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The Path from Invention to Product for the Magnetic Thin Film Head

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In the 1960s, engineers were producing paper designs and theoretical analyses for the smaller magnetic heads that were needed for high density disk storage systems, but there was no way to manufacture the proposed structures. This chapter describes the series of inventions by a small group at the IBM Research Center that led to a unique electrochemical fabrication process and to the invention of a thin film head that could be built with this process. While virtually all computer manufacturers were unsuccessfully trying to adapt silicon processing technology to head fabrication, the research group demonstrated a head built using electrochemical technology. The new technology was accepted by IBM's development and manufacturing groups, and a production line to mass produce the thin film head was ultimately implemented through a joint effort with their research colleagues. The story of the thin film head provides insights into the path of an invention from a laboratory concept to a manufactured product.

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1. Introduction

Innovations in science and technology over the last several decades have changed how we conduct our business and personal lives. Technological inventions and advances, however, can have such immense impact only if the ideas of visionaries in the laboratory are transformed into useful products on a manufacturing line. The traditional approach to achieving a manufactured product has been to have a development group refine the newly invented idea into a functional device with marketable features. The development engineers subsequently hand off the design to manufacturing engineers to implement a manufacturing-worthy process. This approach may work, more or less, with inventions that can be built with existing process technology. However, an invention that brings about a major advance in the state of the art often requires a number of ancillary inventions to achieve a viable manufacturing process. Process inventions and its supporting process and materials science become so intertwined with the design of the device that all three – process, underlying science, and design – must be treated together in an interdisciplinary effort from the inception of the structure to its emergence as a product. Indeed, the interdisciplinary approach can be advantageous even if no new technology is involved.

The importance and practice of such an interdisciplinary program is best understood by following the evolution of a specific invention from initial concept to manufactured product. IBM's creation of the magnetic thin film head, which brought about a quantum jump in magnetic data storage and simultaneously transformed electrochemical technology from a shop art to a precision manufacturing process, provides an appropriate example. Every invention is, by its very definition, unique, and so it is not possible to define the details of a single path that will lead any invention into production. The authors hope that this chapter will help the reader understand the principles that made the thin film head program so successful in advancing information storage on disk and tape, and to adapt those elements appropriate to his or her work to similarly advance today's technology to new heights.

2. The State of the Art in the 1960s

To appreciate how the magnetic thin film head evolved from a concept into a product, one needs a few background details on the state of the art in digital computers and in device fabrication process technology in the 1960s – the period during which the thin film head was conceived and its fabrication process was developed. Maissel and Glang's *Handbook of Thin Film Technology,* published in 1970, provides a detailed discussion of the practice and the underlying science of the various thin film fabrication processes used in the electronics industry at that time [1]. The discussion in this section deals only with those aspects of technology relevant to the thin film head. The time line of manufacturing technology evolution in Figure 1, simplified to focus on these aspects, will help the reader follow the discussion and appreciate how the interplay among fabrication process that were developed for seemingly different applications brought the thin film head into mass production.

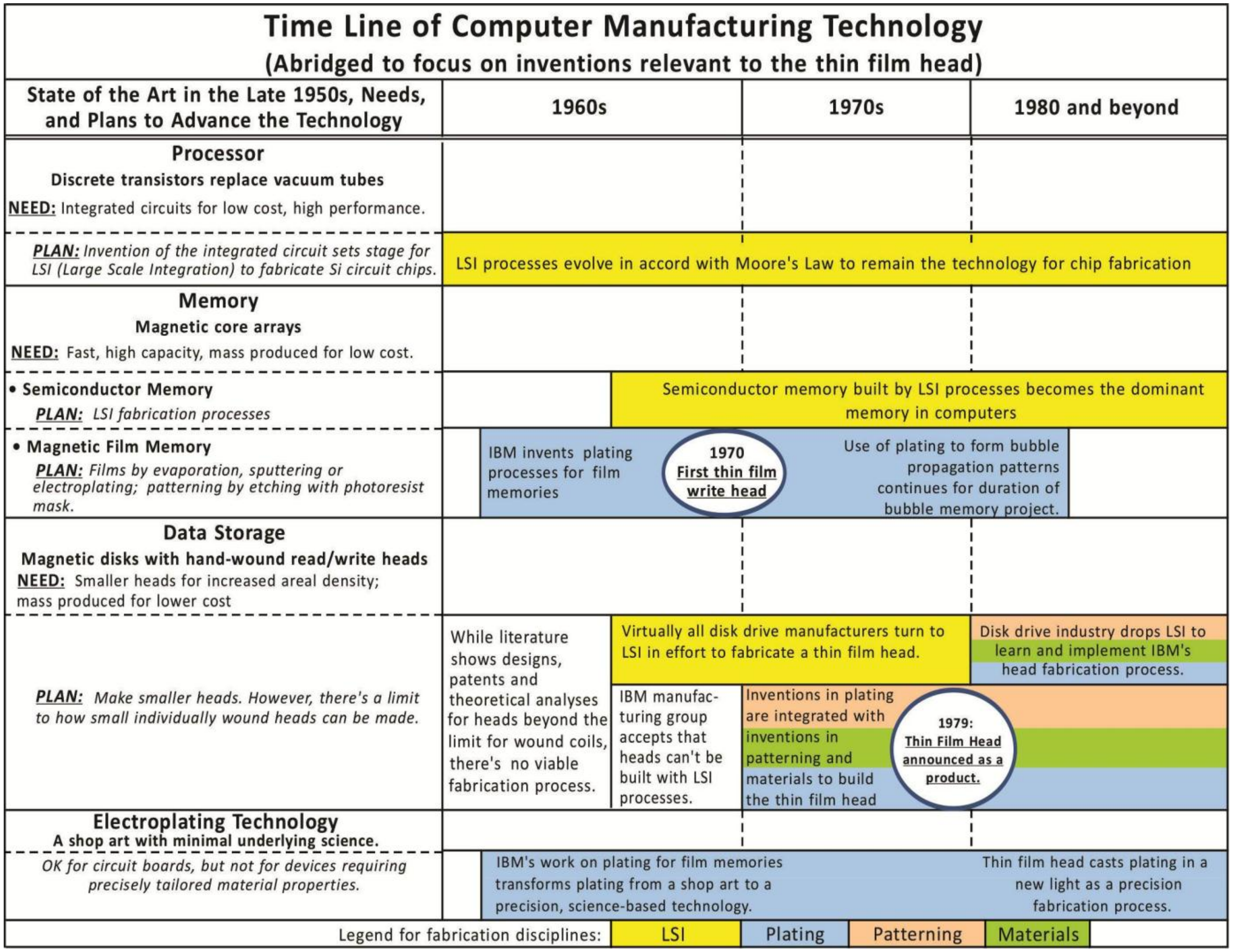
Figure 1 highlights the evolution of process technology for fabricating the three major elements of the computer and for electroplating technology, namely:

- The processor, which rapidly carries out the logical and computational operations specified by the programs,
- The working memory, which the processor uses in performing these operations, and
- The high density, fast access data storage that holds the programs and data. (The thin film head is a critical component of disk and tape storage systems.)
- Electroplating technology, in the fourth row, initially had little relevance to computer fabrication. At the end of the 1950s, where this time line starts, plating was seen as a shop art that lacked the precision and control necessary to build any part of the computer other than the circuit boards. In the next decade, however, plating would become the key technology that enabled mass production of the thin film head. Of course, the processor, memory and storage elements had to be interconnected for the computer to function. As the speed of the computer increased, interconnections became a significant factor in computer performance and took on the form of transmission lines with precisely fabricated structures. While the details of interconnection technology are beyond the scope of this chapter, it may be noted that during the 1990s, electroplating also assumed a key role in the fabrication of critical interconnections. [2,3]

The time axis in Figure 1 starts with the left column, which reflects the state of the art in the relevant manufacturing technologies at the end of the 1950s and the objectives for further advances in each of these areas. The next three columns respectively highlight the 1960s, when the major advances that defined the future paths for each of the technologies were made; the 1970s, when the thin film head became a manufacturable product; and the 1980s and beyond, when technology based on the work of the previous two decades continued to evolve into today's production processes.

2.1. The Processor

The invention of the integrated circuit in the late 1950s [4,5] set the stage for an intensive effort to develop LSI (Large Scale Integration) processes in the 1960s. This technology formed semiconductors on a silicon substrate and interconnected them by thin metal patterns on the flat surface to create functional circuit chips. The essential steps in LSI fabrication included a combination of oxidation processes to form SiO_2 on the silicon surface, photolithographic and chemical etching steps to provide openings in the SiO_2, and diffusion or ion implantation to produce appropriately doped n and p regions for the semiconductor devices. The aluminum (and subsequently aluminum-copper) that was evaporated or sputtered over the surface and photolithographically patterned by wet chemical etching formed the metal elements of the semiconductor devices and the interconnections among them.



Time Line of Computer Manufacturing Technology
(Abridged to focus on inventions relevant to the thin film head)

State of the Art in the Late 1950s, Needs, and Plans to Advance the Technology	1960s	1970s	1980 and beyond
Processor **Discrete transistors replace vacuum tubes** **NEED:** Integrated circuits for low cost, high performance.			
PLAN: *Invention of the integrated circuit sets stage for LSI (Large Scale Integration) to fabricate Si circuit chips.*	LSI processes evolve in accord with Moore's Law to remain the technology for chip fabrication		
Memory **Magnetic core arrays** **NEED:** Fast, high capacity, mass produced for low cost.			
• Semiconductor Memory ***PLAN:*** *LSI fabrication processes*	Semiconductor memory built by LSI processes becomes the dominant memory in computers		
• Magnetic Film Memory ***PLAN:*** *Films by evaporation, sputtering or electroplating; patterning by etching with photoresist mask.*	IBM invents plating processes for film memories	**1970** **First thin film write head** Use of plating to form bubble propagation patterns continues for duration of bubble memory project.	
Data Storage **Magnetic disks with hand-wound read/write heads** **NEED:** Smaller heads for increased areal density; mass produced for lower cost			
PLAN: *Make smaller heads. However, there's a limit to how small individually wound heads can be made.*	While literature shows designs, patents and theoretical analyses for heads beyond the limit for wound coils, there's no viable fabrication process. Virtually all disk drive manufacturers turn to LSI in effort to fabricate a thin film head. IBM manufacturing group accepts that heads can't be built with LSI processes.	Inventions in plating are integrated with inventions in patterning and materials to build the thin film head **1979:** **Thin Film Head announced as a product.**	Disk drive industry drops LSI to learn and implement IBM's head fabrication process.
Electroplating Technology **A shop art with minimal underlying science.**			
OK for circuit boards, but not for devices requiring precisely tailored material properties.	IBM's work on plating for film memories transforms plating from a shop art to a precision, science-based technology.		Thin film head casts plating in a new light as a precision fabrication process.

Legend for fabrication disciplines: LSI | Plating | Patterning | Materials

Figure 1. A time line of advances in technologies pertinent to the invention of the thin film head. Note that a combination of inventions from the areas of plating, patterning and materials science were needed to manufacture the thin film head.

LSI enabled the computer industry to meet the objectives for the next generation processors by mass producing chips with large arrays of interconnected circuits, thus eliminating much of the more expensive manual assembly of individual components. This technology also increased the speed of data processing and transmission within the machines by shrinking the size and increasing the density of the circuits on the chip. The vast majority of people working in advanced electronic fabrication were involved in some aspect of LSI processing, giving rise to rapid advances in this technology. LSI continued to evolve and remains the underlying technology for today's semiconductor devices.

2.2. Memory

The engineers working to advance memory technology were also looking for improved performance and lower cost. State of the art magnetic core memories of the late 1950s were expensive to build because they required several thin wires to be threaded through an array of tiny toroidal cores in specific patterns. Two alternative technologies to replace core memories – magnetic thin film memory and solid state memory – were pursued concurrently.

The solid state memory approach used large arrays of memory cells, each cell being an integrated transistor circuit that could store one bit of data. By 1968, the advances in semiconductor memories and the fact that these memories could easily be combined with the transistor circuitry on the processor chip led IBM to curtail most magnetic memory work [6]. (Some bubble memory work, in which the plating process described in this chapter were used to build magnetic bubble devices, did continue through the 1970s.) LSI processes were effectively used to fabricate semiconductor memory, and, as the yellow time lines in Figure 1 indicate, this technology continues to build both the memory and the processor for today's computers.

