In Sec. 2.2. we focus on tools for designing thin-film heads. In the

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following sections (3 and 5), Philips' head designs are briefly discussed and
typical results obtained with our thin-film head design tools are shown.
Examples cover write heads and yoke-type magnetoresistive read heads.
Results with transmission-line calculations are shown; the application to non-
linear saturation effects in write heads has more recently been developed.
Application of the latter calculations to non-linear saturation effects in write
heads is discussed as well. We will compare the results with those obtained
by a finite-element method (FEM).

Also rather new is the application of transmission-line calculations, in com-
bination with certain approximations for fringe fields, to impulse response,
frequency response and eye-pattern calculations.

A new type of servo write head, also called embossing head, for dynamic
track-following in multi-purpose digital applications is described in Sec. 4.
Typical emboss patterns obtained with this embossing head will be explained
in this section. Last but not least, a new type of read head, which utilizes
anisotropy instead of structuring to obtain very small track widths, is
discussed in Sec. 5.3. Technological details concerning the laboratory-scale
manufacture of wafers and the steps between wafer and finished tape head
can be found in Refs. [1] and [2] and elsewhere in this issue [3].

2. Design tools

2.1. Progress in tools to handle magnetostatic aspects

In the first half of this century, heads were designed mainly by trial and
error, with some limited help from analytical solutions of simple head models.
This approach was followed not because of any lack of abilities of the pioneers
in this field, but because without too much design and technological effort,
heads could be treated as almost ideal. The main reason for this was the
very low information density. Therefore, the gap length could be chosen so
large that the efficiency $\eta$ of the head, defined as the ratio between flux
encompassed by the reading coil or sensor and flux entering the read head,
could often be taken to be ideal, i.e. $\eta$ could be assumed to be 1. The picture
was complete, once the amount of flux entering the head was known. When
the head was not ideal, the track and head widths were large enough that
any flux outside the yoke construction of the ring head could be neglected
completely. This made it possible to treat the head as 2-dimensional (2-D)
instead of 3-D. Applying certain simplifications regarding the flux flow in
the ring-shaped head, the head could be modelled by a single series connection
of reluctances describing the yoke and a single reluctance describing the gap.
No parallel branches of reluctances occurred. In this way the problem of finding the efficiency even reduced to a 1-D problem, and the efficiency could be calculated simply, once the permeability of the core was known. However, the question regarding the amount of flux entering the read head, near the gap, was not yet answered. Measurements revealed that no signal at all was read at a wavelength approximately equal to the gap length. More 'nulls' in the output were measured at wavelengths approximately 2, 3, etc., times smaller than the gap length. Westmijze [4] was the first to calculate these nulls accurately. He used the Schwarz-Christoffel transformation [5] to calculate the field of the head in the tape near the gap in a fictitious write situation and used a reciprocity relation to transform the results to the actual read situation. This reciprocity relation is now known as the reciprocity relation of magnetic recording theory (see Ref. [6], chap. 3, in which alternative reciprocity relations can be found).

In 1980 Ruigrok (see Ref. [6], chap. 8), and Katz [7] each developed semi-analytical models for the calculation of the complex efficiency and the complex electrical impedance of 3-D magnetic heads like video heads. In fact these were 3-D finite-element (FEM) solutions with a small number of complex magnetic elements (10 to 20 in the beginning, 20 to approximately 50 in later versions), representing parts of the head and surrounding air. Because of a proper choice of the elements' shapes and of an accurate expression for each element's reluctance, the accuracy was still reasonable (error 20%) to good (error 5%) [6]. The advantages of these packages, i.e. extremely short CPU time and very quick adaption of head dimensions, are paid for with less flexibility regarding the configuration. Only a certain class of magnetic heads, namely, the class that includes discrete video-, audio- and instrumentation heads, can be analysed by this analytical video head model. Van Vlerken and Blanken [8] applied this concept to transformers. In addition, Blanken and van Vlerken transformed the reluctances network in the head and (rotary) transformer models to impedance networks for direct input in an electronic circuit simulator [9]. The advantages are many: these packages automatically include all kind of possibilities, like adding electronic circuitry to the head, switching from time- to frequency-domain analysis, transient analyses, (thermal) noise and power dissipation calculations, etc. Thin-film heads, however, cannot be treated accurately with the above models.

Purely numerical Finite Element Methods and Finite Difference Methods (FEM and FDM, respectively) were developed in the fifties and sixties for strength calculations. In the seventies, FDM and FEM packages were adapted to solve magnetostatic and electrostatic problems. The first more or less widely used (FEM) packages were MAGGY [10] (for 2-D magnetostatics) and
PADDY [11] (for 3-D magnetostatics), developed in the mid seventies by the former mathematical software group of the Corporate ISA (Informatie Systemen en Automatie) within Philips. For the study of side-fringing fields of 3-D magnetic heads, at Philips van Herk carried out computations with the magnetic-field surface-integral equation method (see Refs. [12] and [13]). The complete head field can also be calculated with this method. From the beginning of the eighties FDM and FEM packages for electrostatic and magnetostatic configurations from specialized firms like Vector Fields entered the market. Algorithms for nonlinear iterative calculations and linear eddy-current calculations were incorporated in these FEM packages right from the beginning. Both the user-friendliness and the number of standard post-processing possibilities were and are continuously increasing. Improvements were often the result of cooperation with customers. Better algorithms with which problems defined in cylindrical coordinates could be solved, were found by Melissen [14] in Philips and introduced into Vector Fields’ Packages. Another example is the simulation of coupled electromagnetic and heat-dissipation problems, worked out by Janssen et al. of the applied mathematics group of Philips Research in 1992 [15]. The incorporation of complex permeabilities in 2-D and 3-D FEM packages was stimulated by Ruigrok in the mid eighties in order to make realistic ferrite video head calculations possible. In these heads, high-frequency effects are caused not by eddy currents but by phenomena like ferromagnetic resonance (see Ref. [6], chap. 8). The resulting frequency-dependent losses and the lag between the flux and the drive current can be taken into account by introducing complex frequency-dependent permeabilities instead of a single real permeability. Since the end of the eighties and beginning of the nineties, it has been possible to use a complex permeability in, respectively, the 2-D and 3-D FEM packages of Vector Fields.

The big advantage of FDM and FEM packages is that nearly all configurations can be treated, including, for instance thin-film heads. The drawback is the long time period required to define the input for a new head, and the CPU time needed to calculate, for instance, the efficiency at many frequencies. The accuracy is good (error < 5%) as long as care has been taken to ensure proper meshing of the configuration. The latter demands experience and understanding of the device under calculation.

2.2. Thin-film head design tools

Thin-film heads can be accurately modelled by using the transmission-line concept. A transmission line consists of two good conductors, separated by an insulator, or more generally, 'a bad conductor'. Due to the high ratio in
the conductivities of the conductors and the insulator, simple second-order differential equations describe the current flow and potential losses, etc. in the transmission line with adequate accuracy. The application of this transmission-line model is, of course, not restricted to electric conductors separated by electric insulators. It can, with good accuracy, be applied to good magnetic conductors, like NiFe, separated by bad magnetic conductors, like SiO₂. Paton was, in 1971, the first to analyse a thin-film head in this way. He applied the concept to a simple uniform inductive head consisting of a single one-turn coil from the tape-bearing surface to the end of the thin-film head. In 1981, the same concept was used by Ruigrok [16] to analyse the response of Yoke-Type MagnetoResistive Heads (YMRHs) and Barber pole Yoke-Type MagnetoResistive Heads (BYMRHs) [16,17]. In contrast to the single-section inductive head used by Paton, these YMRHs consisted of five sections; see e.g. the birdseye view of a BYMRH in Fig. 1, to be discussed later.

