DESIGN AND TECHNOLOGY OF SENSOR-LAST
THIN FILM MAGNETIC HEADS

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Abstract
The first thin film heads produced commercially by Philips were of the so-called sensor-first type, the sensor being processed on the substrate and the remaining parts of the head being processed on top of the sensor. This design has various drawbacks in comparison with a design where the sensor is processed at the end (sensor-last), such as a higher power consumption (low head efficiency) and limitations of use of high-temperature processes/materials. However, initially, topographic structures, step coverage and problems with wet chemical etching were obstacles in realizing the sensor-last design. The introduction of planarization in wafer processing technology opened the way to the sensor-last design. The design was introduced in heads for the DIGAMAX™ system and showed all the expected advantages in comparison with the sensor-first design. It also offers the possibility of applying new materials in the head, an option which is necessary for realizing new generations of recording systems.

Keywords: thin film magnetic head, sensor-last design, planarization, magnetoresistance, wafer technology, barber-pole, DCC.

1. Introduction
1.1. History
The idea of fabricating a magnetic recording head using techniques similar to those used in integrated circuit technology, was generated in the early sixties. The first thin film head was proposed by Gregg [1] in 1961, but it was not until 1970 that research results were published on the fabrication of horizontal and vertical thin film magnetic heads [2,3]. The thin film head is applied in computer disk drives, where it is integrated in the slider that flies
Thin film heads replaced ferrite heads, which have several disadvantages:
- very high inductance, limiting high recording density and data rate,
- track width and throat height are mechanically defined, with limitations for miniaturization,
- low magnetic permeability at high frequencies,
- low saturation magnetization, hence being unable to write on high coercivity media for high-density recording.

The first product containing a single-channel thin-film head was IBM's 3370 disk drive, launched in 1979. Design of thin-film heads has evolved from early single-turn to multi-turn designs with up to at least 50 turns. The high number of turns is mainly necessary for the reading process. More recently, magnetoresistive read heads were introduced.

Magnetoresistive (MR) read heads produce a very high signal per unit track width and can provide media noise limited system performance at very high areal storage density. The signal is independent of media speed and the heads are relatively simple to produce.

Multi-channel thin-film heads with separate read and write elements have been applied to digital audio and data recording. In this application, an inductive write head can be used in conjunction with a magnetoresistive element (MRE) for reading. This combination is a powerful design for advanced recording applications [4].

Within Philips in 1970, work started on 'integrated magnetism'. The subjects included thin-film magnetic heads, inductive heads for writing and MR heads for reading. It was focused on consumer applications such as audio and video recording and on professional recording applications. In all these applications the magnetic head operates in contact with the recording medium. MR heads in contact with tape are subject to thermal noise, but also to wear, corrosion and to electrostatic burn-out. To avoid these problems, in tape applications the MRE is incorporated in a magnetic yoke [5].

Thin film heads in consumer applications can only be price competitive in recording systems where high bit rates are needed in combination with low medium speed, resulting in the need for multi channel heads. The high sensitivity of the MR head offers opportunities for special features. In 1976, the first Philips papers on thin-film head technology were presented [6]. An important feature implemented in this technology was the barber-pole (BP) concept [7]. The MR effect is essentially non-linear, but in almost all applications some kind of linearity is needed. This is realized with the BP bias technique (Sec. 2.2.). Thick gold conductors are deposited on top of the MRE in a BP-like pattern that forces the current in the sensor to flow at 45°. In addition,
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apart from the linearity, the stability of the MR head is also improved. However, the output is reduced by 10 dB compared with other biasing schemes. As a result of the use of BP biasing, a large number of applications could be realized. In 1979 magnetic feedback was discovered [8]: with this method, the MR head could meet severe hi-fi specifications.

In 1982 Philips realized many different types of thin-film heads such as 32- and 64-track write heads and read heads for professional CLS and VLS (Communication and respectively Voice Logging Systems), magnetic MR sensors, a four-track auto-reverse hi-fi read-only head and 22-track write and read heads for an S-DAT (Stationary Digital Audio on Tape) recording system [9]. Philips continued with a small production of professional CLS and VLS heads in Eindhoven in what is now called Digamax [10].