Magnetic film memory and an advanced version, the much denser coupled film memory, were serious contenders to semiconductor memory. The magnetic film approach was to deposit films of copper and permalloy (a magnetic alloy of Ni and Fe with appropriate magnetic properties for memory devices) by evaporation, sputtering or electroplating and to pattern the respective layers by deposition through a mask or by etching with a photoresist mask to produce the various magnetic film memory configurations [7]. Thin magnetic films promised faster switching than ferrites, and building thin film structures was less expensive than assembling core arrays. Using electroplating instead of evaporation would make the thin film structures even less costly to produce, and one of the authors (L.T.R.) was pursuing the electrochemical approach. However, electrodeposition as it was understood and practiced at that time was hard-pressed to reproducibly produce the required magnetic properties. It was the inventions of a new plating tool and of new fabrication processes that enabled IBM to use electroplating in magnetic film memory production. (See Sections 2.4 and 4.2.)

Magnetic film memory was only used by IBM on two System/360 Model 95 computers that were built under special contract for NASA in 1968. With an access time of 67 nanoseconds [6,8], this memory provided a level of performance that was not achieved by semiconductor memory until several years later. However, the most important impact of IBM's magnetic memory program on computers came when the electrochemical fabrication processes that had been invented to build film memory structures became a key enabler of a new technology to manufacture the thin film head for data storage.

2.3. Data Storage

High performance data storage systems entered a new era in 1956 with the announcement of the RAMAC 305, the first IBM system to offer a disk drive storage system. (Figure 2.) This system used fifty 24 inch diameter magnetic disks, each with sets of moving arms containing inductive read/write heads. Data were recorded on both sides of the fifty disks at a density of 2 kilobits/in^2 to create a system with a total capacity of 5 megabytes. Each head consisted of a coil that was hand-wound around a magnetic core and were mounted so that their pole tips were flying in close proximity to the spinning disks. In the write mode, current pulses through the coil encoded data by creating appropriately magnetized spots in concentric, circular tracks in the magnetic coating on the disk's surface. In the read mode, the system used the voltage induced in the coil as the magnetized spots moved past the pole tips to sense the data.

Figure 2. The RAMAC 305, announced in 1957, was IBM's first system to use magnetic disk storage technology. It used 50 disks, each 24 inches in diameter with a storage density of 2000 bits per square inch to provide a total machine capacity of 5 megabytes. The cabinet visible beyond the operator housed the memory of the RAMAC system with its stack of 50 disks.

An important measure of performance for a data storage system was the areal density of data on the disk. A higher areal density, in addition to giving the system greater storage capacity on a smaller diameter disk, also meant faster access to data as well as a reduction in the cost per bit of information stored. The size and configuration of the pole tips at the head/disk interface were key factors in determining the size of the magnetized spots and thus, the areal density. By 1965 engineers had decreased the dimensions of the hand-wound heads and made other improvements in technology to achieve an areal data storage density of 300 kilobits/in^2. There was, however, a limit to how small mechanically wound heads could be made; at best, the existing fabrication technology might be pushed to gain only one or two more orders of magnitude in areal density. And there would still be the need for a mass production process to eliminate the significant cost of winding each head individually. An advanced disk storage device of that era along with a close-up photo of a ferrite head with a wound coil is shown in Figure 3. [9]

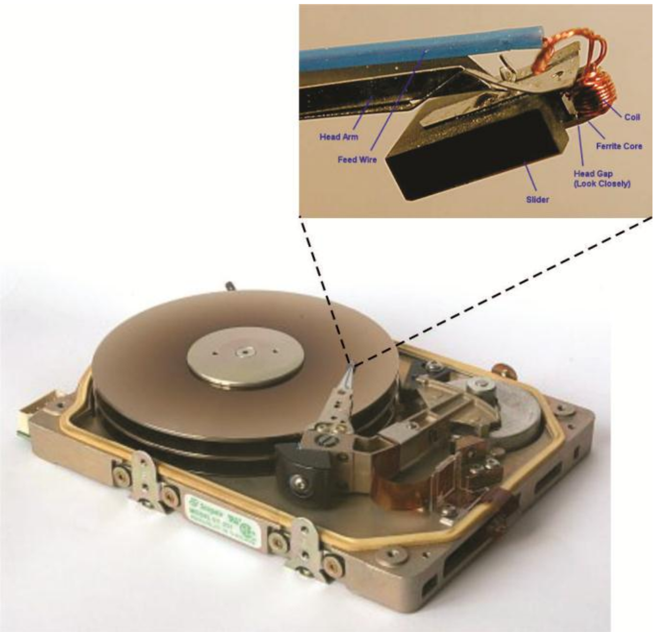


Figure 3. The hand-wound ferrite read/write head remained in use through much of the 1980s until disk drive manufacturers could learn and implement the new thin film head fabrication technology. The figure shows the popular 5.25 inch Seagate ST-251disk drive of that era along with a greatly enlarged view of the ferrite head mounted at the tip of the actuator arm.

Various proposals for miniature structures to replace the wire wound heads had been made over the years since the introduction of the RAMAC system, the most promising of which was the thin film head shown schematically in Figure 4. The first patent for a thin film head was filed by Gregg in 1961 and issued in 1967 [10]. Other patents and publications that appeared throughout the 1960s and ‘70s presented alternate designs and/or theoretical analyses for thin film heads, but there was no viable process that could manufacture the proposed devices in a structure that met the advanced needs of the next generation disk drive system.

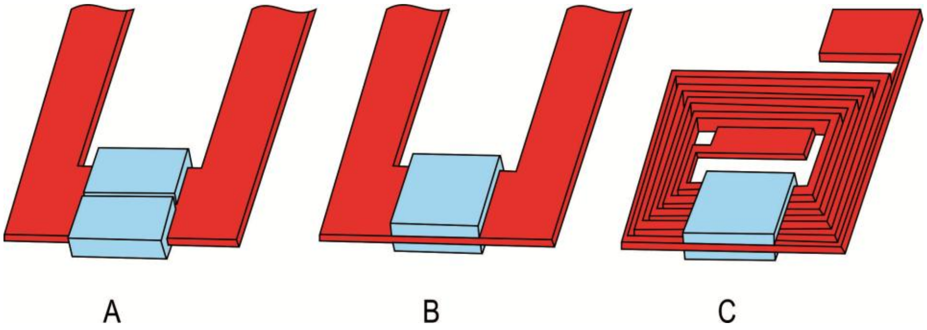


Figure 4. Schematic drawings of thin film head structures discussed in this chapter. (A) A single-turn horizontal head. (B) A single turn vertical head. (C) A multi-turn vertical head.

As computer manufacturers tried to come up with a suitable manufacturing process, the task fell to their experienced device fabrication engineers. Since the vast majority of people working in advanced electronic fabrication were involved in some aspect of LSI processing, it is not surprising that these engineers sought to adapt the technology of the silicon world to thin film head fabrication. As they envisioned the fabrication of the head, permalloy, an alloy of nickel and iron with appropriate magnetic properties, would be evaporated or sputtered as a blanket film and patterned by photolithographic and etching processes to form the magnetic yokes of the head; the copper windings in the head would be created by similar deposition and etching steps; and sputtered SiO_2 would be deposited and patterned by etching to provide insulation. Arrays of heads would be mass produced on a single substrate that would later be diced into individual devices for mounting in the disk drive unit. From the late 1960s through 1979, virtually all computer manufacturers had programs to adapt LSI type processes to the manufacture of a thin film head.

2.4. Electroplating Technology

By the 1960s, electroplating had been in use for many decades to deposit a variety of metals for jewelry, decorative coatings, corrosion protection and wear resistance. However, no attempts to tailor magnetic or most other physical properties in electroplated metallic deposits had been reported. With few exceptions, the processes were carried out by artisans using proprietary solutions and process steps with little understanding of the underlying science. Plating was generally regarded as a shop art and, while accepted for the fabrication of printed circuit boards, had never been regarded as useful in the production of electronic devices with precisely tailored material properties. In particular, those who tried to electroplate magnetic alloys found it difficult to consistently obtain the required magnetic parameters, especially in the configurations required for memory and other devices.

Electroplating did have cost advantages and, with the invention of the through-mask plating process described later in this chapter, offered the greatest precision in fabricating microstructures out of plateable materials. As one of the authors (L.T.R.) was attempting to use plating to fabricate magnetic film memories, he encountered the variable results and the instability of the magnetic properties of plated permalloy that others had found in doing similar work. He, however, was able to develop sufficient understanding of the plating process and of the plated permalloy which led to the inventions of a new plating tool, the appropriate plating solutions, and the deposition and annealing parameters that insured reproducible, stabilized and precisely controlled magnetic properties in the deposited films [11]. The advances in electroplating that came out of these studies were crucial to the invention of the thin film head and are summarized in Section 4.2.

3. Finding the Right Path to Production

3.1. First Demonstrations of a Thin Film Head

The first demonstration of a batch-fabricated thin film write head came not from a program to advance recording head technology but rather, out of the magnetic film memory work that was described above in Section 2.2. One of the structures built during this program, the coupled film memory [12], is shown in Figure 5. As is pointed out in the caption, the lower line is essentially a copper conductor passing through a closed magnetic yoke. Put a gap in the yoke, and you have a one-turn magnetic recording head. To meet the requirements for a high density storage system, however, the gap would have to be very narrow – less than 2 µm.

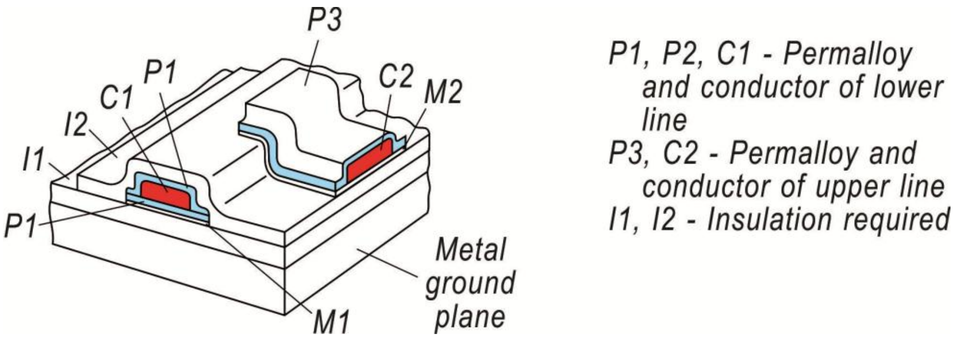


Figure 5. Coupled film memory structure. Although designed for use as a magnetic film memory, the part of the structure comprised of the copper conductor C1 with permalloy layers P1 and P2 wrapped around it could just as well function as a one-turn magnetic head if there were a gap in the permalloy surrounding the copper.

One of the fruits of IBM's film memory program was the invention of through-mask plating, a new fabrication process that did not use the conventional subtractive approach of chemically etching a blanket film of permalloy or copper through a photoresist mask to form the required patterns. Instead, through-mask plating put an inverse mask with openings for the pattern elements on a conductive seed layer, and the required structure was created by the additive process of electroplating through the openings in the resist. Used in combination with the advances in electroplating that also came out of the magnetic film work, through-mask plating had the capability of producing well-defined, thick, 3-D permalloy patterns with precisely controlled magnetic properties. The first batch-fabricated thin-film heads, each a single-turn, horizontal structure such as shown in Figure 6, were produced using the through-mask-plating approach [13]. The gap was created by including a 2 µm wide band of electron beam resist [14] in the mask for plating the upper layer of permalloy.

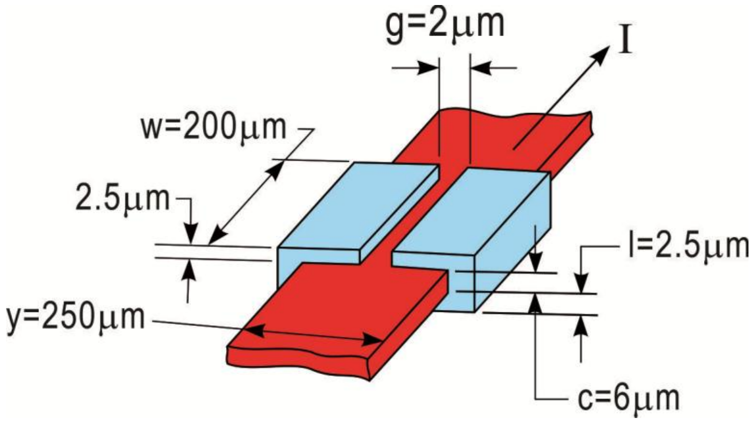


Figure 6. Perspective view showing the dimensions and structure of the first thin recording head fabricated with a 2 µm gap.