In 1991 this transmission-line model was extended to include any amount of sections, MagnetoResistive Elements (MREs) and current-containing conductors. In addition, sections were allowed to be non-uniform, which means that the gap length or track width may increase or decrease linearly within a

![Diagram of a thin-film read head, according to Philips' BYMRH concept; see text. The head is cut through perpendicularly to the surface of the magnetic tape. The chain-dotted line is the line of intersection with the plane of the tape, where the heads are sawn from the wafer. AG is the read gap. CC is a conductor used for wafer tests and for biasing of the magnetoresistive element above CC. In the analog channels of the DCC head this conductor is also used for feedback. P is the upper fluxguide. The yoke of this 'ring head' is further completed by the ferrite substrate which acts as the lower fluxguide in the write head of Fig. 2.](image-url)
section. Bessel functions instead of simple exponential functions then appear in the solutions. Many characteristics of the head can be calculated on the basis of the transmission-line solution. The head’s inductance and resistance, for example, as well as the distribution of the magnetic scalar potential over the heads surface, were explicitly calculated. This potential distribution is essential in the calculation of the head’s impulse response, and subsequently the eye pattern, as published in 1993 by Ruigrok and Bombeeck [18]. The analytical thin-film transmission-line model was also extended to simple but adequate nonlinear analysis. It might seem unbelievable that applicable results are obtained in this way, without iterative calculations, but comparisons with nonlinear iterative FEM calculations (see Sec. 5) show the validity of the analytical results.

For almost any thin-film head configuration, the accuracy of linear transmission-line calculations is comparable to that of the best FEM results (usually errors < 5%). The advantages of transmission-line calculations are the facility to be easily adapted to other dimensions and the extremely short CPU times. The biggest advantage of trying to solve problems analytically is that it gives a better insight into the problem, and this often points the way to solutions.

In the next sections we will restrict ourselves to some illustrative results concerning write heads with YMRHs obtained mainly with analytical thin-film head transmission-line models and subsequent impulse-response and eye-pattern calculations. We will not go into the physical details underlying the models and the detailed mathematical elaboration of the models. Among the examples are write and read heads used in the Digital Compact Cassette (DCC) audio deck, planarized data write and read heads, as will soon be used in data recorders for personal computer multi-media applications, called DigaMax™ [19], special write heads for the production of tape with magnetic tracking information for DigaMax™, and very-small track width read heads for future applications that utilize anisotropy of the permeability instead of structuring of the fluxguides for obtaining very small track widths.

3. Thin-film write heads

From 1970, thin-film versions of ring-type write heads have been topics of investigation. An example of a thin-film two-turn head is shown in Fig. 2. Disk drives (IBM 3370 and 3380) employing thin-film heads with a single-layer multi-turn coil for writing and reading arrived on the market around 1980.

A write head must be able to generate fields that are strong enough to
overcome the coercive field, $H_c$, of the tape. 'Optimal' (long-wavelength) direct recording takes place at depths in the tape where the field amplitude is roughly $2H_c$. For short-wavelength recording the optimal recording depth is roughly $0.5 \mu m$. For optimal long-wavelength direct recording, the field deep in the tape must be larger than $1.5H_c$. This condition is usually not met. For bias recording, a bias field not much larger than $H_c$ is optimal. A larger bias field increases the linearity, but reduces the signal output. For short-wavelength recording it is further required that the field at the trailing side of the gap, where the actual recording takes place, reduces fast enough to a value well below the coercive field. When this spatial decay length becomes comparable to the signal wavelength in direct- or bias- sine-wave recording or comparable to the bit length or desired transition length in digital recording, then the writing head erases just-recorded parts in the tape (see Ref. [6], chap. 7). Good head-to-tape contact and sharp edges of the write gap are thus required. A small gap length is not so important in this respect, because the relative gradient only increases slightly when the gap length decreases from a value much larger than the head-to-tape distance to a value much smaller than the head-to-tape distance.
3.1. DCC write head

Various DCC heads are presented in Sec. 5.1. A photograph of a cross-segment of a digital channel in a prototype DCC head is shown in Fig. 3. The writer parts of these heads consist of the thick shared pole and the thick upper pole. The writers are all the same in the various DCC heads, but the readers are further improved in every new generation. The fluxguides are made of electroplated NiFe, which has a saturation magnetization $B_{\text{sat}} = 1 \text{T}$ and a relative permeability of a few thousands. For a writer gap length $g = 0.7 \mu\text{m}$, throat height of $1.25 \mu\text{m}$, fluxguide thickness $p = 3 \mu\text{m}$ and a (worst-case) relative permeability $\mu_r = 1000$, etc., the efficiency $\eta$ is calculated to be 82%. The analytical calculations show too that DCC writers saturate nowhere when applied for optimal recording of short-wavelength signals on low-coercive media. They fulfill the requirements mentioned in the previous paragraph when applied for media with $H_c < 80 \text{kA/m}$ (1000 Oe). Tapes and media with coercivities well above 80 kA/m cannot be recorded optimally with these DCC heads at distances $y > 0.5 \mu\text{m}$ from the head surface. In general, the design of thin-film write heads for low-coercive tapes is not very critical. At the optimal write current for short wavelengths, no parts of the head approach saturation when the NiFe fluxguides and the coil-chamber are all at least a few micrometers thick and the throat height of the writer head is small.

3.2. High coercivity media and deep recording

When high-coercive tapes, say tapes with $H_c > 80 \text{kA/m}$ (1000 Oe), have to be recorded at head-to-tape distances $y > 0.5 \mu\text{m}$, saturation in the head can give cause for concern. This is also the case when long wavelengths have to be recorded deep into the tape. In thin-film heads with a constant
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Fig. 4. Left: the current at the onset of saturation, \( I_{\text{sat}} \), as a function of the gap length, \( g \). Right: the maximum longitudinal component of the write field at \( I_{\text{sat}} \), \( H_{\text{ll, max}} \), as a function of the gap length, \( g \), for various head-to-tape distances, \( y \). In the calculations, \( B_{\text{sat}} = 1 \text{T} \) and \( \mu_r = 1000 \).

