Thin-film inductive heads

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The development of IBM thin-film inductive recording heads is traced from 1964, through their first introduction in 1979, to the present. We review a number of innovations in thin-film technology materials and processes associated with this type of head. Design and technology changes made since 1979 have led to the development and implementation of heads in several successful recording systems. We also describe efforts to predict the performance of thin-film inductive heads and to understand and control head instabilities and noise.

Introduction

We present this description of the inductive film head and its development, primarily but not exclusively from the point of view of the IBM scientists and engineers who have worked on the technology for thirty years. As an introduction to the subject, we describe the structure of the original prototype for the inductive head of the IBM 3370 Direct Access Storage device, which was first shipped in 1979. The purpose of this account is to familiarize the reader with the basic constituents and design of this type of head, which represents the majority of heads shipped by the disk file industry today.

The next three subsections give an account of the IBM development history of the head, starting with the earliest research and advanced development phases before 1971. In this period the general features of the design and the technology were selected. Next came the development effort, from 1971 to 1979, which refined the structure for the initial products and combined the magnetically active thin-film portions of the head with a viable air-bearing slider connected to a suitable suspension. The period from 1979 to the present, covering a total of thirteen head products and their associated improvements, is described in the last subsection, along with some of the newest versions of thin-film inductive film heads recently introduced by the industry.

The final section describes two special areas of investigation which have been pursued throughout the entire history of inductive film heads. The first is the effort to model the head magnetically and to predict the internal and external head fields and the associated output signals and writing ability. This work has given essential guidance to head designers and fabricators. The second area is the special read-signal instabilities and pseudo-noise associated with the head's magnetic domains. The causal relationships among these signal distortions, the shape and mobility of the domain walls, and the underlying composition and stresses in the magnetic films have been a persistent problem.

Design of the inductive film head

Any conventional inductive magnetic recording head consists of a split toroid of magnetic material wound by one or more conductor turns. As implemented in IBM's first inductive film head product, the 3370 head (**Figure 1**), the elongated split toroid is made up of a top and bottom pair of NiFe magnetic films (A). These provide a path for the magnetic flux, which creates a field between the pole tips (B) during writing. The flux is generated by currents flowing in the eight copper turns (C) in accordance with

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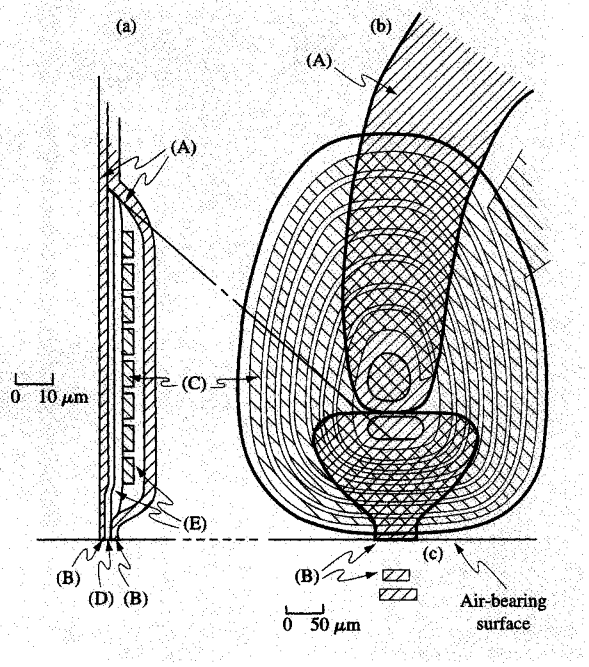

Figure 1

IBM 3370 film head: (a) Schematic cross section showing the magnetic layers (A), pole tips (B), conductor turns (C), gap layer (D), and insulation layers (E); (b) planar view of the film head; (c) pole tip structure at the air-bearing surface.

Gauss's law. To provide a high field, the throat height dimension (the length of the region in which the two pole tips are in close proximity) is kept small. In reading, flux induced by magnetic transitions in the disk media travels around the magnetic circuit linking the eight conductor turns. Changes in the flux linking the turns induce a voltage signal. The recording gap (D) is formed from a nonmagnetic amorphous alumina film. This film, which is deposited over the first NiFe film, is etched away above the turns to provide a contact between the two magnetic layers [Figure 1(a)].

The magnetic pole tips (B) at the recording gap of the 3370 head were made thin to provide a high reading resolution, as shown by Potter [1]. To meet the combined objectives in reading and writing, the first pole tip/gap/second pole tip thickness dimensions were 1.6/0.6/1.9 μm, and the nominal track width was 38 μm. In the pole tip structure appearing at the air-bearing surface, the second pole tip width was made narrower than the first pole tip width to prevent "wrap-around" at the edge of the first pole tip [Figure 1(c)].

To a first approximation, the signal from a recording head increases in proportion to the number of turns, while the necessary write current decreases in inverse proportion. However, there are several reasons why the signal and the number of turns cannot be increased without limit. For a reasonably efficient head, the inductance, which limits high-frequency head performance, increases approximately as the square of the number of turns. Also, because of the flat, elongated shape of inductive film heads, there is a significant leakage of flux between the two magnetic layers outside the throat height region. Turns far from the recording pole tips are ineffective in delivering flux to the pole tips for writing and in linking flux from the media in reading [2]. Both the copper turns and the insulation layers around the turns have been made thick to minimize this leakage and increase head efficiency. Thick, closely spaced turns are also advantageous for minimizing the length of the magnetic circuit and for suppressing noise in the read circuit.

Eight turns were selected for the 3370 head to provide a suitable signal from a 38-μm track width and to write with an economical write circuit.

The copper coils centered between the magnetic layers are in the form of an elliptical "pancake coil" wound to a center terminal located above the magnetic contact point between the Permalloy layers [Figure 1(b)]. The elliptical shape of the coils reduces the resistance without introducing corner constrictions that form points of high thermal stress concentration [3]. An external "overpass lead" to the center terminal is deposited in the same steps that produce the second magnetic layer of the head. Although NiFe is less conductive than copper, this lead can easily be designed to provide less than 10% of the total circuit resistance.

Hard-cured photoresist was chosen to form the thick permanent insulation layers between the coil and Permalloy films [Figure 1(a)]. During curing, a meniscus-like smooth slope forms at the pattern edges [Figure 1(a)]. Because the photoresist was applied as a liquid, it provides a smooth surface over the conductor turns for deposition of the final Permalloy layer. Both features are advantageous for producing uniform NiFe layers with good magnetic properties. The photoresist insulation pattern is limited to the region of the copper coil, as shown in Figure 1(a), and consequently is not exposed as the head is lapped to final throat height.

Research and advanced development

Like many other new technologies, the introduction and evolution of magnetic thin-film heads was a fairly protracted, low-level activity for several years in the beginning, 1965–1970. The initial impetus at IBM came from advanced technology areas with experience in magnetic thin-film memory elements. The attraction of batch film fabrication processes, and the high-speed response of film memories, was quite compelling in competition with the incumbent ferrite core-memory technology. However, by 1964, the future of magnetic film memory was becoming less certain, as interest grew in the emerging semiconductor technology for computer memories.

Magnetic film technologists began to look for new applications for their advanced technology. The micromagnetic structure of Permalloy films was reasonably well understood, especially in anisotropic films; thus, from the magnetics point of view, application to recording heads was a logical step. Early in 1965, a review of the potential of a number of new technologies was conducted, using electron or laser beams, and thermoplastic, photographic, and magnetic media. Magnetic recording on drums, strips, disks, and tape was already the most widely applied technology for data storage. This technology served all storage needs except the highest-capacity requirements (then about 100 GB), which used some type of beam-addressable storage technology. All other applications, using magnetic recording, required magnetic transducers which, at that time, were all inductive recording heads.