The structure described in the previous paragraph had not been designed to fly over a spinning disk. However, the static test results reported in the cited reference [13] supported the conclusion of theoretical analyses that “microminiaturized heads fabricated from thin films are expected to give satisfactory performance.” In particular, (a) “the dimensions of the written bits corresponded very closely to the dimensions of the gap” and (b) no lag in switching was seen with equipment having a time resolution of better than 5 nanoseconds.

The next step was to build a thin film head that could be flown over a spinning disk to test the read and write performance in a real data storage system. This head was similar to the initial demonstration structures except that the new devices were designed as vertical instead of horizontal heads. (Figure 4 shows the head configurations that are relevant to the discussion in this chapter.) The difference was in the location of the gap and how it was created. In the horizontal head, the top layer of permalloy interfaced with the disk, and the gap was the break in this layer created by the e-beam resist. In the vertical head, the gap was determined by the thickness of a non-magnetic layer that was introduced between the upper and lower permalloy layers at one end of the structure where these layers were patterned as pole tips. When the wafer was diced into individual heads, the sandwich of the permalloy pole tips and the non-magnetic copper separator was exposed at the edge of each head. In use, the head was mounted perpendicular to the disk so that the exposed edge interfaced with the disk’s magnetic surface, hence the designation “vertical head.” The vertical head was seen as the preferable configuration for a product because after dicing, the substrate became the slider, which could be aerodynamically designed to fly in very close proximity to the disk without ever touching or resting on the disk. Furthermore, since thin film deposition processes were capable of excellent thickness control, the deposition of a non-magnetic spacer could produce submicron gap widths with tight tolerances and without the need for electron beam lithography. Functional tests found that the head could both read and write data on a magnetic disk, but the read back signal for a single-turn head was too small for a practical storage system. It was clear that a thin film head for a functional data storage product would have to be a multi-turn device as shown schematically in Figure 4C.

3.2. Interdisciplinary Design of a Functional Head

The fabrication of the first thin film write head by technology invented during the film memory program was triggered by the recognition that part of the coupled film memory structure was basically the same as the structure of a single-turn, horizontal inductive head. Furthermore, it was discovered that the plate-through-mask technology could be extended to produce the thick, high aspect ratio structures required for the head. One of the authors of this chapter (L.T.R.), who had invented the plate-through-mask technology and had done much of the research that made the electroplating of permalloy a reproducible process, was now using this technology to build the thin film head. As he became familiar with the head structure, it became apparent that LSI processes would be hard pressed to build the thick, 3-D structures required for the thin film head, and that plate-through mask technology was a more appropriate approach for head fabrication.

When Dave Thompson, an engineer who had expertise in magnetics, joined IBM in 1969, he joined Romankiw's program to design functional heads to be built in Yorktown using electroplating processes. Romankiw and Thompson combined their respective expertise in fabrication and in magnetics to design a multi-turn head that would meet the functional requirements of the next generation data storage system and, although challenging, could be produced with the proposed fabrication paradigm. These challenges and the reasons they had to be resolved to make a viable head included:

- Creating a five-turn coil with 2 μm high by 3 μm wide copper conductors spaced 3 μm apart.

  (The turns of the coil had to be as close to the gap as possible since leakage between the upper and lower legs of the yoke reduced the efficiency of the turns as their distance from the gap increased. For a yoke with 10 μm separation between the legs, this requirement dictated that all the turns had to be within 100 μm from the gap. The plate-through-mask process could form the coils, but, as noted in Section 4.3.3, removing the seed layer from the narrow spaces between turns required special attention.)

- Patterning 2 μm thick, magnetically oriented permalloy with tight composition control and with perfectly smooth edges.

  (Irregularities at the edges could pin the magnetic domains, increase H_c, and create unpredictable domain patterns. Meeting the requirements for permalloy in the head was not possible with through-mask plating and required the invention of the plating frame as discussed in Section 4.3.2.)

- Providing insulation between the coil and the permalloy that had a near-planar surface for the deposition of the upper permalloy film.

(Insulation was necessary in the multi-turn head to prevent current shunting between the turns by the permalloy. The upper yoke had to be deposited on a near-planar surface because any significant surface topography could impede magnetic switching.)

- Producing 2 to 3 µm thick resist patterns with near vertical walls for through mask plating.

  (The only commercially available high resolution resist was designed for semiconductor processing, where only 0.5 µm thick resist was required.)

Addressing these and other fabrication issues while building the 5-turn vertical head was an essential step in learning how to carry out each of the process steps in the specific context of the thin film head and in integrating these operations into a viable manufacturing process. Several additional inventions that were crucial to the successful manufacture of the head were made during this phase of the work and are discussed in Section 4. A cross-section photograph of one of the first 5-turn heads is shown in Figure 7. Details of other prototype heads that were fabricated during this program are shown in Figure 8.

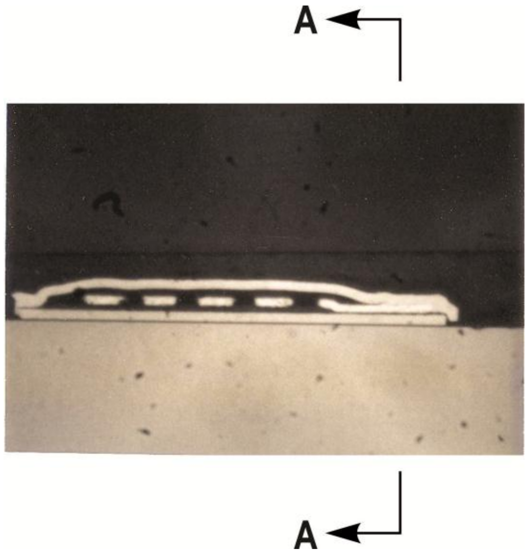


Figure 7. Cross-section of one of the first 5-turn heads that were completed in Yorktown. The first turn of the coil separated the legs at the right end of the head and defined the thickness of the non-magnetic gap that will be exposed when the end of the head is lapped back to the plane A–A perpendicular to the photo.

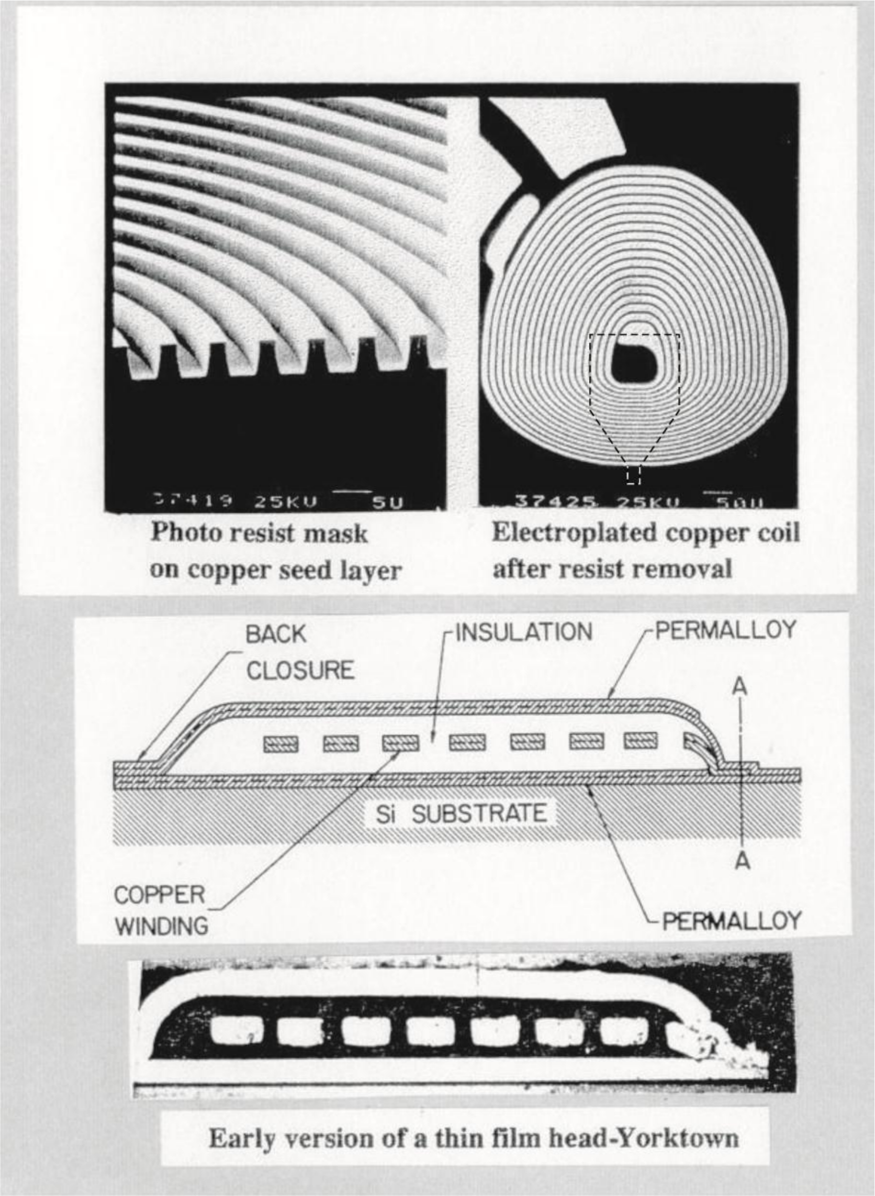


Figure 8. SEM photos taken during the fabrication of prototype versions of product heads. *Upper left:* Photoresist plate-through pattern for a 16 turn coil. *Upper right:* Plated coil after removal of resist and seed layer. The turns were of the order of 3 µm wide with 2 µm spaces where the coil passed through the magnetic yoke to minimize the distance between the gap and the back closure of yoke. Dashed outline shows the area of the yoke. *Center:* Cross-section drawing of an 8 turn head. Cutting and lapping the structure in the plane A-A perpendicular to the plane of the drawing exposed the gap that interfaced with the disk. *Bottom:* SEM photo of a cross-section of the 8 turn head.

It is worth noting that the interdisciplinary design approach, wherein the fabricator of the head was actively involved in its design, resulted in a structure that was so well matched to the capabilities of the fabrication process that it took less than two months from the start of fabrication to the completion of a working head. Furthermore, the tools and processes that were ultimately used in production were basically the same as those created during the thin film memory program even though the permalloy and copper patterns in the heads were nearly an order of magnitude thicker than in the memory structures.

3.3. Early Tie-in to Manufacturing

A crucial factor in bringing the new fabrication approach to the manufacturing floor was the establishment of close ties with IBM's General Products Division (GPD) laboratory in San Jose, the division that had responsibility for developing and manufacturing IBM's next generation of data storage systems. The Watson researchers realized that if their work was to become an IBM manufacturing process, it was GPD that would have to accept and implement the technology. Romankiw and Thompson therefore fostered a relationship with their colleagues in San Jose by keeping them informed on a weekly basis of every step in Yorktown's progress in head fabrication. GPD was aggressively pursuing the LSI approach and initially, showed little interest in an alternative process. However, in the absence of any completed heads of their own, GPD was willing to evaluate structures such as the single-turn vertical head that had been built in Yorktown.

While the 5-turn head was being designed and built at the Watson Research Center using plate-through-mask processes, GPD had also designed a multi-turn head and was struggling to overcome a serious obstacle in patterning the 2 µm high coils by LSI's approach. The coils had to be at least 2 µm tall with a rectangular cross-section to carry sufficient write-current in the head. Since subtractive processes and even lift-off do not faithfully replicate the photoresist mask, the best this process could produce was coils with severely reduced cross-sections [15]. The Yorktown group had avoided this problem by using the through-mask plating process to create the copper coils.

GPD engineers found it hard to believe the results Yorktown was reporting and so, urged by their manager, reluctantly agreed to have one of the authors of this chapter (L.T.R.) come out with all the necessary plating equipment to demonstrate what additive plating through a mask could do. In less than a week, all the equipment had been set up in San Jose and was producing the coil patterns that could not be achieved by subtractive etching. It took only a single meeting after GPD management saw the extremely well-formed copper coils fabricated in their own lab for them to decide that plating was the way to go.

The difficulty encountered in forming the coil in the thin film head highlights the importance of matching the fabrication process to the specific structure. Table I compares the ground rules for designing the most advanced LSI devices around 1970 – the time when head fabrication engineers were looking for a process to mass produce the thin film head – with the actual dimensions of the coil structure in the first manufactured thin film head. The ground rules are based on conversations one of the authors (S.K.) had with Robert Dennard, an IBM Fellow who is widely recognized for his contributions to semiconductor technology throughout his career. The coil dimensions are for the coil structure in the first thin film head product. This comparison makes it clear that chemical etching, even if it had produced a few demonstration samples in the lab, was nowhere near being part of a robust manufacturing process for thin film heads. Chemical etching was the right choice for LSI technology, but GPD made the right choice in switching to through mask plating for the head. [15]

Table 1. The most critical patterning requirements in the thin film head compared with the maximum thickness and smallest lateral dimensions allowed in advanced LSI designs around 1970.