\[
\begin{align*}
H_f \, [\text{mA/m}] & \\
g_1 & = 1 \mu\text{m} \\
\eta & = 84.2\% \\
I_{\text{sat}} & = 565 \text{mA} \\
B_{\text{dgsat}} & = 476 \text{kA/m} \end{align*}
\]

\[
\begin{align*}
H_f \, [\text{mA/m}] & \\
g_1 & = 2 \mu\text{m} \\
\eta & = 87.6\% \\
I_{\text{sat}} & = 695 \text{mA} \\
B_{\text{dgsat}} & = 305 \text{kA/m} \end{align*}
\]

\[
\begin{align*}
H_f \, [\text{mA/m}] & \\
g_1 & = 3 \mu\text{m} \\
\eta & = 88.8\% \\
I_{\text{sat}} & = 757 \text{mA} \\
B_{\text{dgsat}} & = 224 \text{kA/m} \end{align*}
\]

\[
\begin{align*}
H_f \, [\text{mA/m}] & \\
g_1 & = 5 \mu\text{m} \\
\eta & = 89.8\% \\
I_{\text{sat}} & = 816 \text{mA} \\
B_{\text{dgsat}} & = 147 \text{kA/m} \end{align*}
\]

Fig. 5. The longitudinal field component at the onset of saturation of the head depicted in Fig. 4 at different distances, \( y \) in \( \mu\text{m} \), from the head as a function of the position, \( x \) in \( \mu\text{m} \), above the head. The deep gap field at saturation, \( H_{\text{dgsat}} \), is related to the gap length, efficiency and saturation current by \( H_{\text{dgsat}} = \eta \, I_{\text{sat}} / g \). Note that for \( y/g > 1/6 \) the maximum longitudinal field is always at the gap centreline, \( x = 0 \), of the head. In the calculations, \( B_{\text{sat}} = 1 \text{T} \), \( \mu_r = 1000 \).
pole width inside the head, this saturation always starts near the back of the head, since the highest flux levels occur there. With this characteristic in mind it is possible to calculate the current $I_{\text{sat}}$ at the onset of saturation analytically, using the transmission-line model. For the simple configuration depicted in Fig. 4, this saturation current is shown as a function of the gap length $g$. Furthermore, the maximum longitudinal field (at the centreline of the gap; see Fig. 5) is calculated at different distances from the surface of the head. Four effects determine which gap length leads to the maximum write field at a given distance from the head surface, assuming onset of saturation:

- smaller gaps lead to smaller head efficiencies (relation dependent on head design);
- smaller gaps give rise to larger Write-field Distance Losses, DLW (fixed relation);
- smaller gaps let heads saturate at smaller currents (relation dependent on head design);
- a smaller gap, at given $I_{\text{sat}}$ and $\eta$, leads to a larger (deep-)gap field, $H_{dgsat}$, because the magnetic potential over the gap $\Psi = \eta I_{\text{sat}}$ is then still the same. In more detail:

$$H(y, g) = H_{dgsat}H(y, g)/H_{dgsat} = [\eta(g)I_{\text{sat}}(g)/g]DLW(y, g).$$

The variation of the longitudinal component of the fields at different distances, on which the results in Fig. 4 were based, is shown in Fig. 5. A very accurate analytic approximation of the exact ‘Westmijze’ field was used for this purpose (see eq. (5.45) in Ref. 6 and eq. (3.44a) in Ref. 20). The shapes of the curves at 3 and 5$\mu$m gap lengths deviate greatly from the well-known Karlqvist approximation. The slight increase of the relative gradient (at $y = 0.5\mu$m) when reducing the gap length from 5$\mu$m (10$y$) or 1$\mu$m (2$y$) to 0.1$\mu$m (0.2$y$) is ‘visible’ too. The efficiency and saturation current for the various head configurations were calculated by transmission-line calculations. The (field) efficiency $\eta$ only decreased slightly, from 89.8 to 84.2%, when the gap length was reduced by a factor of 5 (see Fig. 5). For a head with a throat much larger than 3$\mu$m, or a head with a uniform gap over the entire height of the head, this effect is much larger. In the case of the uniform gap we calculated a decrease in the efficiency from 89.8% ($g = 5\mu$m) to 66.8% ($g = 1\mu$m). The main drawback of such uniform-gap configurations is, however, the enormous increase of the flux flowing around in the head, which causes a strong reduction of the saturation current. For the write head with the uniform gap of 1$\mu$m length, this saturation current is only 245mA, less than half the saturation current of the corresponding 1$\mu$m gap head with a 3$\mu$m throat as depicted in Fig. 4.
3.3. Nonlinear calculations

In Figs. 4 and 5 calculations were carried out at the onset of saturation with the aid of the transmission-line model. These calculations are very accurate. Not well-known is that calculations are possible even beyond saturation with the transmission-line model. However, some loss of accuracy is then unavoidable. For instance, the value of the permeability in the saturated region and the length of the unsaturated region can be estimated for currents above the saturation current, \( I_{\text{sat}} \). These values can be used to calculate the efficiency, the write field, and the AC self-induction, of the head beyond saturation. This is shown in Fig. 6 for a prototype write head for a Quarter-Inch Cartridge (QIC). The figure clearly shows that saturation takes place at the back side of the head. In heads with uniform width, and with a uniform distribution of the current over the full length of the coil chamber and a via at the end of the coil chamber, saturation always starts at the back side of the head and then extends slowly in the direction of the write gap. Here, two-thirds of the head are already saturated. The resemblance of the analytical approximations to the more accurate iterative nonlinear FEM results is already remarkably high. No iterative procedure was applied: the value of the analytically estimated length of the unsaturated front region (43 \( \mu \)m) of the head and of the analytically estimated value of the reduced permeability of the thinnest fluxguide (the lower one) in the back region (\( \mu_r = 121 \)) of the head were applied in the transmission-line model to directly give the results in Fig. 6. In the front part of the head and everywhere in the upper fluxguide the relative permeability value of 3000 of the unsaturated permalloy was used. The FEM results for the magnetic induction \( B \) are shown in the upper and lower fluxguides at 0.5 \( \mu \)m above and below the ‘coil chamber’, respectively. For the saturation magnetic induction of the fluxguides, \( B_{\text{sat}} \), a value of 0.9 T was used in all calculations of Fig. 6. The block-shaped magnetic induction in the 1-D transmission-line result reflects perfectly the continuity of the total flux in the upper pole. The resemblance of the magnetic induction levels to those of the FEM result shows too that the assumption that magnetic flux flows only through the fluxguides and not outside the head, and crosses the gaps perpendicularly, works quite well. This is even true in the saturated region, where the relative permeability is low, but still very large with respect to unity. Note that the permeability in the transmission-line calculations was only reduced in the thinnest pole. This was done for physical, and not for mathematical, reasons. When we chose for the thicker pole to saturate, then lower values of the permeabilities in the saturated region were obtained, but the same value for the length of the unsaturated region and, hence, the same
Fig. 6. Linear (see table) and nonlinear (see table and curves) calculations on a write head with \( B_{\text{sat}} = 0.9 \) T. (a) Configuration (prototype QIC write head) used for the linear and nonlinear calculations. (b) A comparison between magnetic induction values from an analytical calculation (transmission-line model) and a FEM calculation for a saturated prototype QIC head operating at 55 mA. (c) A comparison between efficiency and self-induction values from the analytical method, from FEM and from measurements, at small current (linear) and at 55 mA (nonlinear). The measurements include leads and parts of the coil outside the yoke, which are obviously of the order 0.15 \( \mu \)H.