In 1993 the Digital Compact Cassette (DCC) system was launched. The first heads to demonstrate the DCC system were made using known technology (separate write and read heads, ferrite substrates). Philips managed to realize the read/write head needed for the DCC system using also existing Seagate technological capabilities [11]. The cross-section of such a head is shown in Fig. 1a. First the MR read head is processed: the inductive write head is built on top (sensor-first design). The magnetic material in the head is permalloy (NiFe), the bias conductor and write coil are either Au or Cu, and the insulator is sputter deposited Al$_2$O$_3$. Polymer (backed photoresist) structures are used to increase the efficiency of the recording and playback yokes and to eliminate step coverage problems.

1.2. From sensor-first to sensor-last

The first DCC head was applied in home decks, but its power consumption was rather high for portable applications. The main reason for the high power consumption is in the design of the MR head. The thin NiFe layer had to be deposited on a perfect surface, in this case a freshly polished Al$_2$O$_3$ surface, to reduce Barkhausen noise. The BP overlay is located between MRE and magnetic yoke and this causes the need for a high DC bias current to linearize the MR response (Sec. 2.2.). In addition, to avoid short-circuit problems the oxide layer separating the MR overlay and the permalloy yoke had to be relatively thick, influencing the read efficiency in a negative way [12].

By reversing the design these problems are solved. In this sensor-last design, techniques for local planarization needed to be introduced to solve the step coverage problems and to have a perfect surface for MRE deposition. The applied planarization technique is a combination of chemical and mechanical polishing (CMP, see Sec. 3.). It is executed a number of times during the
Some advantages of the sensor-last technology are as follows.

— Sensor-last enables freedom in design to obtain high efficiency and a lower power consumption.

— The MR self-biasing influence on the effective BP angle differs significantly between sensor-first and sensor-last designs.

— Sensor-last allows high temperatures for optimizing the magnetic properties of the flux guide material and the possibility of using exotic materials (NiFe MR and in particular Giant MR layers can potentially be degraded or damaged at high temperatures).
Sensor-last thin film magnetic heads

— Large steps no longer occur in the head, implying no step coverage problems and fewer short-circuits, less stress and no problems in wet chemical etching of several materials.
— Sensor-last facilitates the reduction of the smallest dimensions.
— The necessary planar technology offers opportunities for more efficient processing, resulting in smaller technology gaps (i.e. the gap between the substrate and the cover bar) which are favourable with respect to wear of the magnetic tape heads.

Some design aspects with respect to sensor-first versus sensor-last are considered in Sec. 2. Section 3 describes the planarization process which enables the sensor-last design. In Sec. 4, the head materials are discussed. Some considerations on requirements and water testing are given in Sec. 5. Machining and assembly of thin-film magnetic heads are briefly described in Sec. 6. Finally, conclusions are presented in Sec. 7.

2. Design aspects of a yoke-type barber-pole (BP) biased MR head

2.1. Introduction

The BP yoke-type head has proven to be a useful design for the DCC application, especially for the backwards compatible Analog Compact Cassette (ACC) playback function. The DCC thin-film heads were the first to integrate read and write channels with a common flux guide, the ‘shared flux guide’, which is part of both the write and the read head (see Fig. 1a and 1b). The MRE is buried in the head. To obtain an acceptable gap erosion and corrosion resistance for the DCC application, it is necessary to apply a tape bearing surface coating. This coating is electrically conductive, but there is no risk of short circuiting the sense current through the MRE by this conductive coating. The analog playback compatibility function has been optimized by making use of the magnetic feedback principle [8]. In the DCC heads both analog playback channels use their own separate bias conductor.

2.2. Barber-pole biasing

The MR response is \( \Delta R/R = \cos^2 \phi(M, J) \), with \( \Delta R \) being the (change of) electrical resistance of the MRE, \( M \) and \( J \) being respectively the magnetization and current density and \( \phi \) the angle between the directions of \( M \) and \( J \). Without any form of biasing this response is not linear. To create a linear transfer curve, the working point is chosen to be an inflection point. The MR response
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has an inflection point at an angle of 45° and can be linearized by either rotating the current direction or by rotating the magnetization to 45°. The first option is realized by the BP structure (Fig. 2). The sheet resistance of the BP stripes is much lower than the sheet resistance of the NiFe layer of the MRE. The stripes more or less act as electrical equipotential planes. The electrical field just outside the stripes will be aligned perpendicular to the edge of the stripes. In practice, the geometry of the BP structure results in an effective BP angle less than 45°, because the transfer curve will not be perfectly linear.