	Coil dimensions in thin film head	1970 ground rules for advanced LSI structures
Thickness	2.5 µm	< 1.0 µm
Line width	3.0 µm	≥ 5.0 µm
Space between lines	2.0 µm	≥ 3.8 µm

3.4. The Integration of Many Inventions

It is well to pause here and refer back to the time line of Figure 1 to get a perspective of where the thin film head stood on its way to becoming a product. By the late 1960s, researchers had demonstrated the ability to write on magnetic media with the first thin film single turn head and had built the first multi-turn read/write head. Both heads were built using through-mask plating processes that had been invented for the fabrication of thin film memories. The work on film memories had also advanced the tools and processes of electroplating to the state where this technology could produce thick, precisely patterned structures of alloys with tailored magnetic properties. At this time, virtually all disk drive manufacturers were pursuing efforts to use LSI processes – the technology that was bringing rapid advances in the semiconductor industry – to put their respective designs for a thin film head into production. It was the close ties between IBM’s Research Division and GPD that gave GPD engineers the confidence to drop the LSI approach in favor of electroplating processes that were still regarded as a shop art and had never before been used for precision fabrication on a manufacturing line. GPD’s experience with the Research group had shown that Research was not handing off an invention for GPD to turn into a manufactured product on its own. Rather, the Research people they met were cognizant of manufacturability issues at every step of the way and were ready to work with GPD to turn the invention into a product.

Fabrication of the coils by through-mask plating was only one of many inventions related to plating, patterning and/or the materials involved in head fabrication. Furthermore, since electroplating had never before been used to manufacture a precision device like the thin film head, inventions directly related to the requirements of a production line were also needed. Much of the work on magnetic head technology in the 1970s was carried out in a joint effort between the inventors of the thin film head and the manufacturing engineers to integrate these inventions into the process that brought the first mass produced thin film head to market in 1979. Highlights of these inventions are presented in Section 4.

As the work progressed, the Research group expanded into an interdisciplinary team with expertise in magnetic materials, processes and devices ranging from the science underlying the head and its fabrication to the details of the manufacturing tools. The Research and manufacturing groups were now working closely together to make mass production of the world's first thin film head a reality. This relationship continued for more than three decades until IBM sold its magnetic storage business to Hitachi in 2002. During this period one of the authors (L.T.R) regularly visited San Jose and participated in the design and operation of the pilot line. Working together, they anticipated process problems and proposed research programs to address these issues. Many of GPD's newly hired engineers learned the head fabrication technology by spending their first year or so in Yorktown as post-docs doing research on these mutually agreed upon topics before moving on to their permanent assignments in San Jose. The creation and maintenance of strong ties between Research and GPD proved to be one of the most vital steps not only in bringing the new technology into production, but in insuring that the technology could continue to produce new head designs as data storage technology advanced.

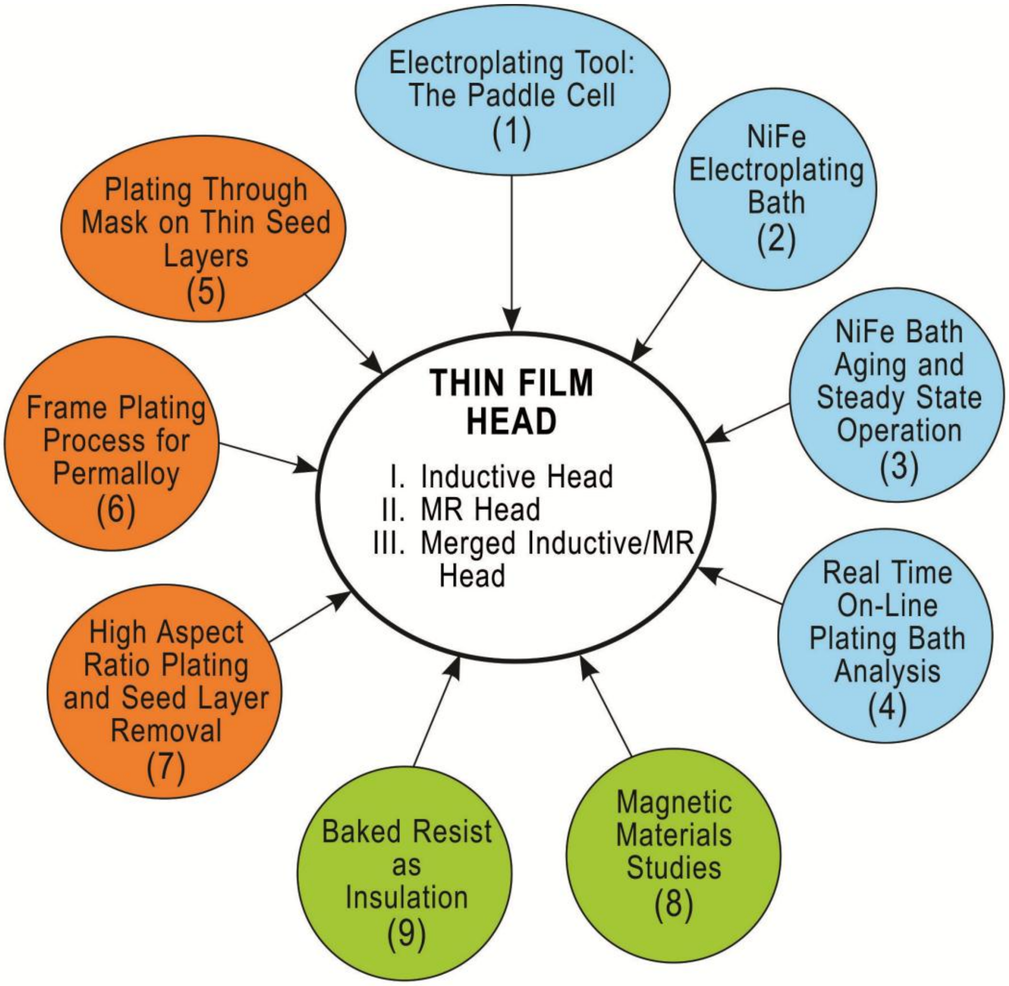
4. Key Inventions for Thin Film Head Production

The invention of through-mask plating to fabricate the coils was crucial to the fabrication of the thin film head, but this invention was only one of many that had to be integrated with each other to produce the final structure. This section highlights these inventions and shows that in implementing a manufacturing process for a particular invention – in this case, the thin film head – it is often necessary to come up with additional inventions to deal with unique aspects of the device being fabricated, the properties of the materials involved, and the tools and process controls required for production. Furthermore, these aspects are often so interrelated, that the design of the device and all the steps in fabrication need to be carefully integrated to produce the device. It is the system of processes rather than each individual step that must be optimized to create a viable manufacturing process.

The key inventions for the thin film head are depicted graphically in Figure 9 as balloons with arrows pointing to the thin film head (center circle) to show that all of these inventions had to come together to create the manufacturing process.

The inventions may be grouped into four categories. (The references give the full citation for the respective patent for each invention or additional references.)

- Device Structures (Center circle)
    - The inductive head – (U.S. Patent 4,295,173) [16]
    - MR head – (U.S. Patent 3,840,898) [17]
    - Merged inductive/MR head – (U.S. Patent 3,908,194) [18]
- The Plating Process (Blue circles)
    - The paddle cell – (U.S. Patent 3,652,442) [19]
    - NiFe electroplating bath – (U.S. Patent 4,102,756) [20]



Device Structures
I. U.S. Patent 4,295,173
II. U.S. Patent 3,908,194
III. U.S. Patent 3,840,898

The Plating Process
(1) U.S. Patent 3,652,442
(2) U.S. Patent 4,102,756
(3) U.S. Patent 5,352,350
(4) U.S. Patents 4,102,756, 5,352,350

Patterning
(5) U.S. Patents 4,315,985; 5,352,350
(6) U.S. Patent 3,853,715
(7) U.S. Patents 4,315,985; 5,352,350

Materials
(8) U.S. Patent 4,003,768
(9) IBM Technical Disclosure Bulletin, Vol. 23, p.2584 (1980).

Figure 9. The key inventions underlying the thin film head are indicated in the circle of balloons. Integration of these inventions into a viable manufacturing process brought the various head structures into production. These inventions are discussed separately in the context of similar, more detailed charts for each invention.

    - NiFe bath aging and steady state operation – (U.S. Patent 5,352,350 [21]
    - Real-time, on-line plating bath control – (U.S. Patents 4,102,756 and 5,352,350) [20, 21]
- Patterning (Orange Circles)
    - Plating through mask on thin seed layers – (U.S. Patents 5,352,350 and 4,315,985) [21, 22]
    - Frame plating process for permalloy – (U.S. Patent 3,853,715) [23]
    - Ancillary patterning issues – (U.S. Patents 5,352,350 and 4,315,985) [21, 22]
- Materials (Green circles)
    - Magnetic materials studies – (U.S. Patent 4,003,768) [24, 11]
    - Hard baked resist as insulation – (*IBM Technical Disclosure Bulletin*, **23**(6), 2584) [25]

The discussion of each of the inventions is carried out in terms of a more detailed chart. Since balloons 2, 3 and 4 are very closely related, a single detailed chart (Figure 12) is used for the discussion of these three aspects of the plating process. The charts serve as an outline of the accompanying discussion and also highlight some of the many interrelated aspects of the manufacturing process. Each of the detailed charts has an inset of Figure 9. Items in several of the detailed charts have connections to other circles in Figure 9, and some of these connections are indicated by dotted links to the respective circles in the inset.

4.1. Device Structures

The first manufactured thin film head used a single inductive structure for both reading and writing. The output of an inductive read head depended on the number of turns in its coil and on $d\varphi/dt$, the rate of change of magnetic flux as the head flies over the disk; the latter parameter was proportional to the magnitude of the flux associated with each bit of data, the radius of the data track and the angular velocity of the disk. As the areal density increased and data tracks became narrower, the magnetized area for each bit of data became smaller. Maintaining an adequate read signal from an inductive head required some combination of increased number of turns in the head, increased rpm of the disk and/or a constraint on the minimum radius of the data track. One marketing requirement imposed on advanced disk drives was that the next generation system had to offer increased storage capacity on a smaller disk. Ultimately, it would be necessary to replace the inductive read head with an MR (magnetoresistive) read head. Since the MR head responded to the changes in resistance at a magnetic transition with no dependence on $d\varphi/dt$, the MR read head permitted the use of much smaller disks by eliminating the constraint of a minimum track radius.

The fabrication paradigm that produced the first heads was fully capable of building an MR read head and a combined MR read/inductive write head. Versions of heads that included MR read elements were built in the lab almost as early as the first inductive heads [26] even though advances in inductive read/write heads continued to meet data storage requirements until 1992, when MR sensing finally had to be introduced. It was a tribute to the power of the new fabrication paradigm that this technology was able to produce heads with a total of 49 turns in three layers to maintain the viability of inductive read heads for more than a decade. When the use of more sensitive read head finally became indispensable, the inventions that produced the first thin film head readily accommodated not only the MR elements but also future advances such as GMR (Giant Magnetoresistance), spin valves and heads for perpendicular recording as these inventions came along without deviating from the structure of the original MR read/inductive write head patent filed in 1974 [18].

4.2. The plating process

It was mentioned in Section 2.4, that the work at IBM had greatly advanced the understanding of permalloy plating that existed in the early 1960s, thereby enabling the use of plating to fabricate magnetic thin film memories. Section 4.2.1 describes the paddle cell that was invented for this purpose and that subsequently was a key enabling invention for the thin film head. Section 4.2.2 focuses on the scientific studies that had to be done to make permalloy plating a viable manufacturing process. This work ranged from the studies of the permalloy plating process that led to the invention of the paddle cell that plated magnetic thin films in the lab to the studies that introduced the steady state “Bleed & Feed” concept that achieved infinitely long permalloy bath life on the manufacturing line.