Efficiency was calculated. The reason is that, in a 1-D transmission-line calculation, the same amount of flux flows (in opposite directions) in the upper and lower flux guides, because of continuity of the total flux, etc. It does not matter, mathematically, whether the maximum available ‘saturation’ flux, \( B_{\text{sat}} \times \text{Area} \), is caused by a reduction of the permeability in the lower pole or by a reduction of the permeability in the upper pole or by any other means.

For more accurate results, the analytically estimated permeability values at different positions in the head can be used as starting values in nonlinear iterative transmission-line calculations. This latter procedure, based on knowledge of the actual progress of saturation in a typical write head geometry, reduces the number of iterations tremendously. In a few steps (for instance, by hand!) results very close to those of 2-D finite-element methods are obtained.
Another possibility for 'manual' calculations that include saturation is to determine how much to reduce the permeability over how large of a region, starting at the back of the head, so as to maximize the region in which the saturation value is reached but not exceeded. In this procedure, use can be made of the mathematical freedom in choosing which permeability to reduce, as pointed out before.

4. Tracking and writing in the DigaMax™ system

In this section we describe a new system for high-speed linear recording of data, called DigaMax™. This system makes use of long-wavelength information, written deep into the medium, for dynamic track following. This deep-servo information is written into the tape with a so-called embossing head. This embossing head writes the servo-track information so deeply into the tape, i.e. mainly between 0.5 and 2 μm, that it is impossible for the data write head to overwrite this information. The emboss head resembles the head in Fig. 4. The data write head is shown in Fig. 23. Besides the number of turns, this data write head also resembles the head in Fig. 4. By using a total current of 160 mA and a gap of 1.3 μm for the data write head, and a current of more than 500 mA and a gap length between 2 and 5 μm for the emboss head, a 0.2 μm surface layer of the embossed tape, where the data field exceeds the coercive field, is overwritten. Since for optimal long-wavelength bias recording deep in the tape, where the data field exceeds the coercive field, the bias field deep in the tape must be roughly $H_c$, high demands have to be made upon the design of this embossing head. In the following sections, the dynamic track following in the DigaMax™ system will be explained, the embossing head design will be outlined and measured side-writing effects will be presented and explained.

4.1. High-capacity, high-speed data recording

There is an ever-increasing demand for high-capacity, high-speed data recording on tape. Given a certain area of tape, the total capacity can be increased by the following means:

- more efficient channel code,
- increased longitudinal density, attained by decreasing the recording wavelength,
- increased track density, attained by decreasing the track width.

The first generation DigaMax™ system uses a modified industry standard QIC cartridge with 72 kA/m (900 Oe) tape. With respect to current QIC
systems, the DigaMax™ system offers high capacity and data transfer rates by using, among other channel improvements, smaller tracks on tape and multichannel thin-film magnetic head technology.

4.2. Dynamic track following in the DigaMax™ system

Mechanical tolerances in a typical cartridge-loaded system are so large that at small track widths severe mistracking will occur between subsequent read and write operations with the data head in a static position. To circumvent this problem, the data head needs to be dynamically positioned to insure error-free tracking. Some kind of dynamic track-following information is therefore needed to inform the system on the relative position of the data head with respect to the position of data tracks on tape.

In the DigaMax™ system the data head is mounted on an actuator which can move the head along the full width of the tape with high accuracy. Dynamic track-following information is magnetically written on tape with a dedicated write head during the cartridge manufacturing process. The data head reads this information during read and write passes.

The tracking (or servo) information is embossed into the tape at the same location as that where the data information is stored. In this way, no valuable space is wasted. The permanent nature of the tracking information is achieved by writing relatively long-wavelength servo signals deep into the tape by means of AC bias recording and a relatively long write gap. By using an appropriate high AC-bias current level during embossing and a data write head with a smaller gap and a lower current level in the DigaMax™ recorder, no deeply written tracking information can be erased, not even after many overwrites.

The data head has no dedicated channels to read the tracking information; the data read channels themselves are used for this purpose. The reading of tracking information by the reader part of the data head works satisfactorily, even when the data head is writing simultaneously and the shared pole is almost saturated. This can be explained as follows.

— The tracking information consists of a very long wavelength signal with respect to the data signal wavelengths. A low-pass filter will reduce the short-wavelength data signals to an acceptable level.
— The yoke-type head has a high sensitivity for long wavelengths; these are directly read by the MR sensor. A possibly saturated shared pole is then fully acceptable.

The tracking information consists of a large number of adjacent longitudinal tracks with a pitch equal to the data track pitch. The embossed tracks contain sinusoidal signals with a 180° phase shift between odd and even tracks.
and with hardly any spacing between adjacent tracks. At intersections of odd and even embossed tracks the output of a data read channel shows a zero crossing. Some embossed tracks, called reference tracks, are wider than the nominal track pitch. In this way, at least one data read channel is always located fully on this reference track and reads a full-amplitude servo reference signal. This reference signal, multiplied by the added servo-signal outputs of the other data read channels located on or near zero crossings, is used as an error indication to steer the head actuator in such a way that the data head channels (with the exception of the reference channel) are always positioned at the zero crossings during data read and write operations.

4.3. Embossing head design

In the DigaMax\textsuperscript{TM} system, the pitch between two data tracks is 37.5 $\mu$m. The pitch of the tracking information must also be 37.5 $\mu$m. It is difficult in state-of-the-art technology, to design a thin-film head with all gaps in one line, which will be able to write adjacent tracks with 180° phase difference and hardly any spacing between the servo tracks (see Fig. 7).

By separating odd and even write channels in two stacked writer layers with a shared pole [21], the functional requirement of no spacing can, in principle, be met (see Fig. 8).

In principle, the head can operate with two electrical connections, as shown in Fig. 8. For fine tuning of zero points (see later), however, the windings in the actual design of each layer have separated electrical connections.

![Fig. 7. Servo write head functional requirement.](image-url)
A stacked dual writer head with a limited distance between the lower gapline and the upper gapline is difficult to construct in a conventional thin-film process with relatively thick polymer isolation layers (see Fig. 19). To eliminate undesired large topographical steps during subsequent depositions, the actual head is processed in a dedicated planar thin-film process without polymer isolation layers; see also the paper on design and technology in this issue [3]. During this process, thin-film layers are planarized by applying chemical mechanical polishing (CMP) [22,23] after each of the layers in the following sequence:

- pole of lower write circuit,
- first winding layer,
- shared pole of both write circuits,
- second winding layer,
- pole of upper write circuit,

The lower gapline to upper gapline distance in this design is only limited by the thickness of the shared pole. The use of a single winding per writer layer
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with a limited winding chamber depth ensures a good efficiency of the head. The cross-section of the upper and lower writers of the emboss head shown in Fig. 8 resembles the writer head in Fig. 4 when \( g = 5 \mu m \), i.e. when the gap length is equal to the thickness of the coil chamber. At a depth of \( 2 \mu m \) into the tape, the head field at the onset of saturation is just equal to the coercivity of the medium (72 kA/m; see Fig. 5), optimal for bias recording. Between 0.5 and \( 1 \mu m \) a write field of \( 1.5H_c \) is reached. Although technologically more difficult, it is obviously better (i.e. it saves current), to use the design in Fig. 4 with \( g = 2 \mu m \). This requires additional steps in the processing to make an extra NiFe ‘plug’ in the throat region of the head. For writing between 1 and \( 2 \mu m \) from the head surface, this gap length is optimal. Even at the distance of \( 1 \mu m \), the preferable field strength for direct recording of long wavelengths, \( 2H_c \), is reached, when \( I = I_{sat} \) is used. The efficiency of these heads, with and without a ‘plug’, is close to 90% according to the results shown in Fig. 5.