A perceived problem for future auxiliary storage was the access gap between the 75 milliseconds required in disk files and the microsecond access times of large-capacity core memories. Multi-track ferrite heads with eight elements were under development for high-rotational-speed disk files to address this need. What was being sought was the access time and data rate of a magnetic drum in a much cheaper disk file. This prompted the proposal [4] of an array of single-turn thin-film heads similar to a matrix of memory elements but with a read/write gap in every element. Such a multi-track head was envisaged to achieve a density of a thousand tracks per inch and to provide around 10-millisecond access time to the information recorded on the disk.

The magnetic device technology group in the IBM Research Division started the first experimental project to fabricate a single-turn film head (**Figure 2**), using the film plating technology developed for magnetic film memory devices. Film heads were seen to offer a number of characteristics different from those of existing ferrite heads, but there was uncertainty about which of these were solving critical problems, and which type offered performance improvements that were highly desirable but unobtainable with existing heads. Furthermore, the early film head designs included some undesirable characteristics, such as low-amplitude reading signals and high writing currents, that would have to be addressed.

Nevertheless, the overall attraction of batch fabrication, and its potential for high yields and low cost, generated sufficient enthusiasm to allow some early trials of different film head designs. One attractive attribute of this technology was that it could provide separately optimized write and read heads accurately positioned and in close proximity [6]. While this turned out not to be a major factor immediately for inductive heads for disk files, the practical realization of separate read and write elements in a disk product was 20 years in the future with the advent of MR read heads.

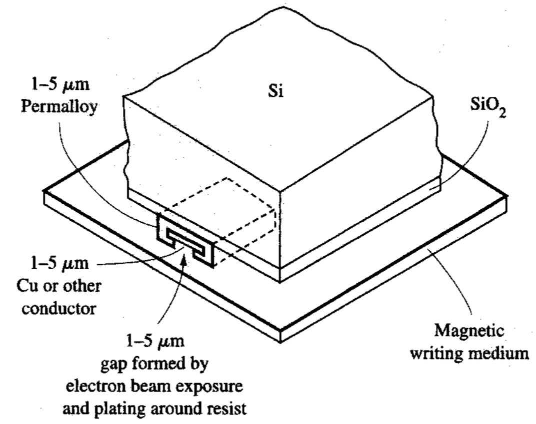

Figure 2

Single-turn horizontal head [5].

About the same time as the horizontal head was evolving at the IBM Yorktown Heights Laboratory, a different approach was being explored at the IBM laboratory in Sindelfingen, Germany, to develop a single-turn vertical head (**Figure 3**). In this design the conducting turn, the magnetic films, and the recording gap were formed simply by vacuum evaporation of a thin 1-μm copper conductor film between two 1-μm-thick vacuum-evaporated Permalloy magnetic film poles. In 1968 it was demonstrated that this structure would record on a magnetic medium. These heads developed a 50-μV read signal at a 2.5-μm spacing.

Single-turn heads

By 1968 there were two different design approaches being pursued for single-turn thin-film heads using evaporated and plated films. The processing techniques used to fabricate film heads were in large part adapted from those employed to make thin magnetic film memories and semiconductor devices. Silicon wafers were initially used as substrates for film deposition because of their surface smoothness and availability, with the unrealized expectation that associated semiconductor functions might be integrated into the common substrate. Vacuum evaporation had been the traditional method of depositing Permalloy films for thin-film magnetic memories, but

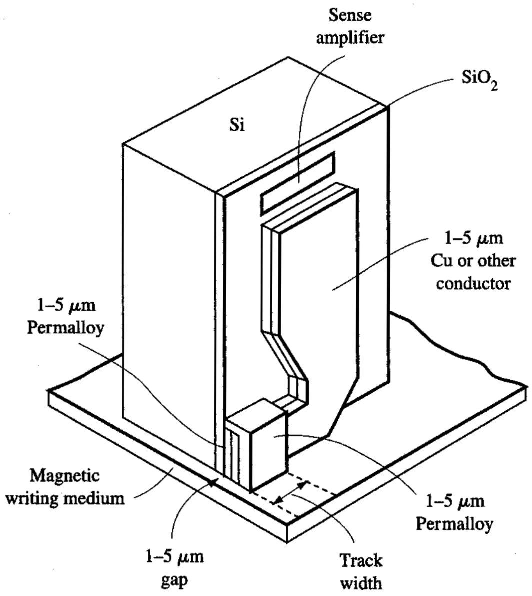

Figure 3

Single-turn vertical head.

considerable effort had been spent in the Research Division laboratory to develop plating techniques to deposit Permalloy films. The advantage seen, besides low cost, was the ability to deposit films over uneven topographies, a capability lacking in the "line-of-sight" deposition characteristic of vacuum evaporation. This advantage had been used in plated-wire memory, and was under development for making coupled-film memory devices. (Basically, a coupled-film device is a planar version of a plated-wire memory cell consisting of copper strip lines coated on all sides with Permalloy.)

Several innovations were required to adapt existing processes to film head fabrication. With the coupled film as a starting point for the horizontal head, a method had to be found to provide the gap in the magnetic film needed for a film recording head. Neither etching nor scribing techniques were found to provide the vertical walls needed for a satisfactory recording gap. The desired gap quality was obtained using high-resolution electron-beam lithography with a polymethyl-methacrylate resist [7]. Fine resist lines 2 μm in width and 2.5 μm thick were obtained, which, acting as a plating mask, formed a well-defined gap in the thick Permalloy plating.

Although the horizontal heads fabricated in this manner [5] functioned in laboratory tests, there were serious concerns about gap smearing and wear of the exposed Permalloy during operation in a disk drive. Hard overcoat materials were considered as a possible solution, but there were concerns about resulting head-to-disk magnetic spacing loss and the possibility of debris generation. While these concerns have since been effectively addressed for coupled-film horizontal geometries [8, 9], at the time they were bypassed by adoption of a vertical head geometry developed in Sindelfingen. Although the original vertical heads had used vacuum evaporation, the relative ease of obtaining thick magnetic films by plating led to the combination of the plating techniques of the horizontal head with the geometry of the vertical head [10].

Multi-turn heads

A limitation of both the vertical and horizontal designs was the single-turn structure, which required write currents of several hundred milliamps to saturate the recording medium. To avoid this limitation and allow the use of low-power integrated circuits, multi-turn configurations consisting of successively deposited conductor films [11] and a planar spiral design [12, 13] were proposed. The latter approach was taken because of its less complicated process requirements. This structure required copper lines with a high aspect ratio of thickness to width in order to have low electrical resistance with the narrow line width needed to minimize the yoke length. Since this aspect ratio could not be obtained by photoetching, the additive process of plating through a photoresist mask developed for gap definition in the horizontal head was used. The spiral coil design also required insulation of turns from one another and from the magnetic films within which the conductors were sandwiched. Attempts to use sputtering techniques to deposit inorganic insulation were unsuccessful because of the thickness of the conductors and the resulting coverage and planarization problems. Hard-cured photoresist provided both coverage and smooth planar surfaces for the deposition of subsequent film layers.

Control of the ratio of iron and nickel to achieve the high permeability and low magnetostriction characteristic of Permalloy presented a significant challenge. The electrodeposition of nickel–iron alloys is complicated by the anomalous relative plating rates of nickel and iron when these are codeposited, yielding a much higher deposition rate of iron than nickel [14]. This results in progressive depletion of iron ions at the cathode surface and decreasing iron content with increasing film thickness. A further complication was the strong dependency of film composition on plating current density, where the ratio of iron to nickel increased steeply with increasing current density to a maximum, thereafter declining with further increase in current. Adequate control of film composition was achieved by plating at currents near the maximum in iron-to-nickel ratio, where the composition is least sensitive to current variation, adjusting the plating bath parameters so that this maximum occurs at a low current density, and by effective agitation of the plating bath. The best results for plating of large wafer areas were found by using a specially designed paddle agitation technique [15]. This approach, combined with further refinements in the low-current plating bath conditions [16], resulted in the basic plating technology used for today's inductive film heads.