4.2.1. The paddle cell

For permalloy plating to become a viable, precision manufacturing process, the plated films had to have uniform and reproducible properties over the entire substrate. Meeting this requirement was complicated by the anomalous co-deposition of the Fe with Ni and by the strong dependence of alloy composition on current density described in Section 4.2.2. The deposition of Fe was controlled by the rate of supply of Fe from the electrolyte to the diffusion layer and by the thickness of the diffusion layer. Therefore, both the concentration of Fe at the electrolyte-diffusion layer interface and the thickness of the diffusion layer had to be well controlled. The deposition of Ni was believed to be discharge controlled, which required a plating cell with a very uniform current distribution over the entire surface of the cathode. Several commercially used plating tools with different methods of agitation were investigated including air or N_2 bubbling through the cell, back and forth motion of the cathode, flow cells and jet cells. None, however, could achieve the high degree of uniform agitation over the entire surface as required to plate permalloy.

The invention of the paddle cell created a tool with the features shown in the blue balloon of Figure 10. The cell incorporated a new method of agitation that insured the required, uniform diffusion layer thickness and Fe concentration, and could readily be scaled up to do the same in a production sized tool. (Agitation is the one aspect of a chemical reactor that has always been difficult to scale up from the development tool in the laboratory to the production tool for manufacturing.) The walls of the cell were designed to promote uniform current distribution across the entire cathode.

A cut-away view of the paddle cell is shown in Figure 11. The cathode sat in a horizontal position at the bottom of the cell. The external permanent magnets provided a 500 oe magnetic field to define the easy axis in the plated films. The wafers with a thin, conductive seed layer and

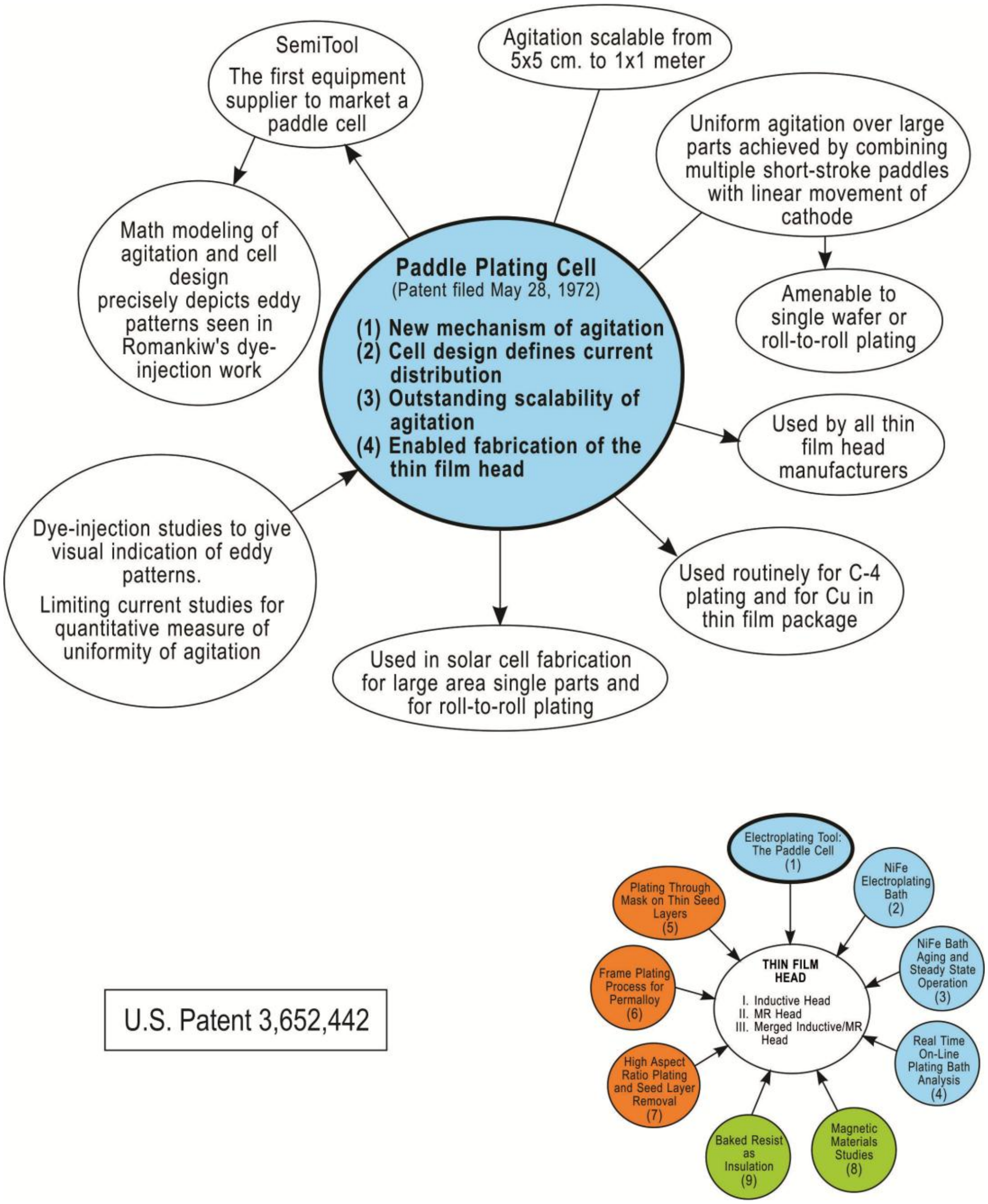


Figure 10. The invention of the paddle cell enabled the plating of permalloy films with consistently reproducible magnetic properties.

the lithographic pattern to be plated were inserted into the circular recesses (the figure shows a cathode designed for round substrates) from the bottom of the stainless steel holder and pressed against a thin lip at its top surface to insure good electrical contact for plating. (This simple wafer holder worked well for small substrates. When the production line moved to using larger substrates, the IR drop in the thin seed layer became large enough to cause a significant reduction in plating current density from the contact edge to the center of the wafer. The wafer holder was modified to include a current thief that could be independently powered to draw current away from the outer parts of the substrate to maintain uniform plating.) The nickel anode, which had a corrugated surface to increase its surface area, was mounted above the cathode and parallel to it. The walls of the cell were designed to constrain the electrolyte to a vertical column between cathode and anode with the same cross-section as the cathode, thus eliminating current spreading and insuring the required uniform current distribution across the cathode.

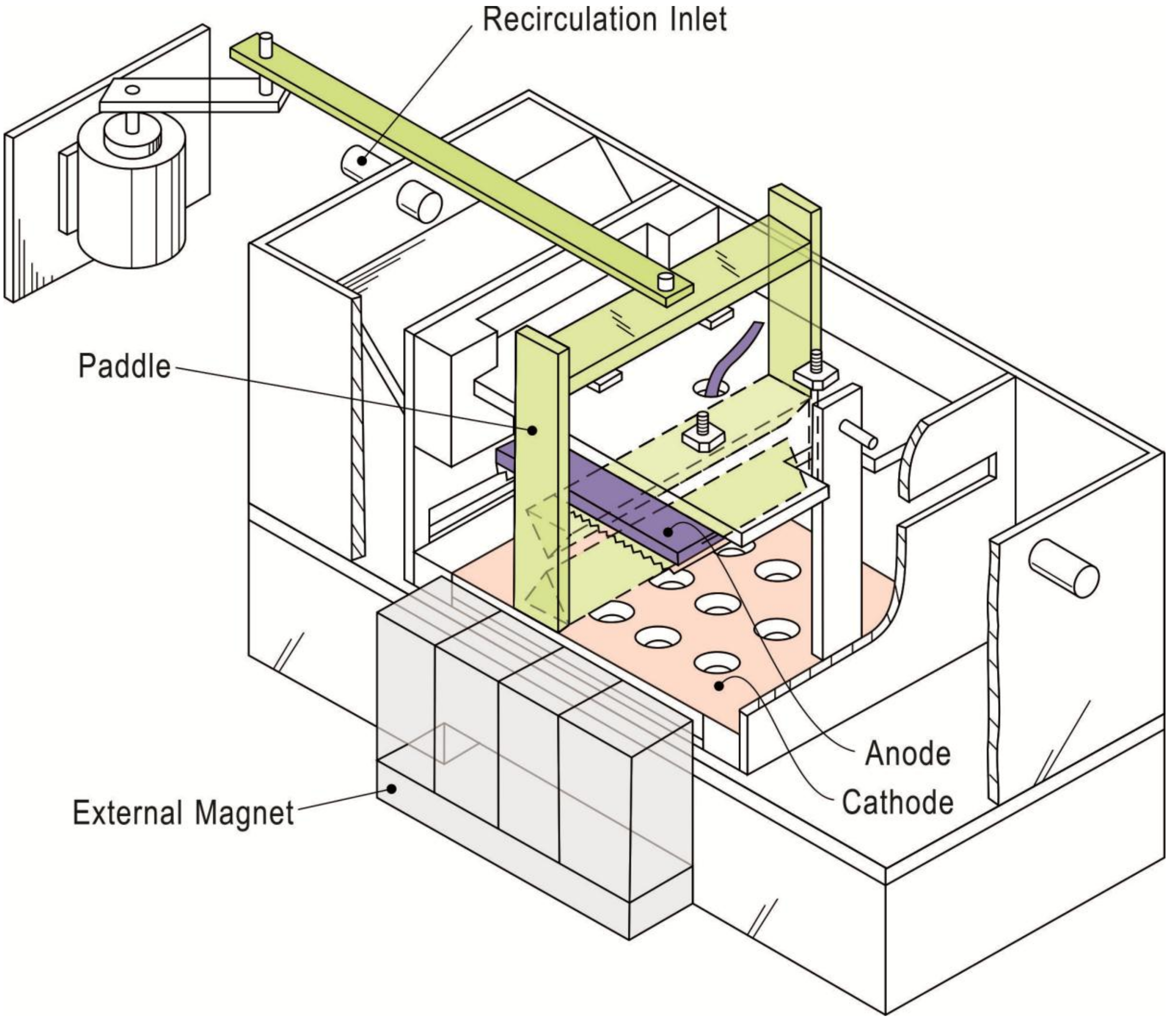


Figure 11. Cut-away view of the paddle cell. The paddle, which sweeps back and forth within 1 to 2 mm from the cathode, is highlighted in green.

Agitation was provided by a paddle (shown in green) that consisted of two triangular bars that moved back and forth across the cathode with a separation of 1 to 2 mm. between the top surface of the cathode and the flat surface of the bottom triangle. The bottom triangle cut into the fluid and scooped the solution up for mixing. The bottom of the paddle created a shear force at its interface with the electrolyte, which resulted in the formation of a very uniform layer of eddies which defined the real diffusion layer.

Plating solution from the recirculation tank flowed through the cell via the entry slot that spanned the width of the tank. The flow was set at just the level needed to replace the iron that was plated out and was intentionally kept slow so as not to have any effect on agitation. Thus, agitation was defined only by the paddle.

The thickness of the diffusion layer was inferred from depositions made on rotating disk electrodes. It was found that at the same current density as used in the paddle cell, the same alloy composition and plating rate were obtained on the rotating disk at 500 to 700 rpm. This correspondence led to the conclusion that the diffusion layer thickness in the plating cell was of the order of 50 to 70 µm depending on the speed of the paddle.

Since the paddle was a narrow bar that moved across the cathode, there was a concern that there would be different degrees of agitation ahead of the bar, near the bar, and behind the bar as it moved across the cathode. Such variations would give rise to variation in composition and magnetic properties throughout the thickness of the deposit. To better understand the mechanism of agitation and its reproducibility, dye injection studies were carried out to give a visual indication of the eddy patterns created by the paddle. A movie of these patterns, made visible by injecting the dye at various selected spots in the cathode, confirmed the concept of paddle agitation. These studies revealed that the eddies set up by the paddle persisted for several seconds and that the diffusion layer remained extremely thin for several seconds after the paddle had passed.

In addition to the dye injection studies, mass transport was investigated by the controlled reduction of ferricyanide on a small Ni strip placed at the center of the cell. The limiting current was measured at the center of the cathode as a function of paddle location as the paddle swept back and forth across the cathode. The measurements were taken at several paddle frequencies in a 6x6 inch cell. At a paddle frequency of 0.34 Hz (7 cm/sec), the limiting current deviated by only ±8% from its average value during one paddle cycle; at 1.5 Hz (40 cm/sec), the deviation was ±15%. The small variation in limiting current throughout the paddle cycle confirmed the uniformity of the thickness of the diffusion layer. Considering the typical current density used in plating permalloy, only one or two monolayers of permalloy are deposited during a single paddle cycle. This fact and the persistence of the eddies for several seconds provided assurance of uniformity through the thickness of the deposit.