4.4. Fluxguide width and side writing

The writer poles and writer gaps have typical thicknesses of \( 5 \mu m \). The angle \( \phi \) between the write-pole’s edge and the shared pole is rather small, \( \pi/2 \), and the gap length is large. Hence, the decay of the write field is small compared with ‘conventional’ writers with structured upper and lower fluxguides (\( \phi = \pi \)) and smaller gap lengths. A rough estimation of the side-writing effect is calculated by assuming that information is effectively written beside the writer pole until the write field equals \( H_c \). This leads immediately to the following

Fig. 9. Side write effects due to trailing pole width.
approximation for the effective width $w_{\text{eff}}$: $w_{\text{eff}} = (w + 2g/\phi) (H_{dg} - H_e)/H_e$, where $H_{dg}$ is the deep-gap field and $H_e$ the coercive field of the medium. For a typical deep-gap bias field, i.e. $H_{dg} = 2H_e$, side-recording effects can be expected over distances beside the write gap of the order of the gap length. With pole widths $w$ of approximately 37.5 µm and gap lengths $g$ of 5 µm, side-writing cannot be neglected for the emboss heads.

To study the influence of side-writing on the emboss pattern, tracks were recorded on tape using slightly different servo-signal frequencies for the two halves of the head instead of a single frequency with a 180° phase difference. This makes it possible to discriminate between the recording effects of the upper half and the lower half. Bias and servo waveform and amplitude were similar to those applied during embossing of DigaMax™ tapes. Profiles of tapes embossed in this way were obtained by scanning a 5 µm track width MR-readout head across the tape. It is clear from Fig. 9 that the width of the recorded tracks depends on whether they were written by the lower or the upper half. With the upper fluxguide at the trailing edge, the track recorded

Fig. 10. The broken lines show the profiles of tracks recorded by the lower half (36 µm wide) and the upper half (45 µm wide) of the emboss head. These profiles were measured separately by applying simultaneously two slightly different servo-signal frequencies to the two head halves. The solid line shows the calculated emboss pattern on the basis of the track profiles measured, assuming a 180° phase difference.
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by the upper half is about 8 \mu m wider than the 36.5 \mu m wide upper pole, i.e. a region with a width of the gap length is recorded on both sides of the upper pole. As long as no saturation effects occur in the poles, this side writing is independent of tape direction and occurs for both halves. However, the tracks recorded by the lower half are overwritten in their side regions by the tracks recorded by the upper half resulting in a final width of about 36 \mu m for the tracks recorded by the lower half. Due to side writing and production tolerances in the width of the individual poles, the distance between odd/even and even/odd embossed track zero crossings will not be an exact multiple of the track pitch. By arranging the wider embossed tracks in such a way that a fixed number of data read channels are always positioned on odd/even zero crossings and the same number of data read channels are always positioned on even/odd zero crossings, these tolerances are effectively cancelled. If the relative level of signal amplitude on odd and even tracks is critical, a further fine tuning of the track widths for even and odd tracks can be realized by changing the servo-signal amplitude for both write layers individually. The solid line in Fig. 10 shows the calculated emboss pattern on the basis of the track profiles measured, assuming a 180° phase difference and an optimized servo-signal amplitude setting for both halves. Zeros are spaced close to 37.5 \mu m apart for both even and odd tracks.

5. Thin-film MR read heads

For writing, heads containing a coil are always used. However, reading is also possible by utilizing the magnetoresistive (MR) effect, e.g. as in Fig. 1, instead of measuring the induction voltage of a coil wound around the yoke of a ring head.

William Thomson, later known as Lord Kelvin, discovered the MR effect in 1856 in iron and in 1857 in Ni [24]. Although the MR effect has been known for over 100 years, it took until the end of the sixties for someone to realize the significance of this effect for reading information from magnetic media. This man was Robert Hunt of Ampex [25]; see also the Preface of Mallinson’s book on MagnetoResistive Heads [26] for historical details.

In this type of head, use is made of the effect that the resistance of some ferromagnetic materials like NiFe decreases considerably when the magnetization direction changes from parallel with (or anti-parallel to) the current direction to perpendicular to the current direction. In the MagnetoResistive Head (MRH) of Fig. 1, according to the Philips concept, the MRE bridges a gap in the yoke of a ring head (YMRH). The output of this YMRH is smaller
than the output of shielded and unshielded heads, having sensors in close contact with the medium. However, our head does not show 'thermal asperity' noise when it is in contact with the tape. For disk applications where this contact noise does not occur, the shielded and unshielded MRHs are undoubtedly advantageous. When, however, it becomes possible to make the magnetic contact between MRE and yoke in the Philips design closer than is currently possible [27], very high outputs will also become available for the YMRH, and disk applications become possible. The YMRH concept has been applied by Philips in various consumer and professional products over the last 17 years (see the section 'Thin-film heads for tape recording' in the paper 'Trends in digital magnetic recording' [19] in this issue).

The advantage of an MR head over an inductive head is its high and frequency-independent sensitivity. Especially the application of an MR sensor with a small cross-section or giant magnetoresistive multilayers (GMRs) leads to a magnetic head with a sensitivity much larger than that of an inductive head. Only above a certain frequency does the inductive head give more output. This so-called turnover frequency was below 1 MHz around 1980, but due to miniaturization and application of GMR multilayers, has now approached 10 MHz. Therefore, application of MR read heads started with audio and later also included medium data-rate computer storage, e.g. QIC tape streamers. In the immediate future, high data-rate video applications can be expected.

5.1. DCC read head

One of the latest applications of YMRHs is in the Digital Compact Cassette (DCC) recorder. The reader parts of these DCC heads all consist of a reader yoke in which an MRE is incorporated. The reader yoke contains the thin lower fluxguide and the thick shared fluxguide. A bias conductor is placed between these. The read heads are of the barber-pole type (BYMRH). The name 'barber pole' is due to conductive stripes on top of the MRE that are applied at 45° with respect to the length direction of the element [28]. The current in the MRE flows almost perpendicularly from one conductor stripe to the other (see Fig. 1). Since the magnetization at zero applied field is approximately in the length direction of the element, it makes an angle of approximately 45° with the main current direction through the element. This is just in-between the extreme 0° and 90° situations where maximum and minimum resistivity is obtained, respectively. Maximum linearity is obtained in this way, although not completely, because, at the edges of the MRE, the current makes an angle much smaller than 45° with respect to the length direction of the element. This is even true for the current in the centre
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Fig. 11. Explanation of the cross-section of the prototype DCC write–read head combination of Fig. 3. All dimensions are to scale: \( h_{\text{MRE}} = 475 \text{ Å} \), \( g_{\text{read}} = 0.40 \mu\text{m} \) and \( g_{\text{write}} = 0.70 \mu\text{m} \).

of the element, because of the finite distance between the barber-pole stripes with respect to the element ‘width’ and because of the imperfect conductivity of the barber-pole stripes with respect to that of the element. Furthermore, stresses, introduced by the barber-pole stripes, will also have some influence on the magnetization direction. A DC current through the bias conductor is applied to compensate for all these effects, in order to obtain maximum linearity. Magnetic feedback (sometimes called servo-bias) is used during playback of analog tapes, in order to increase linearity further and obtain HiFi specifications [29].