By late 1969, there were five separate advanced technology efforts on film heads in IBM laboratories. This included the various inductive head designs described previously, as well as new work on magnetoresistive reading heads. At this point, a more coordinated activity was started to work through the many options offered by this new technology. In addition, this project was also coordinated with similar dispersed projects on thin-film disks. The design objectives for recording density were about 10^7 bits/in.^{2} at a data rate up to 25 Mb/s. Recording tests were verifying the predicted slimming of the read pulse by the finite pole length of the vertical head design. The electronics required to operate the multi-turn versions were compatible with the available semiconductor products and furthermore, in the multi-track design, would be simple to package with the head. While the head wear problem was still not completely quantified at this point, the vertical structure was considered to be the most durable of the all-film head designs.

For film heads, in addition to design and process development, improved materials for wear reduction were included in the program. However, it turned out that the familiar NiFe films provided adequate magnetic and mechanical performance. Alternative inorganic materials were also considered for insulation of the multi-turn coils, but again the original hard-baked photoresist proved to be adequate. The initial slider vehicle for the new film heads was a crowned slider of similar design to the product heads used in the 3330 ("Merlin") file. The film heads on their substrates were fixed by either epoxy or glass into the center of these sliders. It was necessary to evolve a packing technology which required temperature cycling below levels that would cause deterioration of the magnetic properties of the heads. The head electronics were designed with the assumption that about 10 turns would be used, which would deliver about 300 μV (peak-to-peak).

The general design approach adopted at this time was later used in the first development of a thin-film head for a disk file introduced in 1979 [17]. Although a number of important process improvements have occurred since then, the basic design persisted in read/write film heads until the first product containing magnetoresistive heads was shipped. Even today, the writing head in the magnetoresistive head structure is still similar to the basic design evolved by 1971.

Development

The earliest IBM inductive single-turn [18] and multi-turn [13] heads were made with plated copper recording gaps, and it was soon recognized that a more durable gap material was desirable. Copper is relatively soft and subject to smearing during preparation of the air-bearing surface and while in intermittent contact during start-stop operations. Also, the NiFe/Cu/NiFe electrically coupled layers exposed at the air-bearing surface were believed to present a corrosion problem. The most attractive materials for the gap layer were the nonmagnetic amorphous oxides and nitrides, which were already in use in the fabrication of integrated circuits in the late 1960s and which were readily deposited by the newly developed technique of rf diode sputtering [19].

Of the most frequently used dielectrics, SiO_2, Si_3N_4, and Al_2O_3, the first had a very low thermal expansion coefficient and would be subject to high stresses during heating or cooling; the second was difficult to etch. Thus, Al_2O_3 was chosen as probably the most viable material. Notwithstanding, there were early process problems in depositing alumina so that it would not delaminate, crack, or be deposited in an opaque form. The delamination problem was solved by the systematic use of *in situ* sputter-etching of substrates before deposition of the alumina gap layer. This was probably the most important of several rf sputter-deposition techniques adopted early in the program; it subsequently became a required feature of the sputter-deposition equipment used for manufacturing. The alumina had to be transparent to allow inspection of the finished heads. Opaque alumina was soon found to be caused by metallic impurities, which could be eliminated.

Since rf sputter deposition was introduced early in the program to provide the gap layer, it was relatively easy to use this same deposition technique and the associated *in situ* sputter etching of substrates to deposit metallic conductive seed layers for plating. When these techniques were used, adhesion of the relatively thick (>1 μm) plated layers and seed layers was rarely a problem. The film head program was probably the first to use rf diode sputtering exclusively in manufacturing for depositing metallic films, rather than the older, well-established processes of vacuum evaporation.

A key decision was made in the early film head program regarding the choice of slider embodiment. When the film head program was started in the late 1960s, the preferred air bearing for disk file heads was the cylindrical air-bearing design used by the IBM 3330 "Merlin" file, which was first shipped in 1971[1] [20]. With the cylindrical air

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[1] However, the earliest testing was done by attaching silicon film head "chips" to one pad of a tri-pad fixed-head slider developed at the IBM Los Gatos Laboratory [20]. Single-turn head lengths, roughly the equivalent of throat heights, were changed by simply lapping away the heads on a medium at low velocities [21]. Glass slides were also used as substrates for the earliest film heads.

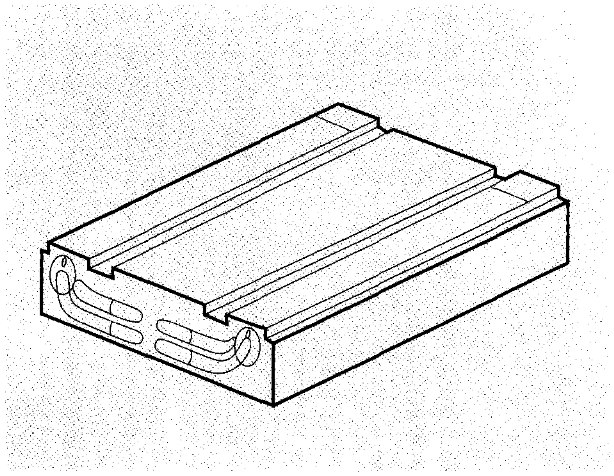

Figure 4

Schematic drawing of the IBM 3370 slider.

bearing, the point of closest slider–media spacing, and the ideal position of the head gap, occurred close to midway along the slider length in the track direction. For the film head, this required the use of a covering piece with a thickness equal to about half the slider length and perhaps an equal piece bonded under the thin substrate containing film heads. For dual read/write heads, a five-part construction was proposed, adding a second film head substrate and a spacer between the read head and write head substrates.

The bonding and the alignment of such assemblies were difficult. Good glass bonding required temperatures between 400°C and 500°C, but these could not be used with the film head, since it would cause melting of the photoresist insulation, stresses and delaminations because of thermal expansion mismatches, and deterioration of the NiFe properties. Epoxy bonding could have been used, but manufacturing experience with epoxy bonding, particularly with the IBM 2314 head [20], had shown such bonds to be subject to slippage, causing displacement of the heads with respect to the air bearing.

Fortunately, the highly successful Winchester IBM 3340 air bearing was developed in the early 1970s [20, 22]. In this case, the slider's closest approach to the media and the point where the head was ideally located was at the trailing edge of the slider. When this design, shown in **Figure 4**, was adopted for the film head, it became clear that it was advantageous to use a substrate whose thickness was approximately equal to the length of the slider [23]. The thin middle rail of the Winchester head, which did not contribute significantly to the air bearing, was omitted in the film head version. To improve yields, two film heads were provided on each slider, one on each rail. Only one head of the two was used. With the IBM 3370, 3375, and 3380 heads, the slider length (substrate thickness) was about 4 mm. In practical manufacturing terms, this required extensive changes in almost all of the tooling used to make the film portions of the head and associated changes in optimum sputtering conditions, photoresist operations, and testers.

Another complex problem arose in selecting the film head slider/substrate material. Since the magnetic circuit of the head was formed by thin-film technology, the designer was no longer constrained to use ferrite as the slider body, as in the case of the Winchester head. The difficulty in selecting the slider material arose, in part, simply because there were so many alternatives and also in part because the ultimate choice had important impacts at every step of the fabrication process, from the use of etching solutions in the film deposition area, formation of rails, lapping of air bearings, through the choice of slider size, mass, and durability.

Silicon, glass, and barium titanate ceramic were chosen early in the film head program, largely on the basis of expediency. Eventually the former two were judged not to be durable enough in start/stop operation, and the latter was too porous and prone to cracking when subjected to thermal shock. The program then moved to using recrystallized glass ceramics such as Corning FOTOCERAM® and an experimental Corning material, "Z16." While both had essentially zero porosity, the former was finally considered to be too soft, and the latter was not available in commercial quantities.

The final choice, a fine-grained mixture of crystalline alumina and titanium carbide[2] [24], was selected primarily because of high yields of chip-free rails and good durability in start/stop operation. Fortunately this material was resistant to the chemicals used in the film deposition process. The slider mass could be adjusted by altering the slider height. This material also has a reasonable thermal expansion match with sputtered alumina. On the down side, the tool life for cutting rails was relatively short and the material was somewhat conductive (of the order of mΩ-cm), and so would short out the film head contacts. This last problem was solved by adding an rf-sputter-deposited alumina undercoat for the head. It was also necessary to use a thick (25-μm) alumina overcoat, since the trailing edge of the slider was subject to microchipping during lapping and in start/stop operation. Without this overcoat, the damage would occur on the pole tips.