In the BP structure, two different types of area can be distinguished: underneath and between the stripes. The areas between the stripes contribute to the electrical signal. In both types of area, the current density makes an angle with the easy axis of the MRE. The easy axis is parallel to the long axis of the MRE. The magnetic field due to the sense current also makes an angle with the easy axis. The component of this magnetic field vector along the hard axis results in self-biasing of the MRE, the component along the easy axis results in additional stabilization or destabilization of the sensor, depending on the direction of sense current and magnetization of the MRE. It has been found that the easy axis component underneath the BP stripes is dominant with respect to stabilizing the MRE. Given a fixed sense current and MR magnetization direction, this implies a design rule for the orientation of the BP stripes with regard

Fig. 2. Barber-pole (BP) schematic drawing: 1, MRE; 2, connections (overlay); 3, BP stripes (J, current density; M, magnetization; H, induced magnetic field for two configurations: sensor-first or sensor-last).
to maximum stability: between the BP stripes, the vector product \( \mathbf{J} \times \mathbf{M} \) must point into the substrate. Stable and unstable configurations are depicted in Fig. 3.

Between the BP stripes, the magnetic field component due to the sense current along the hard axis results in additional biasing of the sensor. The strength of this self-bias field is enhanced due to the presence of the shared flux guide. The direction of the bias field is determined by the sense current direction and by whether the shared flux guide is located above or underneath the sensor, as imposed by Ampere’s law. In practice, the effective BP angle is less than 45°. With the sense current direction chosen for maximum stability, the presence of the pole underneath the sensor results in an increase of the effective BP angle towards 45°. A pole above the sensor results in a decrease of the effective BP angle. In the first generation DCC heads, this distortion increasing offset is compensated for by rotating the magnetization by means of a direct current of 7 mA through the bias conductor. Hence, sensor-first (Fig. 1a) requires an additional biasing in order to have the same linear properties as sensor-last (Fig. 1b).

In addition, in a sensor-first design the BP stripes being located on top of the MRE leads to a lower efficiency, given a fixed insulation thickness between MRE and reader flux guides. The gain in efficiency in the sensor-last design is achieved by moving the MRE towards the tape bearing surface.
By moving to a sensor-last design, the sense and bias currents could be lowered from 10 and 7 mA to respectively 5 and 0 mA without the output level being reduced.

3. The planar process

3.1. Introduction

As explained in Sec. 1 and Sec. 2, due to its advantages the sensor-last design is preferred, and, consequently, local planarization steps are needed.

Planarization has long been a part of thin-film head processing. It is applied to obtain a flat surface at the start, a substrate covered with a polished Al₂O₃ layer and also at the finished wafer surface on which the cover bar is bonded. The process which is used nowadays is still a more or less conventional mechanical polish of an Al₂O₃ layer. The shift to MR thin-film heads triggered the need for more smooth surfaces. By applying a chemical mechanical polishing (CMP) process this requirement could more easily be realized [13]. This explains a tendency in the thin-film head industry to shift to CMP planarization processing.

An improvement of the integral efficiency could be obtained by shifting from the final one-step planarization to 'local' planarization. Total oxide thickness decreased from 40 to 50 μm to 17 to 20 μm (see Figs. 1a and 1b). Moreover, a 40 μm Cu plating step (including the dry resist process) needed for electrical feed-throughs could be avoided.

Since well-controlled smooth surface quality is a requirement for this construction, a CMP process has been chosen for the sensor-last process flow. This choice became possible because at the very moment this decision had to be made, the release of CMP in the semiconductor industry started. In this industry the process is used for the realization of multi-contact layer processes.

3.2. Process description

The principles of the process are very similar to those of the semiconductor industry. However, a few typical differences connected to the application of CMP for the present magnetic heads are (i) the presence of a heterogeneous surface of SiO₂ and NiFe, (ii) the use of a 2.8 mm thick ceramic Al₂O₃–TiC (alsimag) substrate and (iii) the occurrence of step heights as high as 1 to 6 μm.

3.2.1. Surface

At Philips Magnetic Heads & Modules, SiO₂ has been chosen instead of
Al₂O₃ as the oxide material. One of the reasons is that substantially higher deposition rates can be obtained in the plasma-enhanced chemical vapour deposition (PE-CVD) process used for SiO₂ deposition.

In magnetic heads flux guides are the thickest structures. For this reason after each flux guide manufacturing step in general a planarization step is done. From the design point of view it is better to deal with the tolerance from the planarization process as part of the tolerance of the resulting flux guide thickness after planarization (see Fig. 4). The consequence of this choice is to planarize a heterogeneous surface with the need to balance the removal rate of SiO₂ to that of NiFe or any other used flux guide material. Adequate tuning of and control over polishing parameters will keep the resulting step between SiO₂ and NiFe within specification.