Fig. 12. Potential along the top and bottom ‘surface’ of the prototype DCC head of Fig. 11.
5.1.1. Prototype DCC head

A photograph of a cross-section of a digital channel of one of the first prototype thin-film heads for use in a DCC recorder was shown in Fig. 3. The cross section is explained in detail in Fig. 11.

The reader parts of these DCC heads all consist of a reader yoke in which an MRE is incorporated. The reader yoke contains the thin lower fluxguide and the thick shared fluxguide. A bias conductor is placed between these. The efficiency of the MR head is calculated to be 8.9%. Figure 12 shows the magnetic scalar potential over the outer head surface in a fictitious write situation, as calculated with the transmission-line model. The horizontal axis corresponds to that in Fig. 11. In this fictitious write situation, a current flows around the MRE sensor with a current density corresponding to the local sensitivity of the sensor. It is a consequence of the reciprocity theorem of recording theory that the longitudinal field due to this fictitious write current at a certain level in the tape is exactly the response to an impulse-shaped longitudinal magnetization at the same level in the tape. The above fictitious field distribution in the tape is directly related to the above defined potential distribution. Based on this knowledge, impulse responses for different head configurations can be estimated, as will be demonstrated. This 'mathematical' way of calculating the head's impulse response saves orders in computing time with respect to the 'physical' way of calculating the impulse response by shifting the impulse-shaped magnetization alongside the head and calculating the sensors' response at every position of the impulse-shaped magnetization moving with the tape. Using reciprocity, a single complete calculation suffices.

The two large drops in the potential in the fluxguide–MRE overlap region, at 15 and 25 μm, show that primarily the oxide layer between MRE and fluxguide is responsible for the low efficiency. Since the potential is properly normalized (divided by the fictitious current flowing around the MRE), the potential over the gap just equals the efficiency of the head. In addition, losses within the MRE that were due to its extremely small thickness have some negative effect on the efficiency: the normalized potential over the MRE, that is the difference of the potential between the beginning of the MRE at 15 μm and the end at 25 μm, is only 72% while the normalized internal potential of the MRE equals 100% by definition. Thus, 28% is already lost by potential loss caused by flow of magnetic flux through the narrow MRE. The losses in the remaining fluxguides are almost negligible. Note that we are explaining the losses in the head in the 'reciprocity' way. The corresponding 'physical' explanation for the low efficiency is that flux coming from the tape and entering the head has to choose between crossing the gap of the
read head before the MRE and flowing through the MRE. The latter means: crossing the high-reluctant oxidic layer between fluxguide and MRE, then flowing through the rather high-reluctant MRE and then crossing the oxide layer between MRE and fluxguide for the second time. The actual situation is that more than 90% crosses the gap in the head without (completely) flowing through the MRE.

The impulse response was calculated based on this potential distribution and based on the geometry of the tape-bearing surface of the head including the highly efficient write gap. The pulse from the sensitive read gap dominates the impulse response in Fig. 13. The impulse response shows many secondary characteristics of the head. For instance, a small signal is picked up by the write gap (positive pulse at $+4\,\mu m$) and by the edges of the head (negative peaks at $-1\,\mu m$ and $+7\,\mu m$). Furthermore, long-wavelength information at the MRE side of the head couples 'directly' with the MRE (wide negative 'tail' between $-60\,\mu m$ and $-5\,\mu m$). The impulse response is a fingerprint of the head. By measuring the impulse response and combining it with the present

![Impulse response](image)

**Fig. 13.** Calculated impulse response of the digital channel in a prototype DCC head.

![Frequency response](image)

**Fig. 14.** Frequency response of a digital channel in a prototype DCC head ($v = 4.76\,cm/s$).
Fig. 15. Cross-section of the digital channels in an improved prototype DCC write–read head combination with reduced element size. All dimensions are to scale: \( t_{\text{MRE}} = 475 \ \mu\text{m}, \) \( g_{\text{read}} = 0.40 \ \mu\text{m} \) and \( g_{\text{write}} = 0.70 \ \mu\text{m}. \)

type of model calculations, the geometry of the thin-film head can be roughly estimated. It sometimes saves having to make a cross-section by sawing and polishing.

The frequency response of the digital channel of the prototype DCC head is obtained with the Fourier transform of the simulated impulse response. The result in Fig. 14 shows small undulations due to interferences of the signals read by the read gap with the signals read by the write gaps and the edges of the thin-film head.

Fig. 16. Potential along the top and bottom 'surface' of the improved prototype DCC head of Fig. 15.
5.1.2. Improved prototype DCC head

The read efficiency of the YMRH can be increased by reducing the potential losses in the MRE (in the fictitious write situation according to the reciprocity relation). This can be done either by reducing the flux through the element or by reducing the length of the flux path in the element. A digital channel of a prototype DCC head implemented according to the latter idea is shown in Fig. 15: the total height of the element is reduced from 20 to 10 μm, and the overlap regions are reduced from 5 to 2.5 μm each.

If the overlap regions had not been reduced accordingly but had remained 5 μm each, the efficiency would have been increased from 8.9 to 10%. Since, however, the overlap regions were reduced accordingly, the efficiency decreased to 6.7%. Nevertheless, the output at constant sense current increased more than 2 dB due to the almost doubled (1.7×) resistance of the element with respect to that of the DCC head of Fig. 11.

In Fig. 17 the calculated impulse response of the digital channel of the

Fig. 17. Calculated impulse response of a digital channel in an improved prototype DCC head.

Fig. 18. Calculated eye pattern of a digital channel in an improved prototype DCC head.
improved prototype DCC head is shown. The only visible difference with respect to the impulse response of that of the prototype DCC head in Fig. 13 is the location of the maximum in the tail, which shifted from \(-15\) to \(-12\) \(\mu\text{m}\).

From the simulated impulse response an optimum equalization (differentiating read amplifier, two-stage IIR filter and 12-tap FIR filter) was calculated to approximate a \(\cos^2\)-shaped overall frequency response with flat group delay. Subsequently the optimum equalization was applied to the simulated impulse response. The eye pattern in Fig. 18 is a result of a simulated reading of a characteristic DCC sequence of 255 double transitions with an optimally-equalized read head with the above impulse response. This means that the DCC sequence was cross-correlated with the equalized impulse response, after which the 255 double transitions were projected over each other. It is noted that the cross-correlation equals the convolution only if the impulse response...
Fig. 21. Simulated impulse response of the digital channel in an actual DCC head. Note the decreased secondary pulse with respect to those of the prototype DCC heads.

is symmetrical. Although the eye pattern is not perfect, it is quite good. The imperfectness is mainly due to the secondary pulse caused by the writer. Noise was neglected in the calculations (see remarks in Sec. 5.1.3.).