The use of such thick layers of alumina, probably the thickest films used in the microelectronics industry at the

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[2] M. Cook, R. MacDonald, and T. Cowan were largely responsible for the selection of the Al_2O_3/TiC material.

Table 1 Inductive thin-film head products.

	GA	*TPI*	*KBPI*	*AD* (Mb/in.^{2})	*P1* (μm)	*P2* (μm)	*G* (μm)
3370	1979	635	12.1	7.7	1.6	1.9	0.60
3375	1980	800	12.1	9.7	2.0	1.9	0.70
3380	1981	801	15.2	12.2	1.7	2.0	0.60
3380E	1985	1,386	16.2	22.5	1.6	1.9	0.60
9335	1986	1,600	16.2	25.9	1.6	1.9	0.60
3380K	1987	1,600	16.2	25.9	1.6	1.9	0.60
3380K	1987	2,089	15.2	31.7	1.6	1.9	0.60
9332	1988	2,017	23.6	47.5	3.0	3.0	0.55
3390*	1989	2,242	27.9	62.6	0.9	1.0	0.55
Aptos*	1990	2,242	27.9	62.6	0.9	1.2	0.55
3390-3*	1991	2,984	30.0	89.4	0.9	1.2	0.55
Tanba Turbo*	1992	2,436	59.8	146	3.0	3.1	0.35
Tanba-3*	1993	3,041	61.0	186	3.0	3.1	0.32
Ritz-1	1994	4,000	80.0	320	3.5	3.5	0.25
Ritz-2	1994	4,000	80.0	320	3.5	3.5	0.25

Note: *Ion milled

	P1W (μm)	*P2W* (μm)	*Turns*	*Layers*	*R* (Ω)	*L* (nH)	*Efficiency* (L/N^2)	*Slider length* (mm)	*Slider width* (mm)	*Slider height* (mm)
3370	38.0	34.0	8	1	7	80	1.25	4.0	3.2	0.850
3375	27.5	24.5	8	1	7	80	1.25	4.0	3.2	0.850
3380	29.5	26.5	8	1	7	80	1.25	4.0	3.2	0.850
3380E	15.0	12.0	18	1	15	350	1.55	4.0	3.2	0.850
9335	13.5	11.0	18	1	15	350	1.55	4.0	3.2	0.850
3380K	8.5	6.5	31	2	24	650	0.67	4.0	3.2	0.850
9332	10.5	8.5	31	2	24	800	0.83	4.0	3.2	0.850
3390	8.0	8.0	31	2	24	800	0.83	4.0	3.2	0.850
Aptos	8.0	8.0	31	2	24	800	0.83	4.0	3.2	0.850
3390-3	5.6	5.6	37	2	31	950	0.69	4.0	3.2	0.850
Tanba Turbo	8.4	8.4	44	2	39	1,400	0.72	2.5	1.6	0.425
Tanba-3	6.4	6.4	44	2	39	1,200	0.61	2.5	1.6	0.425
Ritz-1	6.3	4.8	45	3	29	800	0.39	2.0	1.6	0.425
Ritz-2	6.5	5.0	36	3	20	500	0.39	2.0	1.6	0.425

time, required that extensive studies be made of alumina deposition rates, substrate temperature, film stresses, and adhesion [25]. In fact, the ultimate alumina optimization was based on the characteristics of the films during row slicing, lapping, and thermal cycling in the process of making sliders and air bearings.

The use of a thick overcoat to protect the head of necessity gave rise to new techniques to make contacts to the head. Initial attempts to etch holes in the thick alumina were unsuccessful because the photoresist masks used were not durable in the alumina etchant. Finally a new method was adopted in which thick (>25-μm) copper contacts ("studs") were plated on the head leads before the alumina overcoat was deposited. To make contact, the alumina overcoat over the studs was lapped away after deposition, exposing the copper.

For electrical contacts of leads to the exposed copper stud, there was a choice among soldering, thermal compression bonding, and ultrasonic bonding. Soldering was rejected because of the need for high temperatures, which could lead to cracking of the alumina. The use of either thermal compression bonding or ultrasonic bonding required forming gold pads over the exposed copper stud, since both of these techniques required the formation of bonds between the gold pads and gold-coated wire. Ultrasonic bonding was adequate and was found to be the least likely to result in damage.

In the inductive film head, magnetic flux is conducted to the gap region through NiFe films that are typically 1–3 μm thick. It was clear from the outset that in order to achieve adequate reluctance in the head gap, the distance over which the first and second NiFe layers are in close proximity, known as the throat height, should ideally be equal to fractions of the NiFe pole tip thickness. Heads with greater throat heights are inefficient in reading and may not be able to saturate the media adequately on writing. For manufacturing economy, it is also clearly desirable to lap many heads in row form to the final throat height at the same time. In light of these basic throat height requirements, it was necessary to maintain

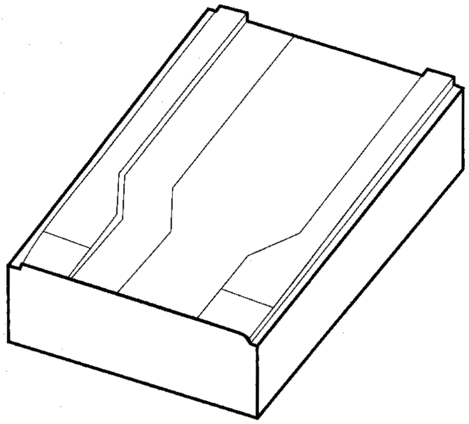

Figure 5

ABS design of the IBM 3380K slider.

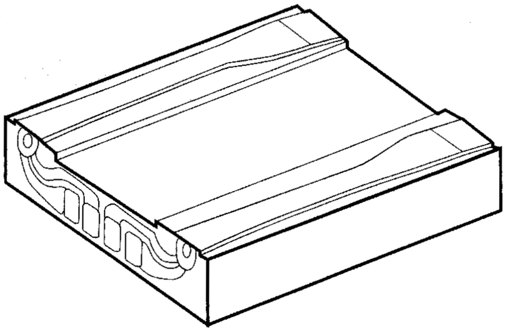

Figure 6

Positive-pressure ABS design of the IBM 3390 slider.

parallelism and accuracy of the order of 1 μm across the row during throat height lapping.

Fortunately, it was possible to provide film structures, "electrical lapping guides," which were deposited at the same time the head's films were laid down. These structures changed resistance as the lapping of the air bearing proceeded and as the throat heights diminished [26]. The signals from the electrical lapping guides, which were at the ends of the row, were used through computer control to change the pressures exerted along the row and the associated local lapping rates [27]. This, together with elaborate controls of the lapping motion and dispensation of lapping slurry, allowed throat height dimensions to be controlled to unprecedentedly tight tolerances.

Inductive head products and refinements

IBM introduced the first inductive thin-film head in the disk drive industry with the shipment of the IBM Model 3370 DASD in 1979. This marked the inauguration of a series of IBM disk drive products employing thin-film head technology, which is still being used today. Thin-film head technology has fueled the rapid increase in storage density at a 40% compound growth rate during this period. In 1991 IBM introduced the novel magnetoresistive-read/inductive-write heads in its DASD product line, and focused future inductive read–write heads on the OEM component market.

Table 1 lists the significant physical parameters of various IBM inductive heads and the corresponding recording IBM DASD products. The high-end DASD products, including the 3370, 3375, 3380, and 3390 series, incorporated separate heads for the inner diameter (ID), outer diameter (OD), and servo positions. The ID head exhibited the highest performance, in particular the highest recording density and lowest flying height, compared to the OD and servo heads. The characteristics of the ID head are listed in Table 1. Since the performance demands were less stringent for the OD heads, the gap and pole tips of the OD heads were larger than those of the ID heads. The servoing heads were low-resolution and read-only, and had correspondingly larger gaps and pole tips.