An additional benefit of paddle agitation comes from the reduced pressure that exists at the trailing edge of the paddle as it moves over the surface. This effect promotes the release of gas bubbles that may be trapped in the small lithographic features of a plate through mask and is particularly valuable in the permalloy plating process which, with an efficiency of only 80%, generates H_2 bubbles that can cause voids in the deposit if not immediately removed. The reduced pressure can also assist in removing air bubbles that may arise due to incomplete wetting of very deep narrow crevices during the initial immersion of the part in the electrolyte.

Today, the paddle cell is used by all thin film head manufacturers. However, its unique method of agitation provides advantages that have brought it into use for applications spanning the full range from very small MEMS and NEMS structures to large 300 x 600 mm solar panels. Commercial versions of the tool are now available. Intermediate sized applications include C-4 plating for chip attachment and copper plating for packaging. The ability to scale paddle agitation to the wide range of tools needed for diverse structures stems from the fact that agitation is produced locally at the cathode interface where it is needed rather than by rapidly moving a large mass of electrolyte in the plating cell and recirculation tank. This aspect of paddle agitation also makes a large paddle cell less expensive to run than a comparably sized flow cell or jet cell, since the cost of the energy needed to move the electrolyte in a flow cell, and especially in a jet cell, becomes significant for large tools.

The growing use of paddle cells has led to more recent scientific studies of paddle agitation. The thickness of the diffusion layer was measured in 1987 by Schwartz *et al* [27], who found that paddle agitation creates a Nernst diffusion layer that ranged in thickness from 35 to 75 µm as the paddle velocity went from 34 to 10 cm/sec. Modeling of the paddle cell in 2009 by McHugh *et al* [28] showed the same agitation patterns that had been observed in the dye injection studies. The agreement of these studies with the early laboratory observations that established the paddle cell as a plating tool in the 1960s raises the question of just how much science needs to be done when bringing an invention into production. It takes intuition and engineering judgment to weigh the cost and possible delay of the product by doing more science against the risk of production problems or even failure to produce a product by not doing enough.

4.2.2. The electroplating bath, deposition parameters, and controls

The ability to electroplate NiFe alloys with uniform composition and thickness over a large area was of paramount importance in the mass fabrication of the magnetic read/write head. The particular composition 81%(wt) Ni and 19wt(%) Fe, known as permalloy, was of particular interest because it had the magnetic properties that were required for the head as enumerated in the center circle of Figure 12. This alloy could be produced with a coercivity H_c <1.0 oe, an anisotropy H_k between 2.0 and 5.5 oe, and had a high permeability. Permalloy was also resistant to corrosion and had zero magnetostriction (a measure of the sensitivity of the magnetic properties to external stress).

Interest in electroplated magnetic films for memory devices and as media for recording systems grew in the early 1960s. Electroplating at that time (See Section 2.4.) was practiced with limited understanding of the deposition process for single elements and with even less understanding for the plating of alloys. The deposition of NiFe alloys from simple acid solutions as reported by Brenner [29] showed anomalous co-deposition in that a small concentration of iron in the plating solutions resulted in a very large concentration of iron in the deposit. Wolf [30,31] added small quantities of iron salt to the Watts Ni plating bath and obtained NiFe of permalloy composition on small samples which he cited as useful for magnetic memories. Wolf's work triggered electroplating activity on depositing permalloy and on anomalous co-

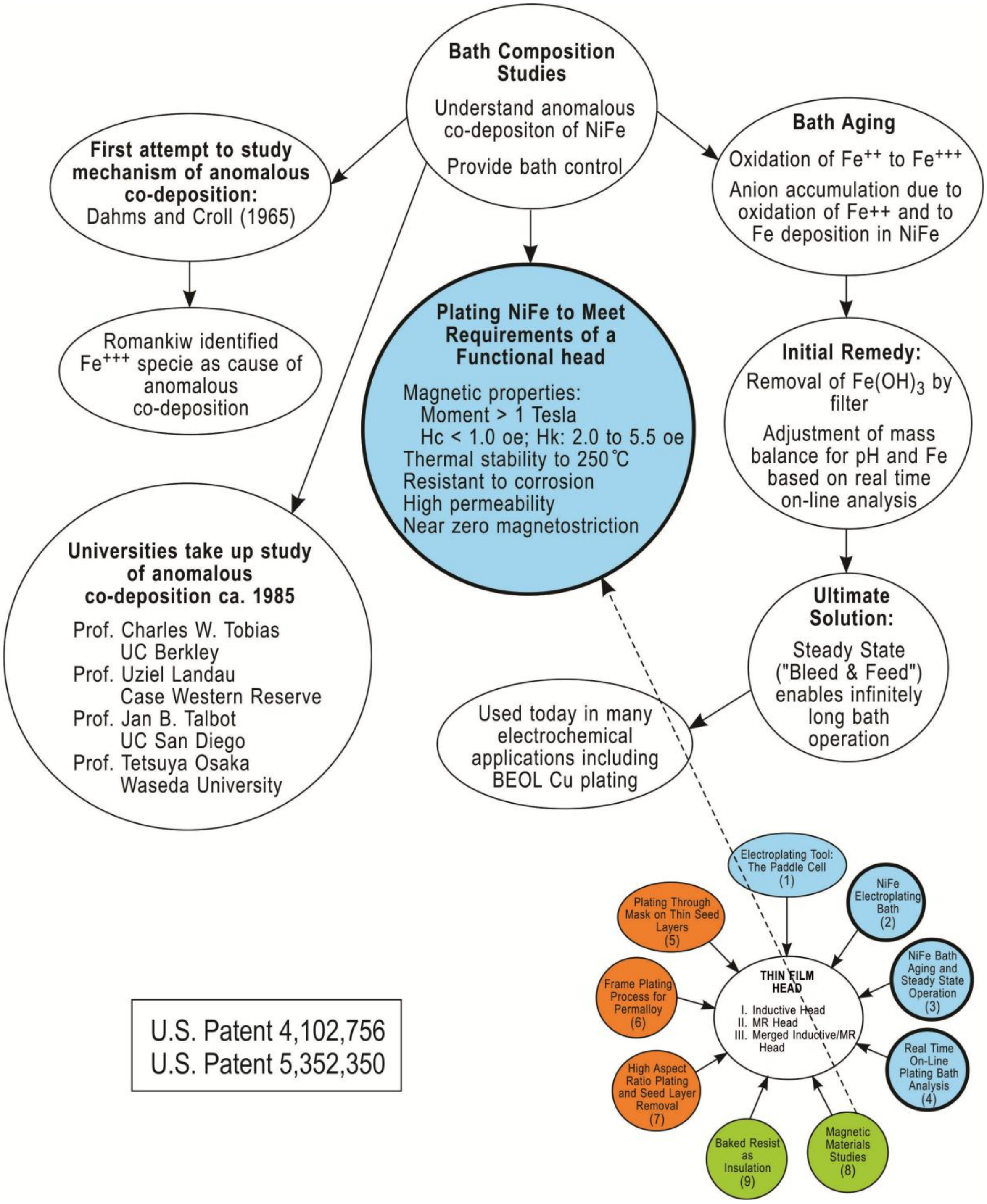


Figure 12. The inventions pertinent to every aspect of the plating bath are so inter-related with each other that they are treated together in this section.

deposition at the IBM T.J. Watson Research Center and at other companies. One of the more notable studies on anomalous co-deposition was reported in 1965 by Dahms and Croll [32]. Their explanation of anomalous co-deposition postulated an increase in pH at the cathode, allowing the formation of ferrous hydroxide that in turn blocked the deposition of Ni. In 1986, Romankiw presented work showing that it was ferric, not ferrous, hydroxide that was blocking the surface [33]. Other works listed in the balloon in the lower left side of Figure 12 have contributed to a fuller understanding of the mechanism of anomalous co-deposition.

Plating parameters

For practicality in manufacturing, permalloy was electroplated from a diluted NiFe plating solution where the Fe in the deposit was supplied by an iron salt added to the solution and the Ni came from a soluble nickel anode. This solution was similar to Wolf's plating bath; however, Wolf's original formulation was not practical for a manufacturing operation in which control of the composition of the deposit was critical. Figure 13 shows the NiFe composition in

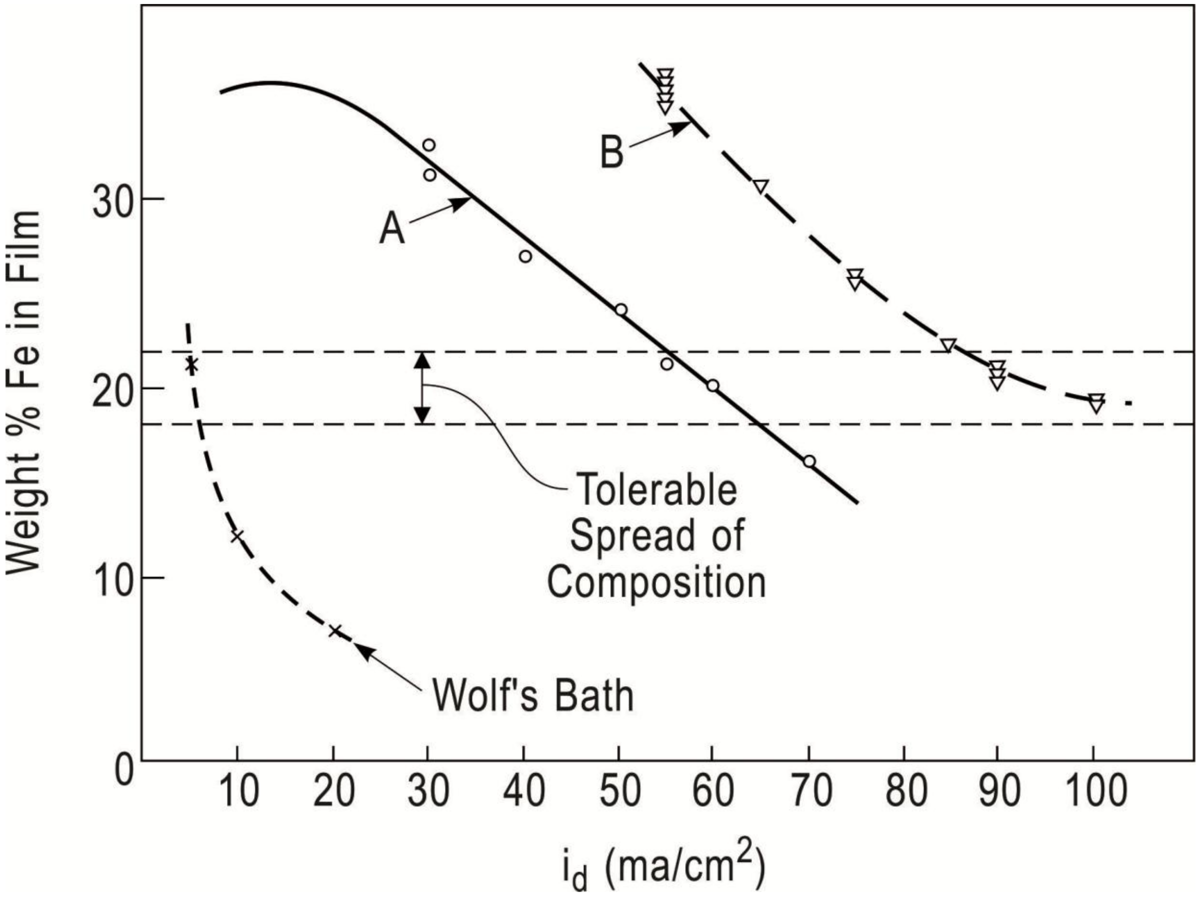


Figure 13. An extensive study of the dependence of composition on bath chemistry and plating parameters provided the information necessary to insure the deposition of permalloy with consistent magnetic properties on the production line.

the deposit as a function of plating current density for plating parameters pertinent to this discussion. The curve at the left shows the extremely strong dependence of composition on current density for permalloy deposited as prescribed by Wolf. It would have been virtually impossible to maintain the required 20% Fe within the specified tolerance from run to run or even within a single wafer using Wolf's bath.

A systematic study of the properties of permalloy plated in a paddle cell was carried out as a function of bath chemistry, degree of agitation, and current density to establish the optimum conditions for production plating. These studies found that diluting Wolf's bath by a factor of two or more allowed much tighter control of the plating process. Curves A and B in Figure 13 show the dependence of composition on current density for permalloy plated from a diluted bath with moderate agitation. These curves could be translated up or down with an increase or decrease of iron in the bath or with an increase or decrease in agitation rate. (Curve B is an extension of Curve A, but plated with higher iron content in the bath and/or greater agitation to bring it into the composition range of interest.) It can be seen that the diluted bath provided two plateaus, one in the region of 5 to 20 ma/cm^2, and the other around 100 ma/cm^2. The plateau at the lower current density was chosen as the operating point for production. At this current, the required thickness of permalloy could be deposited in about 20 minutes, which met the throughput needs of the line and allowed for excellent control of the thickness. Working in the lower current range also avoided the burning (oxidation) which was seen in some deposits at 100 ma/cm^2.