5.1.3. Actual DCC heads

In actual DCC heads (see e.g. Fig. 19), the efficiency $\eta$ is increased from 6.7 to 10.6% by reducing, in the fictitious write situation (!), the flux through the element and through the separation layer between MRE and fluxguide. The considerable reduction in the thickness of the MRE, $t_{\text{MRE}}$, from 475 to 350 Å, reduced the efficiency increase only slightly. For the output or sensitivity of the head, the reduction of $t_{\text{MRE}}$ is of great importance, since the resistance as well as the flux density of the MRE are inversely proportional to $t_{\text{MRE}}$. Hence, the output, which is proportional to $\eta/t_{\text{MRE}}^2$, increased by almost a factor of 3. The head shown is applied in portables that have a recording facility.

Fig. 22. Eye pattern simulation of the digital channel in an actual DCC head. Note the improvement with respect to the eye pattern of the improved prototype head.
The flux reduction is obtained by increasing the distance between the shared pole and the lower pole by approximately a factor of 2 and by reducing the distance from TBS to the MRE section from 15 to 12 μm. Less flux then flows in the ‘ring head’ at the same fictitious write current around the MRE. The direct explanation, without using the reciprocity relation, is the following. A smaller part of the flux entering the head during reading crosses the gap between the shared pole and the lower pole, such that more read flux finally flows through the MRE. The increased distance between the shared pole and the lower pole is obtained by a 1 μm polymer on top of the gap oxide and a much thicker oxide above the bias conductor than in the prototype DCC heads of Figs. 11 and 15. A further advantage of the polymer layer above the MRE is the reduction of stress in the MRE and, therefore, a higher stability of the magnetoresistive element.

Figures 21 and 22 show the simulated impulse response and eye pattern of this actual DCC head. The eye pattern includes equalization. The improvement over the previous prototype DCC heads is obvious: the extra pulse from the write gap decreased with respect to the main pulse from the read gap and hence the eye pattern improved. In Ref. 18 we showed the good correspondence between the simulated and measured impulse responses and between the simulated and measured eye patterns of this type of DCC head. The recording in Ref. 18 was carried out on a well-erased tape.

We will not reproduce these measurements here, but only comment on the meaning of the good correspondence between simulation and measurement. This correspondence means that, for the given tape (CrO₂) and read track width (70 μm), the imperfect equalization, and not noise, is fully responsible for the imperfect eye pattern, since no noise was added in the calculations. On improperly erased tape, however, spurious ‘old-recording’ signals add to the noise and might easily deteriorate the eye pattern. Although the eye pattern of the actual DCC head is not perfect, it is evidently so good that almost no bit errors occur on pre-erased tape when tape and tape transport are in optimum condition.

When we compare the impulse response of the actual head with those of the prototype DCC heads, we observe that the pulse from the write gap decreased. As a result, the eye pattern improved with respect to those of the prototype DCC heads (see Fig. 18).

The geometry shown in Fig. 19 is also applied for the digital channels in a head, in home DCC recorders, but with a 1-turn write coil instead of the 2-turn write coil shown in Fig. 19. Due to the two turns in the portable version, the write current is halved, reducing the total power consumption in the portable recorder considerably.

In the home recorder, use is made of a mechanism to rotate the head for
reverse recording and playback. In such rotary DCC heads [30,31], which have nine digital read/write channels and two analog playback channels, three bias conductors are present, from which two are used for independent feedback of the analog read signals.

No mechanism to rotate the head in the portable recorder is applied. In these fixed DCC heads, which have two times nine digital read/write channels and no dedicated analog channels, the analog playback function is performed by adding the output of two digital read channels per analog track on tape. Such a head has four separate bias/feedback conductors. During analog playback, the two channels per track are fed back (and biased) together.

Fig. 23. Cross-section of digital channels in a planarized write-read head combination for multimedia (DigaMax™) applications. A SEM picture of a similar type of planarized head, but including a two-turn writer coil and barber-pole stripes, is shown elsewhere in this issue [3].

Fig. 24. Potential along the top and bottom ‘surface’ of the planarized DigaMax™ head of Fig. 23.
5.2. DigaMax™ heads

For the planar head of Fig. 23, the head technology is completely different: the MRE is processed on top of the read head and the read head on top of the write head. The absence of steep edges in the topography of a head, planarized at critical levels has many advantages: smaller dimensions now become possible. For instance, a reduction of the distance from tape-bearing surface (TBS) to MRE is now possible. This has the same positive effect on the efficiency of a YMRH as increasing the distance from the shared pole to the lower pole. In the DCC-head technology, because of thin-film deposition and etching-process tolerances and lapping inaccuracies, in combination with the topography of the head, a further reduction of the throat height was impossible. A drastic improvement of the efficiency is also possible when the thickness of the separation oxide is reduced. However, in the DCC-head technology, the barber-pole conductors on top of the MRE were embedded in the separation oxide in between the MRE and the fluxguide. Therefore, extra thick separate oxides were necessary to avoid short circuits and electrostatic discharge from MRE to fluxguide.

For the planarized head, drastic reductions were possible in the separation-oxide thickness, from 0.6 \( \mu m \) to only 0.3 \( \mu m \), and in the distance from TBS to MRE, from 12 to 7 \( \mu m \), because:

- sharper steps with less tolerances apply, etc. (reader polymer no longer necessary for a good efficiency);
- less steps apply, because barber-pole stripes are avoided (unnecessary in purely digital application) and the MRE is processed on top of the planarized read head;
- long-wavelength analog signals can no longer overdrive the sensor (feedback levels would otherwise be too high), only a single weaker

![Simulated impulse response of the DigaMax™ head.](image-url)
long-wavelength signal, from the 0° and 180° emboss tracks in the neighbourhood of the data read head, is sensed by the MRE.

As a consequence of all the improvements, the efficiency increased tremendously, from 10.6 to 18.6%.

The planarized head is applied in a linear tape drive named DigaMax™ for multi-media purposes, e.g. in personal computers. For this purely digital application without any analog playback functions, some distortion can be accepted and, hence, the linearizing barber-pole stripes could be avoided. Due to the elimination of the barber-pole construction, the resistance of the MRE is increased by almost a factor of three (2.6). In addition, the MRE’s thickness, \( t_{\text{MRE}} \), is further reduced from 350 to 300 Å. Therefore, in total, the sensitivity with respect to that of the actual DCC head increased by a factor of \( 6 \times (18.6/10.6) \times (350/300)^2 \), and with respect to that of the ‘improved prototype DCC head’, by a factor of 10. Due to the shortening of the front part of the head, not only the efficiency of the reader improved strongly, but also the coupling to the writer gap decreased strongly. This is visible in the large reduction to the writer pulse, which is hardly visible at 9 μm distance from the main pulse in the impulse response of the DigaMax™ head in Fig. 25. After optimal equalization, for the present comparison with the DCC equalizer, an almost perfect eye pattern is obtained (see Fig. 26).

In the last, ‘speculative,’ paper of this issue [27], directions are indicated along which heads with even higher efficiency and sensitivity might be and are being developed.