The IBM 3370, 3375, and 3380 heads differed only in pole tip widths and thicknesses and gap dimensions. Figure 4 shows a schematic diagram of the first inductive thin-film head slider (IBM 3370). The dimensions of the slider were 4.0 mm × 3.2 mm × 0.85 mm.

To achieve the required increased track density, the 3380E and 9335 head designs have increased coil turns and significantly reduced track widths, as shown in Table 1. The key development work concentrated on optimization of the saturation characteristics of the head, in particular the geometry of the yoke and back gap and the implementation of shaping layers on P1 and P2. The relationship of Permalloy composition to head stability was also defined.

The third-generation 3380K head introduced several advances in thin-film head design and process technology. It embodied a higher number of coil turns using a new, dual-layer coil design. One novel feature of the coil design was the etched recess in the undercoat layer. The etched recess (Figure 9, shown later) simplified the photolithography processing and permitted a narrower coil pitch. To enhance flyability and reliability, the head employed a novel dual-rail, positive-pressure air-bearing surface (ABS) design fabricated using reactive ion etching. The ABS design is illustrated in **Figure 5**. IBM's strategy was to increase storage density by increasing track density. The extremely narrow track-width dimensions of the 3380K head mandated strict control of head stability. IBM engineers conducted numerous experiments and gained a fundamental understanding of the relationship of stress anisotropy to domain stability. The relationship between the physical parameters of the head and recording performance was defined in detail.

IBM introduced its first thick-pole head design for high-coercivity, thin-film media in 1988. The increased write field associated with the new design permitted higher linear densities.

The final three-head products for high-end DASD application (3390-1, 3390-3, and Aptos) employed ion milling of the pole tips for track width definition. Ion-milled pole tips permitted higher output and minimized adjacent track interference. To achieve the reduced line width and spacing associated with the 37-turn 3390-3 design, a new photoresist process was developed. All three heads utilized positive-pressure air-bearing designs for improved flying height control, as shown in **Figure 6**. For improved throat height control, the 3390-3 design incorporated a new resistive-switch lapping scheme.

The Tanba Turbo head was IBM's most complex and advanced inductive thin-film head product. It incorporated several key features, including reduced slider size (2.5 mm × 1.6 mm × 0.425 mm), silicon/carbon overcoat, 44-turn dual-layer coil design, ion-milled track widths coupled with thick pole tips, very narrow gap dimensions, center element location, and novel tri-rail air-bearing design. The structure of the head is shown in **Figure 7**, and the ABS is illustrated in **Figure 8**. Placement of the active element in the center of the slider afforded decreased sensitivity to roll. There were serious process challenges with ion milling using thick photoresist masks for the pole tips. The Tanba-3 head had a slightly narrower gap length and reduced flying height compared with the Tanba Turbo head design. The Tanba Turbo and Tanba-3 heads represented the first inductive film heads used in IBM low-end DASD products manufactured in Japan.

The most recent evolutions of inductive film head technology at IBM are the Ritz-1 and Ritz-2 heads for the OEM component market. These heads have a new three-layer coil structure, plated track widths, reduced slider size, and a novel negative-pressure air-bearing design with the element located at the trailing edge of the rail. The coil structure and ABS design are shown in **Figures 9** and **10**, respectively. The 45-turn Ritz-1 head was designed for 2.5-inch hard disk drives, while the 36-turn Ritz-2 head was earmarked for 3.5-inch drives.

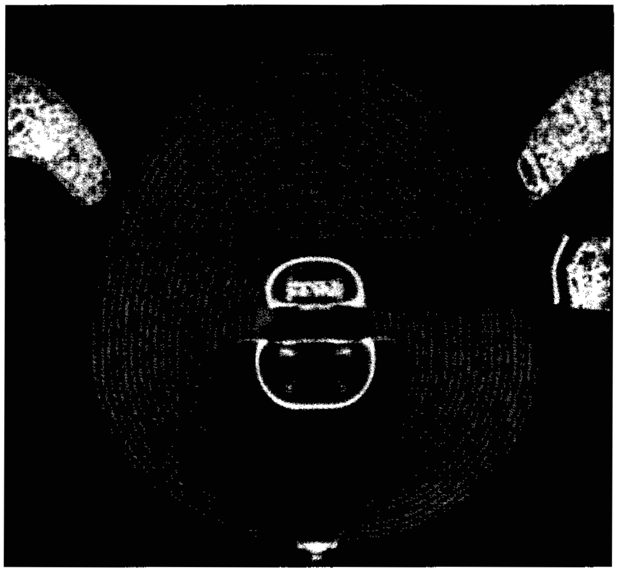

Figure 7

IBM Tanba Turbo 44-turn, two-layer coil structure.

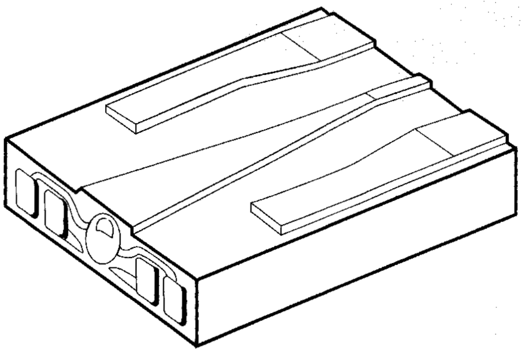

Figure 8

ABS design of the IBM Tanba Turbo slider.

In 1994, IBM introduced the third generation of magnetoresistive-read/inductive-write heads and completed the transition from inductive head to magnetoresistive head technology through all of its disk drive products. IBM's lead in magnetoresistive head technology forced competitive head companies to extend inductive head technology incrementally. The strategy to achieve higher storage densities and data rates with inductive head technology included multi-layer coil structures, pole tip

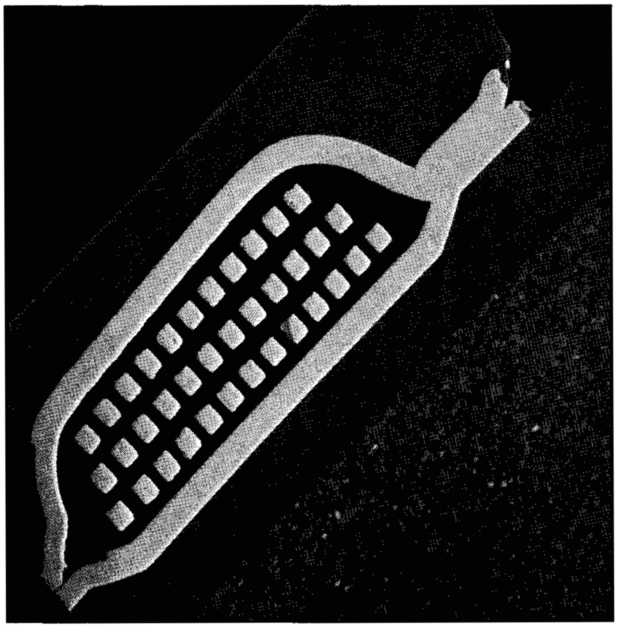

Figure 9

IBM Ritz 36-turn, three-layer coil structure.

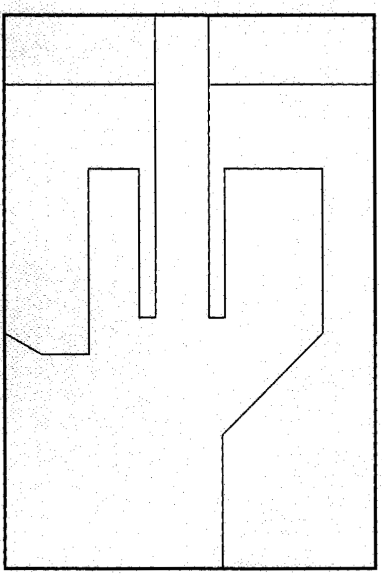

Figure 10

Negative-pressure ABS design of the Ritz slider.

trimming, novel yoke structures, and dual-gap structures. **Figure 11** illustrates the high topography of a 50-turn, four-layer coil head. The multi-layer head structure leads to increased head efficiency. Several companies employed a row-level ion-milling process for track-width definition of the pole tips and undershoot elimination. To achieve higher output and lower inductance, Mallary et al. developed an elegant double-yoke structure [28, 29] with interleaving coils, as shown in **Figure 12**. This "diamond head" exhibited recording performance superior to that of conventional thin-film designs, but the three-closure structure was a potential source of magnetic domain stability problems.