3.2.2. Substrate

The non-uniform removal rate over the wafer diameter is typical for a polishing process. This can be corrected for by introducing a bow to the substrate while loaded in the machine. Special carriers are available for achieving this. The use of a thick ceramic substrate with its relatively high stiffness makes it somewhat tougher to correct. Moreover, other parameters add to this non-uniform process: (i) non-uniformity of the oxide layers and of NiFe layers, (ii) type of planarization step, (iii) initial bow of the substrate, (iv) application of a flat and (v) varying non-uniformity due to wear of the
polishing pads. Process reproducibility is obtained by tight off-line control of the removal rate and the uniformity factor (i.e. the ratio between removal outside/removal centre).

3.2.3. Process types of planarization

To create a sensor-last design without polymer and overcoat layers, the thin-film layers need to be planarized at four locations in order to have suitable flat surfaces for writer coils, bias conductor, MRE and chip surface for mechanical mounting of the cover bar (after deposition of the writer flux guide, the shared flux guide, the reader flux guides and the protective oxide layer, respectively). The writer efficiency can be enhanced by adding an additional planarization step after deposition of the writer coils (this step has not been implemented for the DCC heads as shown in Fig. 1b). Various planarization types are described in the following:

'Buried' flux guide (Fig. 4a). This type is chosen for flux guides that need good width control (within ±2 μm) in order to define track width in relatively thick layers (3 to 6 μm). This is obtained by the etch of the SiO₂ layer (4 to 6 μm) in which the flux guide is buried. Special attention has to be given to the step coverage of NiFe over the etched pattern. An additional process parameter for this type is the amount of overlap of the NiFe over the SiO₂. A trade-off has to be made between the robustness of the etching and the planarization.

'Taper etched' flux guide (Fig. 4b). This is used if no tight specification on the flux guide width is needed. The smooth slope of the flux guide results in a good step coverage of SiO₂ over the relatively thick NiFe pattern (5 to 8 μm).

Reader flux guide (Fig. 4c). The flux guide is formed by the ‘box/lid’ or ‘plating through mask’ method [10] which gives flux guide width control defined by the lithographic process. This method is more accurate (±0.5 μm) than the wet chemical etching process of Fig. 4a. However, step coverage over the straight edges is the demerit of this process which only makes it usable for relatively thin layers (0.5 to 1.5 μm). Attention also has to be paid to sufficient spacing between the patterns in order to prevent formation of voids. Because of the application for relatively thin layers, this type of planarization is sensitive to non-uniform polish and even to effects of local non-planarity due to underlying planarized structures.

'Top' planarization (Fig. 4d). This type is usually a finishing step of the wafer
processing applied to planarize the top structure (in our case the MRE) mainly consisting of leads (total structure height 0.7 \mu m). It is typically a homogeneous SiO\textsubscript{2} surface planarization, used to obtain a flat surface in order to achieve a good performance of the cover bar glue process (see Sec. 6.2.1.).

Future trends in the planarization process for magnetic heads are towards improved cleaning procedures, implementation of programmable adjustment of carrier bow and introduction of alternative flux guide materials.

4. Head materials and processes

A magnetic head basically consists of soft-magnetic layers, electrical conductors, insulation layers and the MRE. In the following section the material choices for the former three classes of functional layers as applied in the head, are elucidated in relation to the opportunities the sensor-last design and the planarization process have to offer. The MRE is discussed in a previous chapter of this issue.

4.1. Materials and technologies for present heads

The wide range of materials and deposition methods that are applied in the single device is typical for the MR magnetic heads. Table I gives an overview of the process variety that is presently in use at the waferfab of Philips Magnetic Heads & Modules in Eindhoven, The Netherlands.

4.2. Soft-magnetic layers

Unlike permalloy, which is deposited in a magnetic field, some soft-magnetic materials need to be annealed in a magnetic field to obtain the desired magnetic properties. The required annealing temperature may exceed the maximum temperature beyond which the MRE is damaged. As contrasted to the sensor-first design, in the sensor-last design this annealing temperature is not limited any more by the presence of the MRE. Hence, the sensor-last design offers the possibility of application of new flux guide materials, needed for more advanced magnetic recording systems.