The studies to determine the optimum operating conditions for plating permalloy played a key role in establishing electroplating as a viable process for producing magnetic films with tailored, tightly controlled properties. It is far beyond the scope of this chapter to present all the details of these studies and to properly reflect their depth and importance. More extensive treatments of this work can be found in the patent issued for the plating process [20] and in chapters by Andricacos and Romankiw [34] and by Romankiw and Thompson [11] in the respectively referenced volumes.

Plating controls

The plating process, of course, caused changes in the plating solution as the permalloy was being deposited. Iron was consumed by being plated out in the deposited permalloy and by the oxidation of Fe^{++} in solution to Fe^{+++} which, because of its low solubility product ($k_{sp} = 6x10^{-36}$), was immediately precipitated out as gelatinous $Fe(OH)_3$ and was trapped on the filter. Also, because the deposition was less than 100% efficient, there was some dissociation of water at the cathode with the formation of hydroxyl ions and H_2 gas. Continuous adjustment was required to compensate for the losses of iron and for the continuous upward drift in pH of the solution caused by the hydroxyl ions produced at the cathode.

Monitoring pH was simple; measurement of Fe^{++} was complex and could not readily be done in real time. Fortunately, it had been observed that the oxidation of Fe^{++} to Fe^{+++} was accelerated by the recirculation of the plating solution between the holding and plating tanks. Since pH drift only occurred during plating and the bulk of the oxidation took place during plating (the only time the recirculation pump was on), the loss of iron could be linked to the change in pH without the direct measurement of Fe^{++}. Mass balance calculations, confirmed by empirical measurements, determined the correlation, thereby greatly simplifying the bath control issues.

The operating temperature also affected the deposition process. As the temperature increased, the anomalous behavior decreased and disappeared completely above 75 ºC. For practical reasons, it was chosen to operate the plating solution between 25 and 35 ºC. The main reason for this choice was that the oxidation rate of Fe^{++} to Fe^{+++} increased with temperature. At temperatures above 35 ºC it became difficult to maintain iron in the Fe^{++} state since most of the add Fe^{++} was oxidized and trapped on the filter.

"Bleed and feed"

Three phases of bath aging were noted in operating the plating bath: (1) The gradual build-up of Fe^{+++} and $Fe(OH)_3$ colloid; (2) Continuous stable operation for several months; followed by (3) Excessive anion build-up and deterioration of the bath. The ultimate solution to bath aging was the introduction of steady state operation, which was named "bleed and feed." This was an important innovation in the electrodeposition industry which up to that time had been relying on batch operation, i.e., discarding a deteriorated bath and starting the aging process all over again with a fresh bath. Steady state operation relied on bleeding off a pre-established amount of used plating bath per unit time of operation and replacing it with an equal amount of fresh plating solution. The "bleed and feed" procedures could be initiated at any chosen point during the second phase of bath aging to freeze the bath chemistry along with the properties of the deposit at that bath age. The NiFe plating bath could then be used for years rather than months without having to dump and replace the entire bath. The bled portion could also be used to initiate operation of a new, pre-aged bath. The "bleed and feed" concept is now used not only for plating magnetic materials, but also in plating solder interconnects and in plating copper in packaging and on silicon chips.

While it is good to have a clear understanding of the mechanism of the reaction, this section shows that good engineering practice and common sense achieved reproducibility and control of the complex NiFe plating operation and brought the thin film head into production several years before a satisfactory mechanism of phenomena had been achieved.

4.3. Patterning

4.3.1. Plate thru mask

An important key to building the micron dimensioned 3D structures required for the head was the invention of plating through masks. (Figure 14.) An in-depth study by one of the authors of patterns formed by wet chemical etching, sputter etching, ion milling, lift-off and plating through mask provided an objective comparison of the capabilities and limitations of each process [15]. The study showed that only through mask plating could produce the 2 to 3 µm wide and 2 to 3 µm tall structures with precisely defined side walls required for the thin film head. The results of this and similar studies are summarized graphically in Figure 15.

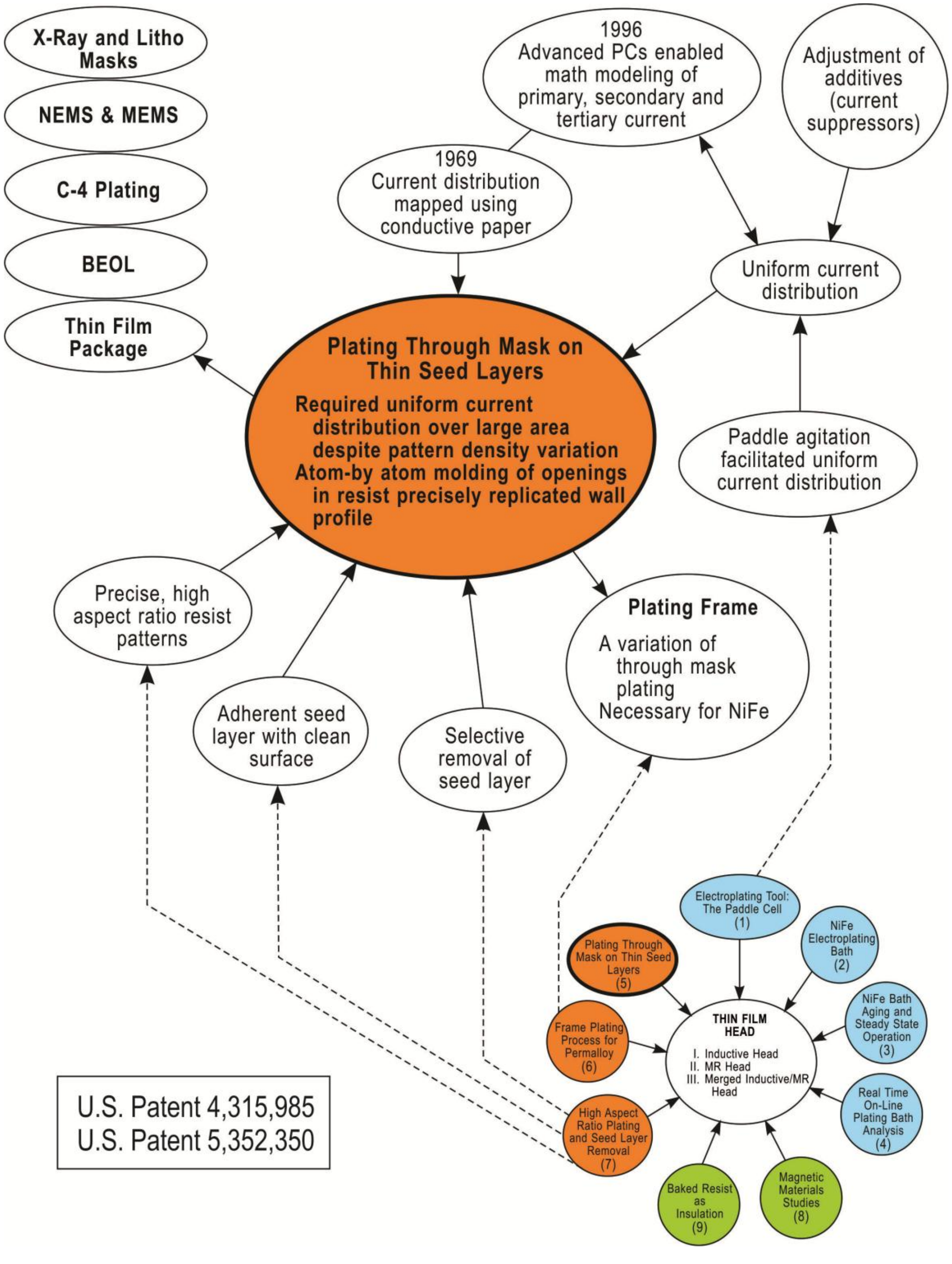


Figure 14. Through mask plating was an atom-by-atom molding process that precisely replicated the wall profile of the photoresist mold.

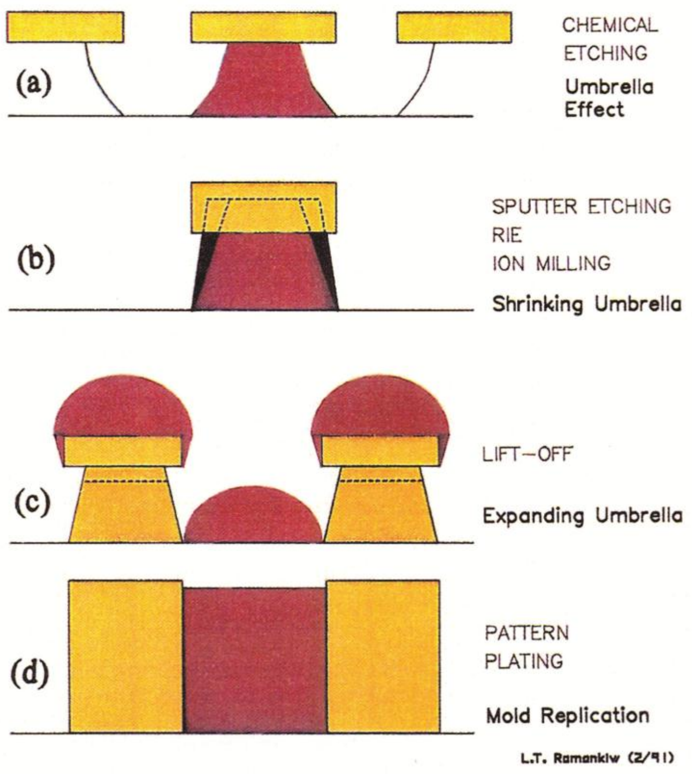


Figure 15. Comparison of pattern replication achievable by the major patterning processes for micro-electronic fabrication. Undercut of the mask during chemical etching (a), erosion of the mask during sputter etching or ion milling (b), and expansion of the mask during lift-off deposition (c) all resulted in narrowing of the pattern and distortion of the side wall. These effects became more pronounced as the pattern thickness increased. Pattern plating through a mask (d) faithfully replicated the resist mold with atomic precision. Removal of the thin seed layer (typically no more than one thousand Angstroms) could be done with minimal effect on the pattern; any adverse effects of seed layer removal became less significant as the pattern thickness increases.

The through mask plating process is described in Figure 16. This process is essentially an atom-by-atom molding of the electrodeposited material in the openings in the resist that precisely replicates both the lateral dimensions and the wall profile of the resist down to atomic dimensions. The smallest possible features were limited only by the capabilities of photolithography and by the ability of the plating solution to penetrate the openings in the resist pattern. Similar considerations determined the height of the structure. Even with the limited capabilities of high resolution resists that were just coming into use in the early1970s, one of the authors was able to demonstrate 12 µm high copper coils with 3 µm wide turns spaced 1 µm apart [35] whereas chemical etching could not produce conductors that were narrower than 5 µm in 0.5 µm thick Al or Cu. Through mask plating was originally invented to produce conductors with a rectangular cross-section in thin film memory structures, but it soon became the only way to produce x-ray masks [36] and magnetic thin film heads and was also an effective way to fabricate magnetic propagation patterns for bubble memories [37].