The most novel inductive head structure was the planar silicon head (PSH) developed by Lazzari [9]. The head was fabricated using semiconductor processing technology and utilized a horizontal coil structure, as illustrated in **Figure 13**. The merits of the planar structure and process include increased output with reduced inductance, self-aligned pole tips for precise track-width definition, no undershoots for advanced channel signal processing applications, and convenient personalization of the wafer in the final steps of the wafer process. Since machining processes are eliminated, the planar head offers a cost advantage compared with conventional technology.

Special inductive film head studies

- *Head modeling*

The literature on modeling of various types of recording heads is accessible in reviews [30, 31]. Here we discuss a number of papers focusing on those aspects of thin-film heads which, during their development, distinguished them from the existing ferrite head technology. The most important of these features is the highly planar geometry of the thin-film head. The effect of this feature was first discussed by Paton [32], who analyzed the simplest single-turn head with a type of analysis which has come to be known as a transmission line model (TLM). This work was important because it showed that magnetic flux impressed at some point in the head (such as at the pole tips during read-back) decayed exponentially with distance from the source. The characteristic flux decay length was given by a simple expression involving the thicknesses and permeabilities of the two magnetic layers in the head and the gap separating them. This work was extended by Jones [2] to the case of a multi-turn head yoke with a nonuniform spacing between the magnetic layers. The TLM analysis showed that the contribution of a given turn to the total head signal decreased with distance from the pole tips until a distance was reached comparable to the flux decay length, beyond which the turn contributed relatively little to the signal. The TLM established a quantitative methodology for optimizing the performance of thin-film inductive heads as a function of their

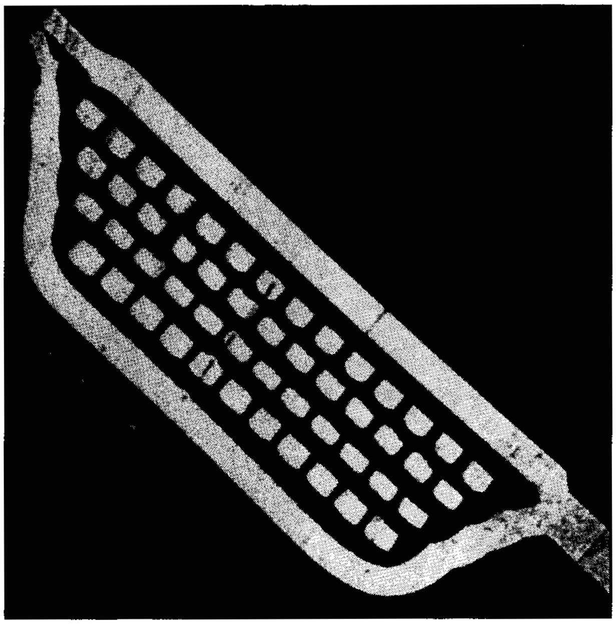

Figure 11

Topography of a 50-turn, four-layer coil head.

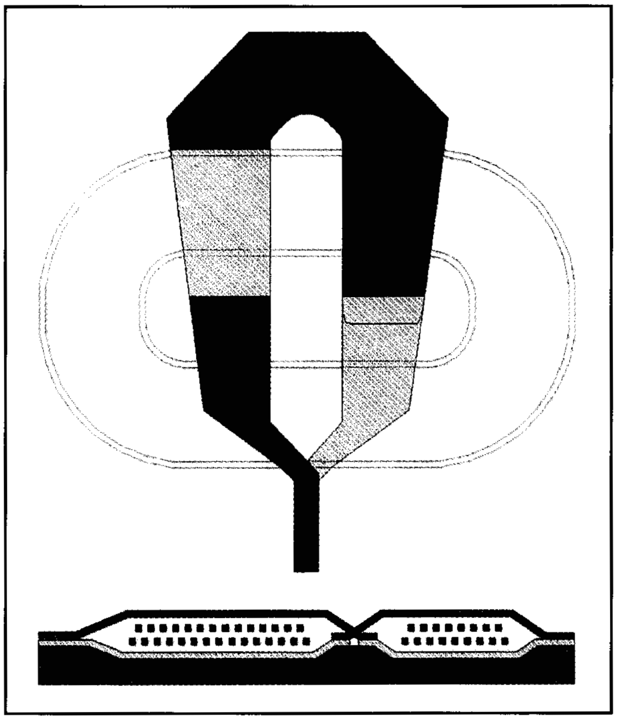

Figure 12

Diamond head coil structure.

geometry (film thicknesses, gaps, etc.) and magnetic parameters (permeability, saturation induction, anisotropy field).

Another, more quantitative, approach was taken by Potter [33], who applied finite-element techniques to the analysis of cross sections of thin-film inductive heads. Although this type of analysis is less transparent than the TLM, it has the virtue of being able to accurately treat aspects of the head geometry which are idealized in the approximations of the TLM. The TLM and the work of Potter and others [34–36] dealt only with the cross-sectional geometry of the head, i.e., a uniform-width head structure. Yeh [37] extended the TLM formalism to include variation in the width of the head with distance from the pole tip, as is typical of thin-film head designs. This yielded a more accurate picture of the flux distribution in the head during writing. The dependence of the head signal and head inductance on the shape of the head yoke could also be analyzed with this approach.

Another feature distinguishing thin-film from ferrite inductive heads is their finite pole tip thickness of 1–3 μm. Because of the flux concentration occurring at any sharp corner in a soft magnetic structure, two effects were expected to be associated with the outer corners of the pole tips: 1) the occurrence of fields of opposite sign to the gap field during writing, with a possible data erasure problem, and 2) the presence of undershoots in the pulse during read-back, with their impact on signal processing in the file. A conformal mapping analysis of Potter [38] for an equal-thickness pole tip head showed that these effects were tolerably small (**Figure 14**). Szczech [39] later developed a widely used empirical model for the case of unequal pole tips.

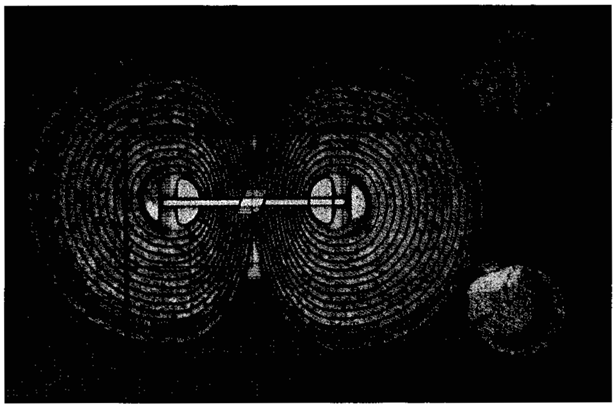

Figure 13

Planar silicon head coil and ABS (top view).

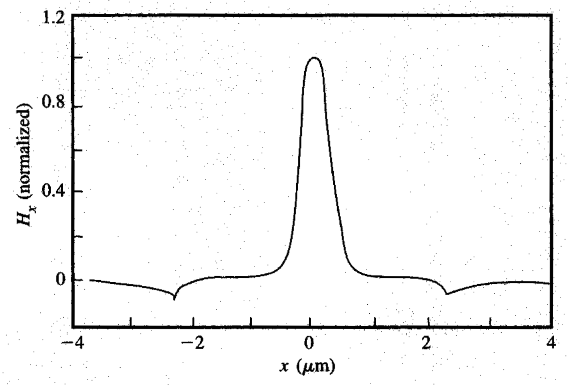

Figure 14

Negative undershoots are shown in the pulse waveforms of a thin-film head [38]. Gap thickness = 0.4 μm; pole tip thickness = 2.0 μm; x = distance from center of gap; H_x = readback flux.