4.2.1. Demands

Demands on the soft-magnetic layers concern magnetic, electrical, mechanical and chemical properties and deposition techniques. They depend on the head specifications and on the function the layer fulfils in the head, i.e. being a flux guide in the recording and/or play-back circuit or being part of the MRE.
### TABLE I
Overview of processes used in the fabrication of thin film magnetic heads.

<table>
<thead>
<tr>
<th>Deposition process</th>
<th>Material</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrodeposition</td>
<td>NiFe</td>
<td>Flux guide</td>
</tr>
<tr>
<td></td>
<td>Cu</td>
<td>Writer coil</td>
</tr>
<tr>
<td></td>
<td>Au</td>
<td>Feed-through*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bond pad</td>
</tr>
<tr>
<td>Physical vapour</td>
<td>NiFe (in-field)</td>
<td>MRE, plating base</td>
</tr>
<tr>
<td>deposition (PVD)</td>
<td>CoPt</td>
<td>Permanent magnets</td>
</tr>
<tr>
<td></td>
<td>Mo</td>
<td>Adhesion, dry etch mask</td>
</tr>
<tr>
<td></td>
<td>Au</td>
<td>Leads, plating base</td>
</tr>
<tr>
<td></td>
<td>Cu</td>
<td>Plating base</td>
</tr>
<tr>
<td>Plasma enhanced</td>
<td>SiO₂</td>
<td>Insulation</td>
</tr>
<tr>
<td>chemical vapour</td>
<td></td>
<td>Planarization overcoats*</td>
</tr>
<tr>
<td>deposition (PE-CVD)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Lithography processes**

**Standard processes**
- Thick resist processes
- Dry resist process*
- Lift-off processing*

**Various processes**

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet chemical etching</td>
</tr>
<tr>
<td>Dry etching</td>
</tr>
<tr>
<td>Planarization</td>
</tr>
<tr>
<td>Cleaning</td>
</tr>
<tr>
<td>Measuring</td>
</tr>
<tr>
<td>Water probing</td>
</tr>
</tbody>
</table>

*) Not used for the planar process.
For the flux guide materials, relevant magnetic properties are coercivity $H_c$ (soft-magnetic behaviour), saturation magnetization $M_s$ (determining the maximum write field), permeability $\mu$ (affecting the head efficiency), magnetostriction (representing the coupling stress/soft-magnetic properties), anisotropy and the magnetic domain structure. The specific electrical resistance, $\rho$, of the material should be high to keep the reduction in permeability due to eddy currents, especially at higher frequencies, as low as possible. With respect to mechanical properties, thermal expansion coefficient (stress), hardness (differential wear), adhesion and machinability, the soft-magnetic material should match to a greater or lesser extent the other head materials. As for the chemical properties, the material should preferably be able to be structured wet chemically (if not electrodeposited, see Sec. 4.2.2.) and it should be corrosion-resistant.

Commonly applied deposition techniques are sputter-deposition or electrodeposition. In general, electrodeposition is preferred because it is a cheaper technique with a higher deposition rate and it offers the possibility of pattern definition by plating through mask.

4.2.2. Materials

In Table II, three classes of soft-magnetic layers are distinguished. NiFe is electro-deposited in a magnetic field. The amorphous Co alloys and the nanocrystalline Fe alloys may be sputter-deposited in a magnetic field, but still have to be annealed in a magnetic field at temperatures of 350°C or more to obtain the desired magnetic properties.

<table>
<thead>
<tr>
<th>Class</th>
<th>Examples</th>
<th>$\mu_0M_s$ (T)</th>
<th>$\rho$ ((\mu\Omega) cm)</th>
<th>$\mu$</th>
<th>Deposition method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permalloy</td>
<td>NiFe</td>
<td>0.8–1.0</td>
<td>20</td>
<td>2000–3000</td>
<td>Electro-deposition</td>
</tr>
<tr>
<td>Amorphous</td>
<td>CoZrNb, CoZrTa</td>
<td>1.0–1.4</td>
<td>110–130</td>
<td>1500–3000</td>
<td>Sputter deposition</td>
</tr>
<tr>
<td>Co Alloys</td>
<td>FeTaN, FeAIN, FeNbSiN</td>
<td>1.4–2.0</td>
<td>80</td>
<td>3000–10 000</td>
<td>Sputter deposition</td>
</tr>
</tbody>
</table>
It may be obvious from Table II that for high-frequency and high-density applications permalloy will no longer be satisfactory. The $M_s$ is too low to generate a sufficiently high magnetic field to magnetize high-coercivity tapes without saturating the NiFe layer. In addition, eddy current losses at the required high frequencies are too high due to the low $\rho$. Hence, amorphous Co alloys or nanocrystalline Fe alloys are needed (see also [14,15]). Investigations on electrodeposition of amorphous Co alloys are reported (see e.g. [16,17]), but coercivity and/or corrosion sensitivity may be too high. If these materials cannot be electrodeposited successfully with the required properties, the plating through mask method and the corresponding tight tolerances cannot be applied. Hence, a reproducible wet or dry etching process is then needed to pattern these layers within the required tolerances.