5.3. Heads with anisotropy-determined track widths

Yoke and shield materials for thin-film heads are usually deposited or annealed in a magnetic field to induce a magnetic anisotropy axis. This
anisotropy leads to a permeability which can be highly dependent on direction. The ratio of hard-axis permeability to easy-axis permeability for NiFe is typically around 30, which implies that the flux transport along the low-permeability easy-axis direction is significantly smaller than that along the hard-axis. This offers interesting design possibilities for thin-film heads. For instance, 'full-density' readout heads can be designed, suitable for the reading of several adjacent data tracks during one pass of the tape. In the following sections we will describe the design and discuss the microtrack response profiles of full-density MR readout heads in which a single elongated front fluxguide with a highly anisotropic permeability is shared by several channels.

5.3.1. Effect of anisotropy on effective track width

To understand the behaviour of thin-film heads which incorporate fluxguide elements that are much wider than the track width on tape and which have anisotropic permeabilities, we extended the existing analytical transmission-line model (see Ref. 6, chaps. 2, 5 and 11, and also Ref. 32) to include the anisotropy of the permeability. For similar calculations see Ref. 33. A worst case for the widening (in the transverse or $z$-direction) of the flux density profile across a fluxguide (i.e. in the perpendicular or $y$-direction) is obtained by neglecting the flux leakage from upper to lower fluxguide (i.e. in the longitudinal or $x$-direction). Reflection effects caused by the presence of the MR element and the finite dimension of the fluxguide along the head surface (measured in the $z$-direction) are both neglected. With these simplifications a simple expression for the relevant longitudinal component of the magnetization, $M_z$, is obtained. The magnetization is normalized to the magnetization in the centre.

Fig. 27. Calculated magnetization profile at 4 $\mu$m from the head surface for a 9-$\mu$m wide track on tape. The magnetization is normalized to the magnetization in the centre.
in the fluxguide can be derived:

\[
M_y(y, z) = \frac{\arctan\left(\frac{z+w/2}{\beta y}\right) - \arctan\left(\frac{z-w/2}{\beta y}\right)}{2 \arctan\left(\frac{w}{2\beta y}\right)}
\]

where \( \beta = \sqrt{\mu_x/\mu_y} \) is the anisotropy parameter and \( w \) is the width of the track on the tape.

A very accurate approximation of the spread-out, \( \Delta w \), defined in Fig. 27, is easily calculated from eq. (1) and reads \( \Delta w = \pi \beta y \). Assuming an easy-to-hard axis permeability ratio of 1/30 (\( \beta = 0.18 \)), the track-broadening at a depth of 4 \( \mu m \) into the head, i.e. at a realistic cross-over position to fluxguide and MR element, amounts to \( \Delta w = 2.3 \mu m \). Figure 27 shows the calculated magnetization profile at this position for a 9-\( \mu m \) wide track. To a great extent the width at half of the maximum value is independent of the depth \( y \) into the head and equals the track width of 9 \( \mu m \). Applying a MR detection width of, for instance, 2, 5 or 8 \( \mu m \), the cross-talk is estimated to be sufficiently low for a ‘full-density’ system applying a track pitch of 6 \( \mu m \), 9 \( \mu m \) and 12 \( \mu m \), respectively.

\[ (1) \]

5.3.2. Design of an 8-channel YM RH with shared fluxguide

Eight-channel readout heads were designed to verify the feasibility of
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anisotropy-determined track widths in YMRHs sharing a single elongated front fluxguide. Top views of the fluxguide and MR element layout for two designs are shown in Fig. 28.

The difference between the two head designs is in the front fluxguide, which is structured to the read track width for the design in Fig. 28a and is continuous for the design in Fig. 28b. Both heads are meant for reading a width of 5 \( \mu \text{m} \) and consist of a continuous 8 \( \mu \text{m} \) high MR element over all tracks and comb-like barber-pole connections for the different tracks. For multi-channel operation, a sense current is applied to the MR element by the two outermost contacts and the channel responses are determined by the differential voltage variations across two adjacent ‘barber pole’ leads. The overlap between front fluxguide and MR element is 2 \( \mu \text{m} \) and the pitch between channels is 9.4 \( \mu \text{m} \). After assembly, heads were lapped to a total height of 5 \( \mu \text{m} \) for the front fluxguide.

5.3.3. Measurements on 8-channel YMRH with shared fluxguide

Microtrack response profiles of full-density readout heads were measured on a QIC drive with the heads mounted on a micro-positioner with a resolution of 0.1 \( \mu \text{m} \). Special care was taken for a good tape guidance and a stable tape position with respect to the head. Microtracks with a width of

Fig. 29. Microtrack response profile of a head sharing a single elongated NiFe front fluxguide (filled circles) and of a head with several NiFe fluxguide elements structured to the desired read width (open circles). A 1.5 \( \mu \text{m} \) wide microtrack head was used for writing.
either 1.5 or 2.5 μm were recorded with special sandwich heads consisting of a thin unlaminated CoNbZr fluxguide layer, a discrete coil and a tape-bearing surface profile suitable for linear recording. The small write gap length of 0.2 μm for these heads minimizes side writing effects. Tracks with a 5 μm wavelength were recorded at a tape speed of 0.5 m/s on Co-doped Fe₂O₃ tape with a coercivity of 70 kA/m.

In Fig. 29 microtrack response profiles are shown of heads with electroplated NiFe fluxguides using the 1.5 μm wide microtrack write head.

It is clear that both types of head show similar read profiles with a full width at half of the maximum output of 5 μm. Small irregularities in the track profiles occurred due to tape positioning inaccuracies. The microtrack response profiles shown are an average of two consecutive measurements; this was done to reduce certain effects of the tape fluctuations on the shape of the profile. A certain smoothing or even broadening of this profile due to imperfect tape guidance and the finite width of the microtracks is, however, inevitable; the actual response profiles of the heads are therefore better than measured.

The response profile for the head with the shared front fluxguide shows that the anisotropy of the permeability is indeed sufficient to limit the signal detection to a large extent to the area on the tape between the contact on the MR element.

In a few of the channels of heads with 5 μm wide NiFe-fluxguide elements, increased Barkhausen noise was observed. Due to the large demagnetizing energy in single-domain front fluxguides with a width and a height of 5 μm, a multidomain configuration is likely to occur in these elements, resulting in Barkhausen noise. Full-density heads with a shared front fluxguide seem to be less susceptible to these domain instabilities. This indicates that the application of fluxguides with an anisotropic permeability might also be useful for conventional (multichannel) YMRHs as described earlier in this chapter. As long as the anisotropy is sufficient, the front-fluxguide width can be enlarged without significantly increasing the read width. In this way, conventional YMRHs can be designed for high-density applications with improved stability of the front fluxguide.

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Authors Biographies

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Hans W. van Kesteren: graduated in physics in 1981 and received his PhD degree at the State University of Leiden, The Netherlands, in 1985; Philips Research Laboratories, Eindhoven 1985-. From 1985 to 1989 he conducted research on quantum-well structures and defects in semiconductors by means of Optically Detected Magnetic Resonance and photo-luminescence spectroscopy. Since 1989 he has been working in the field of magnetism of thin-film media and devices. This work included the characterization and optimization of metallic multilayer media for Magneto-Optical recording and since 1993 has focused on the design, modelling and evaluation of thin-film heads for magnetic recording. He is currently involved in the development of heads for the DigaMax tape storage system.