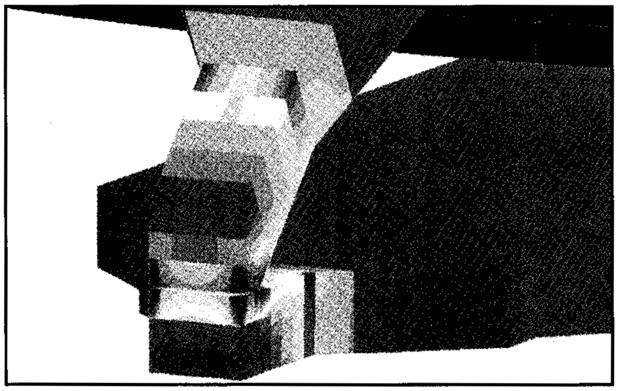

Figure 15

Finite-element analysis of an inductive film head, showing flux levels at the onset of magnetic saturation.

Since this early work, commercial software packages have become available for not only two-dimensional but also three-dimensional analysis of recording heads. These programs solve for the three-dimensional fields for arbitrary geometries using either finite-element or boundary-element numerical techniques. An example of this type of analysis is that of Cain et al. [40]. Another example of the type of information which can be obtained is given in **Figure 15**, which shows the levels in a thin-film recording head near saturation at the corners of the pole tips.

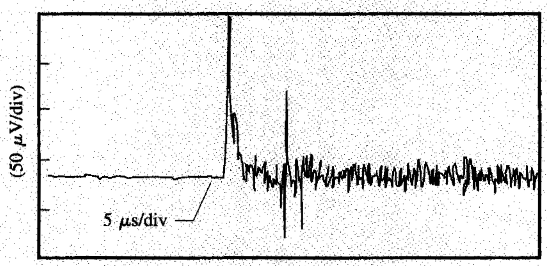

Figure 16

Barkhausen noise after write. A head output voltage trace captured when the write operation ends and shortly thereafter.

Signal instability

Two forms of inductive film head magnetic instability have been found: write and read instability [41]. It should be noted that ferrite heads are also afflicted with this phenomenon of magnetic instability [42]. Both write and read instabilities are associated with small irreversible jumps in domain wall positions which produce abrupt changes in the coil-linked flux, ϕ. These abrupt changes in flux induce transients in the head output voltage proportional to $Nd\phi/dt$. (N is the number of linked turns.) These transients, which are referred to as "Barkhausen noise," result from interactions [43, 44] of walls with local defect sites (pinning). A defect can be a scratch, surface roughness, edge "rat bites," inclusions, or voids in the Permalloy films. In yokes with a nonzero magnetostriction NiFe composition, a defect can also be due to local stresses built in during deposition or resulting from the lapping and grinding processes. The thermal agitation of the spins in the walls will at times show a coherent component large enough to spontaneously "unpin" a wall, resulting in a flux jump which in turn causes a transient voltage in the head output.

Write instability, which is often referred to as "noise-after-write" or "popcorn noise," occurs predominantly after termination of a write operation. Noise in this time frame is particularly undesirable in drives which employ sector (or embedded) head-position servo, since servoing must occur immediately after writing and interspersed with longer write operations.

To observe noise-after-write events, testers are used which allow a certain hold-off or delay time after termination of a write burst before an observation (listen or read) window is opened during which a noise event is counted if the signal is larger than a certain threshold value. An example of a captured noise trace is shown in **Figure 16**. The termination of the write operation (straight line) is followed by a large, decaying transient caused by head demagnetization ("inductive kickback") and amplifier recovery. The rest of the trace shows Barkhausen noise events, which can be voltage spikes having polarity the same as or opposite to that of the inductive kickback [41].

The probability of occurrence of noise events falls off rapidly with time after writing (**Figure 17**). The delayed relaxation cause for noise-after-write has been confirmed by various authors [45–49]. In Reference [49] a high noise-after-write was correlated with spike-like domains near the back gap closure of the yoke. Reference [48] concludes that the domain structure in the upper part of the yoke in plated thin-film heads is very sensitive to NiFe composition variations, even those for which the magnetostriction is very close to zero. Therefore, the conclusion in Reference [45] that the mechanical stress variation, introduced by the cooling off of a nonzero magnetostriction yoke after writing, contributes to the noise-after-write is an almost obvious one. The decay of the noise probability is consistent with an effective thermal decay time of approximately 10 μs [50].

Support for this conclusion is found in the dependence of the probability of noise-after-write events on write pulse duration. For longer (>10-μs) durations and normal write currents, the probability of occurrence of Barkhausen events reaches a steady-state value, indicative of the head reaching a constant temperature in a time frame that is long compared to the thermal rise time of the head. Furthermore, the probability of noise events is virtually independent of write frequency in the <1-MHz range [41, 47] consistent with a heating effect.

More generally for low write durations and/or low write amplitudes, the probability of noise-after-write events is a complicated function of write duration and amplitude, reflecting nonuniform magnetic saturation and heating of portions of the yoke. The noise threshold and number of trials also significantly influence the results [41].

The complex dynamics of the demagnetization process occurring directly after termination of a write operation can leave a yoke in (slightly) different domain patterns after each write operation, some of which are unable to relax further because of "pinning." This gives rise to a nonreproducible reading response from write to write and degrades potential read performance, since the read channel must be capable of operating even with the head in the most disadvantageous domain state. Read instability also can be caused by domain wall configuration changes in response to signal excitation and/or stray magnetic fields, although these occur relatively infrequently.

The most striking symptom of read instability is the distortion of the (isolated) read-back pulses in the form of transient phenomena located predominantly on the trailing edge of the pulse [51], as shown in **Figure 18**. This instability is sometimes referred to as "head wiggle" [52]. The "ringing" in the wiggles in Figure 18 is due to the resonance of the coil inductance, the coil capacitance, and the preamplifier's input capacitance [51]. Reference [53] confirms that most of this read instability occurs on the trailing edges of the data signal.

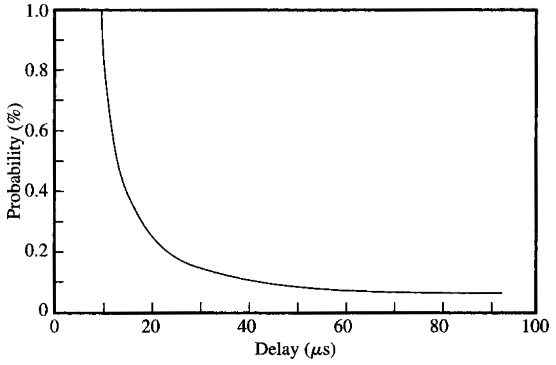

Figure 17

Arrival time distribution. Shown here is the probability of a Barkhausen event arriving in a 0.1-μs-wide interval around the plotted abscissa value [41].

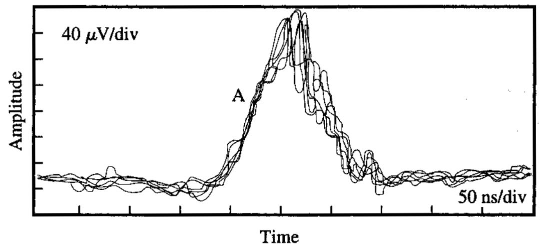

Figure 18

Read waveforms, triggered at point A, showing read instability.

In **Figure 19**, the difference is shown between the (track-averaged) pulse lengths (as measured along the track) with and without write excitations. The difference is quite substantial for a read-unstable head.