A well-defined, stable domain pattern in the soft-magnetic layer is essential for an optimal and stable performance of the head. The domain pattern is determined by the anisotropy, but is also stress related through the magnetostriction. In tuning the magnetostriction to zero (through composition and annealing process), the effect of stress on the domain pattern is minimized. However, for very small track width applications a negative magnetostriction is often used to obtain a stable domain pattern. In general, the induced anisotropy can be fixed by annealing or depositing in a magnetic field, but the ultimate domain pattern also depends on the shape and topography (pinning points) of the magnetic layer and the neighbouring magnetic layers.

As an example, in Fig. 5 domain patterns in CoZrNb layers are shown. It is

![Fig. 5. Magnetic domains in CoZrNb layers (variation of deposition/annealing sequence and topography): (a) deposition on a flat surface, magnetic field annealing before etching (taper etched flux guide, see Fig. 4b); (b) deposition on a flat surface, magnetic field annealing after etching (taper etched flux guide, see Fig. 4b); (c) deposition on a topography (in a hole), magnetic field annealing before polishing (buried flux guide, see Fig. 4a); (d) deposition on a topography (in a hole), magnetic field annealing after polishing (buried flux guide, see Fig. 4a).](image)
very obvious that the best domain pattern is obtained by first depositing the layer on a flat surface, then annealing it in a field and finally patterning it (Fig. 5a). The other procedures yield lower-quality products.

In conclusion, NiFe is a good soft-magnetic layer for application in present thin-film heads, but for new, more advanced applications (high density and high frequency) new materials are required. Amorphous Co alloys and nanocrystalline Fe alloys are promising options. Work along these lines is being continued [18].

4.3. Electrical conductors

In the sensor-first design, polymer layers served as a means to planarize the surface underneath the shared flux guide. In the sensor-last design, due to planarization the thicknesses are minimized and the polymer insulation layers and the overcoat are omitted (compare Fig. 1a and Fig. 1b). The relatively thin protective oxide layer enabled the elimination of the thick electrical interconnection studs.

In thin-film heads in general, Cu or Au are used for electrical conductors because of their low specific resistance, $\rho$ (bulk values: Cu, 1.68 $\mu\Omega$ cm; Au, 2.24 $\mu\Omega$ cm; and, for comparison, Al, 2.65 $\mu\Omega$ cm). The application of Au in the barber-pole, overlay and bias coil originates from the technology module 'MoAuMo', a module in which Au cannot be replaced by Cu. For the writer coil Cu is used; the bond pads are made of Au because it is more suitable for bonding foils or wires than Cu (oxide layer). Both Cu and Au can be electrodeposited or sputtered. In general, the sputtered layers have a somewhat higher $\rho$ than the bulk values (sputtered: Cu, 2.0 $\mu\Omega$ cm; Au, 2.4 $\mu\Omega$ cm), whereas those of the electrodeposited layers agree more with the bulk values. Apart from this, the choice between electrodeposition and sputtering is also based on technology arguments and cost/time aspects.

4.4. Insulators

Due to the application of planarization in processing sensor-last heads thick polymer layers are not requested any more: planarization enables the application of much thinner insulation layers.

Insulators are used to separate the soft-magnetic layers and electrical conductors in the head electrically and to fill the space between them. Pin holes and contamination can cause short circuits, especially when the insulation layer has to be very thin [gap layers, separation layer between MRE and read flux guide (some tenths of a $\mu$m)]. By constituting such a layer out of a stack of intermittently deposited layers (possibly with additional cleaning...
between successive depositions), the insulating quality may increase. Commonly used materials are SiO\textsubscript{2} and Al\textsubscript{2}O\textsubscript{3}. The disadvantage of SiO\textsubscript{2} in comparison with Al\textsubscript{2}O\textsubscript{3} is its very low thermal expansion coefficient in comparison with the other head materials, which may result in stress problems when subjected to temperature changes. On the other hand, SiO\textsubscript{2} can be deposited by PE-CVD, whereas Al\textsubscript{2}O\textsubscript{3} is sputtered: a major advantage of PE-CVD is its much higher deposition rate and better step coverage than that of sputtering. In general the wet chemical etching behaviour and mechanical hardness of SiO\textsubscript{2} are better. The choice of whether to use either PE-CVD SiO\textsubscript{2} or sputtered Al\textsubscript{2}O\textsubscript{3} therefore depends on the application (e.g. if very thick layers are needed, Al\textsubscript{2}O\textsubscript{3} may be the only option when the use of SiO\textsubscript{2} might result in too much stress).

5. Requirements and wafer testing

The head is subdivided into two functional parts, each having their own requirements for optimal performance. Modelling plays an important role in the development of thin-film heads [19]. Without going into detail on this modelling, an attempt is made to outline the specific requirements and to note the limitations which are met on implementation in the technology.

5.1. Write head

The requirement for the write head to create a sufficiently high magnetic field to magnetize the tape, means obtaining a high current density in the head close to the tape. The magnitude of this field is restricted by current level and resistance of the write coil. It can be translated into the need for a small pitch multi-turn coil of low resistance. For this coil therefore, Cu layers (1 to 3μm) are deposited by electrodeposition. The structure of the coil is made by means of a standard resist plating mask. Pitches of less than 10μm are needed. Good step coverage of SiO\textsubscript{2} over this Cu coil is needed in order to obtain good reliability. These requirements result in critical lithographic processes with special emphasis on resist slope control.

Demands on the properties of the flux guide materials, especially for new applications, were discussed in Sec. 4. In general, the tendency is also towards smaller flux guides with tighter tolerances for the track width. The realization of these tolerances in this thick technology is not easy.

5.2. Read head

Next to the efficiency of the MRE (thickness and width) in the read head,
much can be gained (within the limitations of the yoke-type head) by designing a high efficiency flux path from tape to sensor. Some of the key issues are as follows [12].

— The length of the flux path is limited by the amount of process steps needed to make the construction: it is limited by a summation of overlaps. Taking into account process tolerances and layer-to-layer alignment accuracy, these overlaps should be minimized to well below 1 \( \mu \text{m} \). Although line widths of the structures are not very critical, tight tolerances are not easy to obtain. A careful choice of equipment and processes is made in order to obtain state of the art efficiencies needed for the coming generation of small-track high-frequency magnetic recording heads. All specifications can be met with the available systems used for VLSI semiconductor processing.

— The separation between flux guides in the yoke should be large enough to restrict parasitic leakage of flux. Since the gap region is formed by two flux guides with limited distance (< 0.5 \( \mu \text{m} \)), steps, realizing more distance, should be formed as close as possible to the gap region, preferably within a few \( \mu \text{m} \) (see Fig. 1b).

— The separation between flux guide and isolated MRE should be small in order to obtain efficient transport of flux to the MRE. Limitations are found in the reliability of the head. Breakdown of the oxide will result in yield losses in the back-end processing of the heads.

5.3. Integration-related issues

In addition to these design-based technological issues, the MR thin-film magnetic heads also suffer from other integration-related processing issues. These can be summarized by three main subjects:

— magnetic instability which is mainly due to uncontrolled magnetic behaviour caused by movement of inherently present magnetic domain walls,

— electrostatic discharge (ESD) robustness, limited by step coverage over thick layers and application of thin oxides,

— adhesion (in combination with mechanical stress) on all of the interfaces: bad adhesion is a continuous threat for the mechanical robustness needed for the back-end processing.

5.4. Wafer testing

Apart from providing a means for additional MRE biasing, the bias conductor can be used to test the MR sensors for performance characteristics on wafer level. This feature has proven to be a valuable tool during
development and in production. An alternating current is superimposed on the bias conductor current which results in an MRE output comparable with the typical output on tape from finished heads. Parameters such as output, harmonic distortion and Barkhausen noise are easily measured. Application-realistic performance testing is performed by measuring these parameters at various bias current settings. By supplying intermediate pulses through the writer coil and the bias conductor, latent instabilities can be detected. Rejection criteria are imposed on output variation between pulses and on maximum Barkhausen noise.