Although it has long been held that read instability and read noise are associated with domain wall motion [11, 54], and a number of head sites have been proposed as the principal location of the noise [11, 55–58], only after extensive experimentation have the offending walls been predominantly (but not exclusively) located in 180°

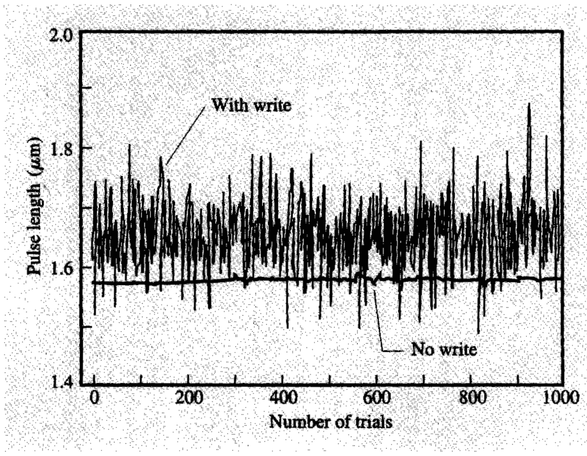

Figure 19

Track-averaged read-back pulse length with and without intermittent writes.

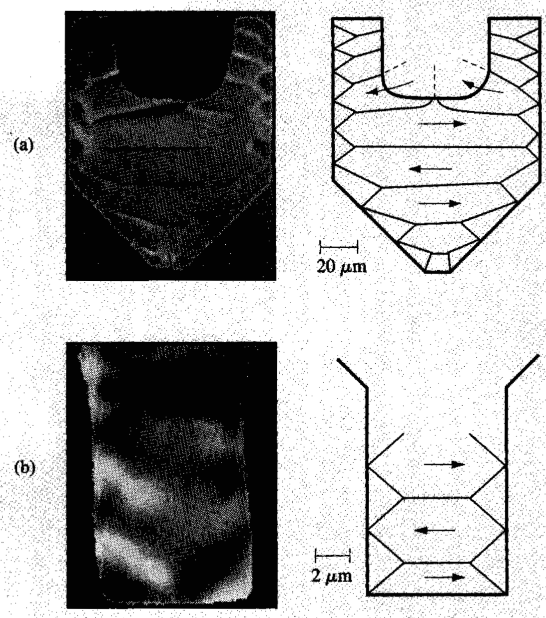

Figure 20

Domain images of a low-noise head with 1.6% read-back amplitude variation: (a) top yoke; (b) top pole.

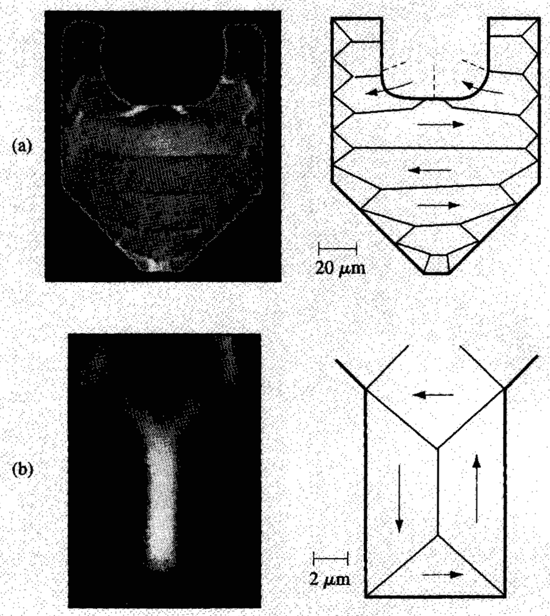

Figure 21

Domain images of a high-noise head with 4.6% read-back amplitude variation: (a) top yoke; (b) top pole.

walls oriented in the direction of flux flow in the pole tips and lower apex region of the top pole tip, a site where the signal flux density is largest. **Figure 20** shows an example of the domain images of a low-noise head, while **Figure 21** shows an example for a high-noise head. The domain images were made with a scanning Kerr-effect microscope in the tickle-field mode of operation [58], using a statistical analysis of many images [59]. The heads were made from plated NiFe films with a saturation magnetostriction of -1.6×10^{-6}. The average standard deviation of the read-back amplitude measured after repeated off-track writes was taken as the measure of read noise. For the low-noise head, the average standard deviation was less than 2% of the read-back amplitude; for the high-noise head, greater than 3%.

These two heads exemplify the trends observed. The yoke regions show no significant differences in their domain configurations. Neither the cusp in the transverse (in the cross-track direction) 180° wall near the back closure nor the size of the closure domains in the yoke differs significantly between low and high read-back-noise heads. The number of transverse 180° walls in the yoke is not unique and changes when the head is pulsed with write currents [60]. In contrast, the pole regions show significant differences. Triangular-closure domains with substantial amounts of transverse magnetization are found in the low-noise head, while a longitudinal (in the direction of signal flux flow) 180° wall and mostly longitudinal magnetization are found in the high-noise head.

This observation is confirmed by a quantitative image analysis of the pole domain states shown in **Figure 22**, where the amount of read-back variation is plotted versus the fraction of longitudinal magnetization, M_l, from statistical analysis of the top pole regions of 22 heads.

The value of M_l was determined by calculating the amount of magnetization in the longitudinal direction and normalizing by the total scanned area. In a preferred-domain configuration, as shown in Figure 20, most of the magnetization is transversely oriented, giving a low M_l value. The undesired configuration depicted in Figure 21 gives a high M_l value. There is a clear trend showing the correlation between the read-back distortion noise and the magnetization in the pole region, which is in turn correlated to the length of the 180° walls in the signal flux flow direction.

Longitudinal magnetization becomes energetically favorable in the sloping region of the top NiFe layer if the stress-induced anisotropy there is in the longitudinal direction and outweighs in magnitude the transverse anisotropy induced during plating. The magnitude of the stress-induced anisotropy is proportional to the product of the local NiFe magnetostriction constant and the local stress anisotropy. If either is small enough, the transverse anisotropy induced in plating will prevail, and 180° wall segments parallel to the signal flux will be minimized [48, 61, 62]. Stress anisotropy varies from point to point in the head because of local head structure and materials and the effects of deposition and machining processes [62, 63]. Three-dimensional stress modeling of film heads has shown that local stress anisotropies greater than 10^9 dynes/cm^2 are possible in the pole regions [64, 65], indicating a need for tight control of the local NiFe composition.

Conclusions

In 1998, magnetic recording will reach its 100th anniversary. It has succeeded in major product applications in many consumer and data storage markets. In every one of these applications, inductive magnetic heads are used exclusively for recording on many different forms of magnetic media. Playback is also accomplished with inductive heads, although the conversion to magnetoresistive (MR) heads is under way in some applications. Thin-film versions of inductive heads have been introduced into disk and tape products over the last 10–15 years. They now dominate the application to magnetic disk drives and have largely replaced ferrite heads as their price differential has decreased. In the future, as the price of magnetoresistive heads is reduced, the migration to MR designs will accelerate. Nevertheless, for the foreseeable future, every magnetic recorder built will contain inductive recording heads. This is a remarkable achievement, since no other recording component can claim a century of ubiquitous application. Inductive film heads have played a major role in the advance of two orders of magnitude in storage density in disk drives since their introduction in the IBM 3370 drive in 1979. In conjunction with MR film reading heads in the future, they will contribute to further density advances of at least one to two orders of magnitude.

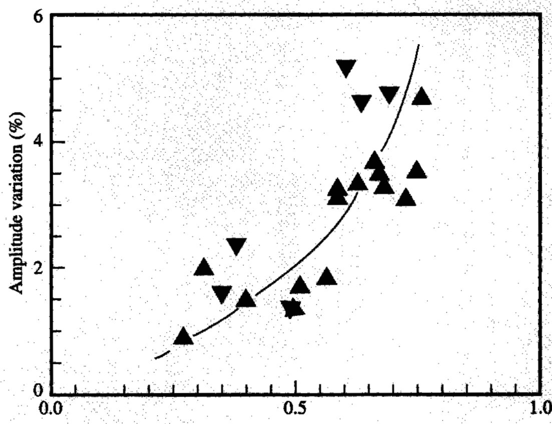

Figure 22

Read-back amplitude variation versus M_l.

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