6. Machining and assembly

6.1. Functional requirements for a finished thin-film head

The individual devices on the wafer have to be separated in order to create individual magnetic heads. After this separation some kind of head contour needs to be realized in order to enable tape to move along the thin-film magnetic gaps (the tape running direction is perpendicular to the thin-film wafer). These steps are performed in the machining process.

The throat height of these heads (being the height of the gap in the direction perpendicular to the head surface) is defined in this machining process. The output of the head increases significantly at decreasing throat height, but when considering head life time a large throat height is preferred. It is obvious that the throat height has to be controlled very accurately: the most optimal value with respect to head output and life time has to be realized within tolerances as small as possible.

The integration of the machined thin-film devices with an electrical connection and a housing is performed in the assembly process.

6.2. Machining process

6.2.1. Introduction

The machining of thin-film magnetic heads starts with a finished thin-film wafer and is shown schematically in Fig. 6. The flow is represented by the following steps:
- the thin-film wafer is sliced into bars and the cover bars are cut and lapped at one side,
- the cover bars are bonded on the thin-film bars,
- the head contour is formed by means of grinding and lapping,
- the bars are cut into individual pieces.
Normally the cover bar and substrate material are chosen to be the same. By means of grinding and lapping a head contour is formed perpendicularly to the wafer surface.

Dealing with the smaller getting chips is one of the future challenges in machining technology.

6.2.2. Machining guides

In the machining and assembly process, special alignment markers processed on the wafer are used for an accurate reference to the thin-film devices. During the head contour shaping the actual throat height is realized by means of precision lapping. Compared with the non-planar design, the planar design has a much thinner thin-film gap. For the planar design this results in a smaller level difference between the thin-film gap and the surrounding substrates at the head surface (so-called hollow out), and, consequently, a smaller signal loss due to a smaller head-to-tape distance.

In order to create a relatively small throat height with high accuracy, special throat height detection devices, called machining guides, are incorporated in the thin-film technology. A typical target for the throat height is $1 \pm 5 \, \mu m$ with future tolerances moving towards $\pm 0.25 \, \mu m$. There are two types of machining guides.
The Optimal Machining Guides (OMGs) are visible in the thin-film gap. These structures allow the determination of the throat height by means of optical inspection. Examples of OMGs are depicted in Fig. 7.

Electrical Machining Guides (EMGs) are mostly resistive structures and are read out electrically. EMGs have the advantage that they can be read out during the lapping process. With EMGs a fully automated lapping process can be realized.

There are basically two types of EMGs: analog and discrete. During lapping, the resistance of analog EMGs increases continuously, the resistance of discrete EMGs increases in a stepwise manner. An appropriate material to implement EMGs is the relatively thin MR layer.

The machining process of the planar heads applies a novel discrete EMG.
Sensor-last thin film magnetic heads

(see Fig. 8). By means of structures in the MR and barber-pole layer a network of parallel low and high valued resistors is formed. Through lapping, the low valued resistors in the Barber-Pole layer are broken at 0.5 μm steps, thereby increasing the total resistance of the EMG with the value of the resistors in the MR layer.

6.3. Assembly process

A typical assembly flow for the planar heads can be summarized as follows:
— coating the thin-film device with a protective layer,
— connecting a flex foil to the machined thin-film device,
— mounting the thin-film device into the head housing, at this stage the plate with integrated tape guidance is already glued on the head housing,
— securing the final assembly with spacers.

A typical DCC multichannel thin-film head has at least 30 connections. With a typical width of the thin-film device of 4 mm, the bondpad pitch is less than 150 μm (future heads: less than 100 μm). The only practical solution is to use a flexfoil for the electrical connections to the application. The wires of the flexfoil are bonded ultrasonically with the bond pads on the thin-film device.

7. Conclusions

The sensor-first design has various (electrical/magnetic and technological) drawbacks in comparison with the sensor-last design. By introducing the planarization technique in the wafer processing, the sensor-last design has become feasible. Further optimization of design of processes had resulted in a technology that is used for manufacturing the heads for the DIGAMAX™ system [20]. In combination with the sensor-last design the CMP process and its ability to introduce local planarization has proven to be beneficial in the production of magnetic heads, in performance as well as in process efficiency, and in machining and assembly.

The sensor-last design also offers possibilities for the application of new materials needed for new generations of recording systems.

Acknowledgements

Many colleagues of Philips Research (including the magnetic head workshop) and of the Development and Engineering department of Philips Magnetic Heads & Modules, now called Digamax, have contributed to the work as described above. The authors wish to thank all of them for their contributions.
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