While the concept of through-mask plating appears to be quite simple, several issues had to be addressed to successfully use this process to build the thin film head. These issues are highlighted in Figure 14 and in the dotted links to other inventions. A major concern was

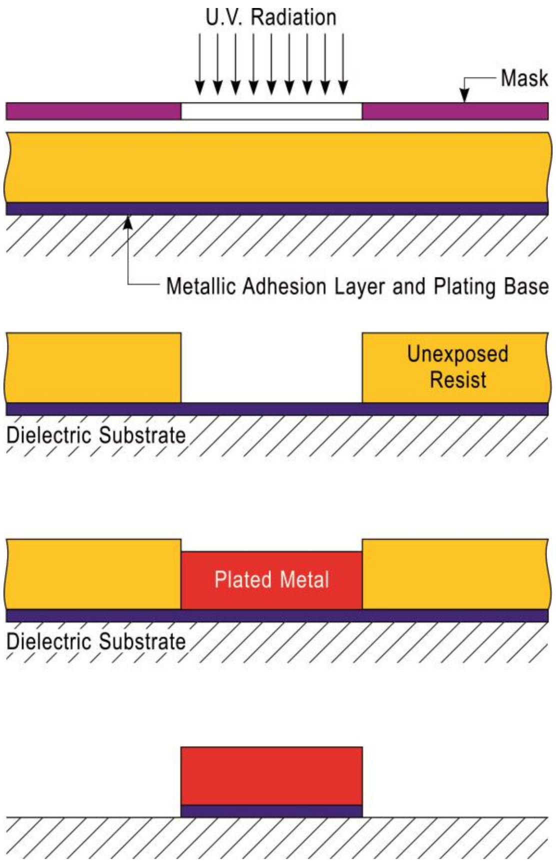


Figure 16. Plating-through-mask process. A thin conductive layer which served as a plating base was deposited (typically by evaporation or sputtering) and covered with a photo resist mask that was photolithographically patterned to provide openings in the resist for the desired plated pattern. The resist had to be thicker than the final thickness of the plated pattern. The next step was to electroplate the desired metal through the openings in the resist. The thickness of the deposit from this operation was determined by the plating time and current; the walls of the pattern were precisely defined by the photoresist mold. The final step was to remove the resist mask and to etch away the exposed seed layer, preferably by ion milling.

achieving a uniform plating current density across the substrate. It was known that plating on a patterned surface gave rise to variations in current density that depended on the non-plated spaces between the patterns and the density of the features being plated. In copper plating, this effect causes a variation in thickness of the elements across the substrate. For permalloy, where the composition also depends on the current density, both the thickness and composition can vary across the pattern. The balloons in the upper right area of the figure highlight how the effects of current density variation were understood and minimized.

Today one would start by modelling the operation to better understand the primary, secondary and tertiary current distribution in the cell and the effects of the pattern being plated [38,39]. In 1969, however, the required mathematics was not available, and even if it were, the modelling would have required a lot of expensive computer time on a main frame system. Therefore, dye injection studies were used to observe the eddy currents created by the agitation, and conductive paper was used to simulate the electric current distribution in the cell. This work led to the invention of paddle agitation discussed in Section 4.2.1, which contributed to a more uniform current distribution. The adjustment of current suppression additives in the copper plating solution further improved the uniformity of the copper deposits. In permalloy plating, work on the NiFe bath composition and operating parameters (Section 4.2.2.) minimized the dependence of composition on current density. Furthermore, the invention of the plating frame, a variation of through mask plating discussed in Section 4.3.2, reduced the current variation across the pattern to negligible levels.

It is important to note that the sophisticated modelling done in 1996 after advanced PCs became available, showed remarkable agreement with the findings of the 1969 dye injection and conductive paper studies [40]. The most complex math and calculations are not always necessary if there is a reasonable understanding of the phenomena (in this case, the behavior of the diffusion layer under given agitation or flow conditions) and this understanding is combined with good engineering and intuition. Modelling is a valuable tool in expediting advances in technology, but the importance of good engineering and intuition should not be under-estimated.

In addition to the electroplating issues mentioned above:

- No high resolution resist was commercially available that could form a plate through mask thick enough to produce 2 to 3 µm thick copper and permalloy patterns.
- There was no viable process for assuring a residue-free surface for plating after forming the resist pattern. The standard approach to residue removal in LSI fabrication used an oxygen plasma, which would have destroyed the photoresist and oxidized the permalloy seed layer.
- The plating base and its adhesion layer had to be removed after plating without adversely affecting the coil or yoke structures.

The resolution of the above issues is dealt with Sections 4.3.2 and 4.3.3.

4.3.2. Frame plating

The plating frame process, a variation of through mask plating that was essential for plating permalloy, is outlined in Figure 17. Like through mask plating, the plating frame process started with a conductive seed layer. However, the first mask, instead of providing openings only where the structural elements of the device were to be plated, outlined each element with a narrow (approximately 10 µm wide) frame of resist. Plating was thus done over a pseudo-continuous area with only minor perturbations by the frames. After plating, a second layer of resist was applied and patterned to cover the tops of the structural elements. The combination of the resist frame and the second resist pattern provided essentially complete encapsulation of the plated device features during subsequent seed layer removal.

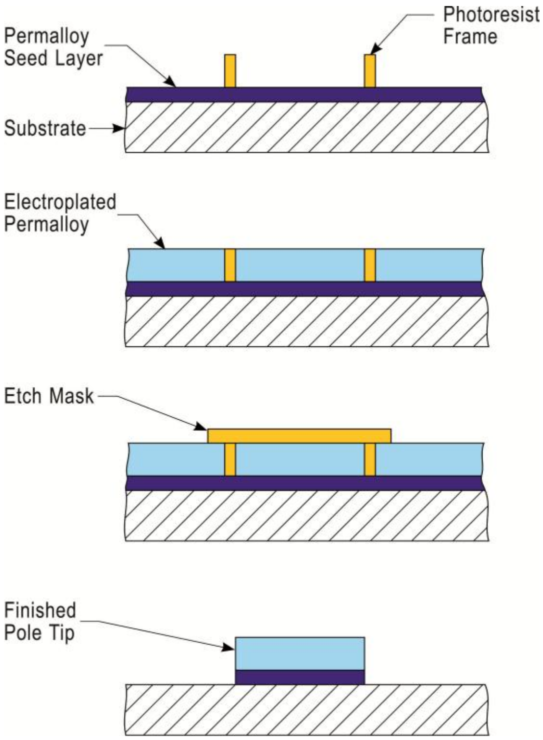


Figure 17. Steps in the plating frame process. The initial resist pattern on the seed layer outlined the desired structure with a narrow (about 10 µm) band of resist, and a pseudo-continuous film was plated over the entire wafer. A second resist mask was applied to protect the desired structure, and the surrounding permalloy was removed by chemical etching leaving a structure with side walls precisely as defined by the plating frame.

The primary requirements for the permalloy pole tips and yokes were (a) uniform thickness and alloy composition across the magnetic elements, (b) a properly defined magnetic easy axis, and (c) side-walls with very smooth edges. The benefits of the frame plating process

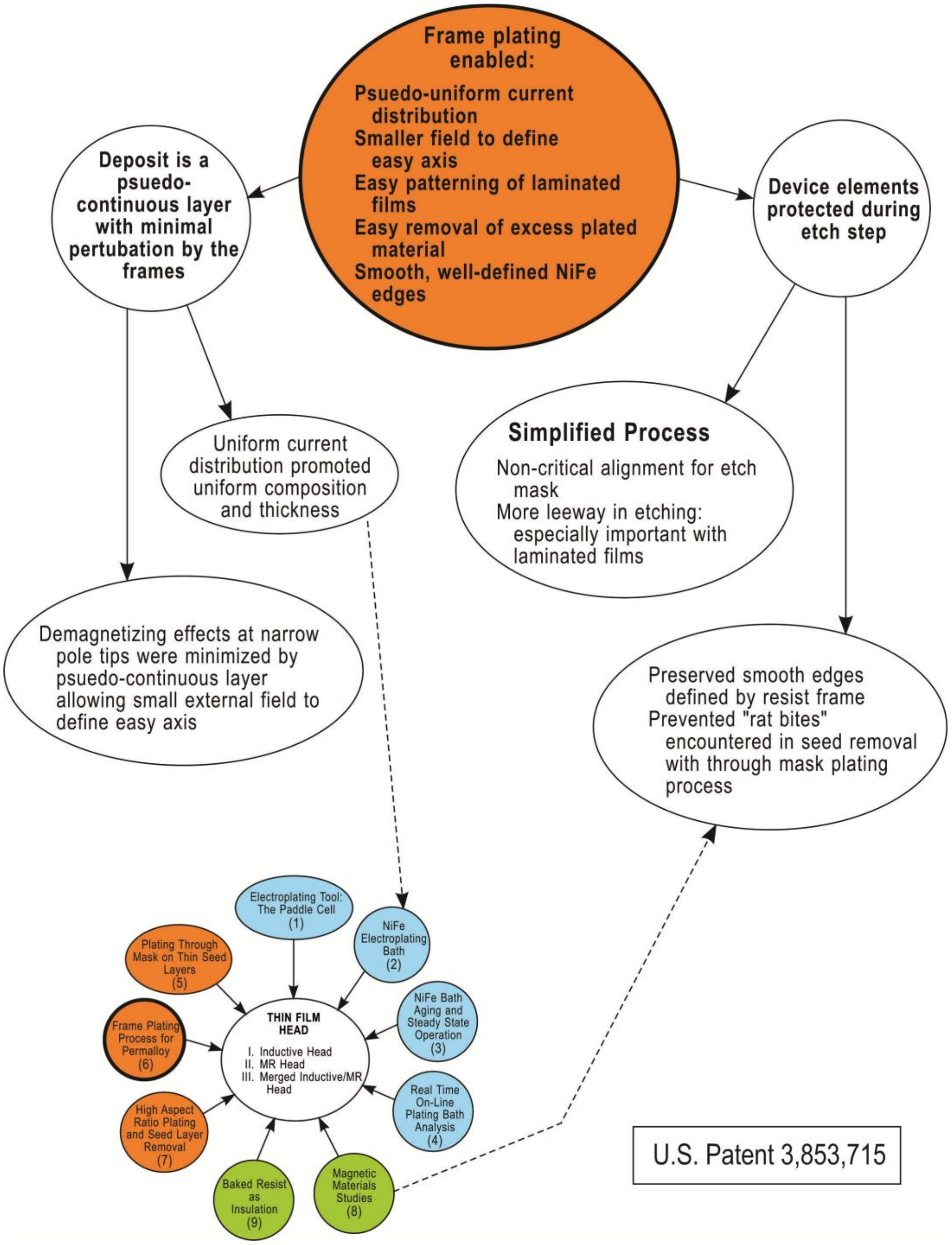


Figure 18. The invention of the plating frame resolved a number of issues in fabricating the yoke and pole tip of the thin film head.

enumerated in the colored circle of Figure 18 show why frame plating was necessary to fabricate the permalloy yokes and pole tips.

The left side of the figure focuses on the benefits that come from plating a pseudo-continuous film. As noted in the previous section, through mask plating resulted in pattern-dependent variations in plating current density across the substrate. For copper, the effect on the deposit was minimized to an acceptable level by additives and by proper agitation in a paddle cell. For permalloy, where the composition of the deposit and hence its magnetic propereties were also affected by the current density (See Section 4.2.2.), depositing a pseudo-continuous layer as produced by the plating frame process effectively provided the same uniformity of current density that occurs during plating a continuous sheet film. This uniformity was confirmed by electron microprobe analysis, which showed no detectable variation in permalloy composition across a 25 µm pole tip plated with a 10 µm wide frame.

The pseudo-continuous layer also played a critical role in allowing the use of a relatively low, easier to manage 500 oe field to define the easy axis of the permalloy yoke. (The easy axis is the direction of magnetization in the film in the absence of an external field and is created by iron atom pairing along the direction of an externally applied magnetic field during deposition.) Magnetic considerations dictated that the easy axis for the head in the read mode be oriented across the pole tip as shown in Figure 19. The orientation field must be of sufficient magnitude to overcome the demagnetizing field that exists within any magnetized structure. (The reference cited here provides a fuller discussion of the demagnetization factor and other magnetic parameters [41].) The demagnetizing factor is strongly dependent on the geometry. For a continuous, flat film this factor approaches zero, so that an easy axis can be defined with an

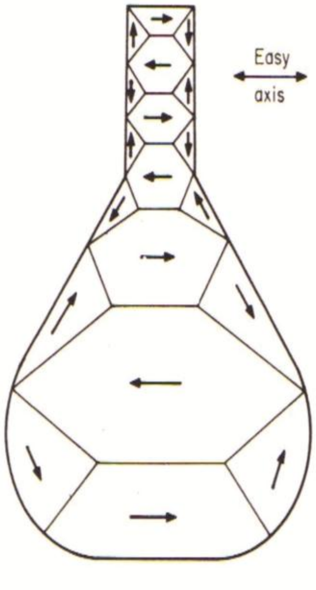


Figure 19. Typical domain configuration in the permalloy pole tip and yoke.

external field of a few tens of oersteds; in a narrow structure like the pole tip, the demagnetizing flux can approach the saturation magnetization of the material (about 1 Tesla for permalloy). The much-reduced demagnetizing field in the pseudo-continuous deposition inherent in the plating frame process makes it possible to properly orient the pole tips with a modest external magnetic field.

The complete encapsulation of the permalloy by the combination of the plating frame and the second resist mask resolved the issue of maintaining a smooth edge on the permalloy features when removing the seed layer. The etchants used to remove the excess permalloy that formed the pseudo-continuous plating were quite aggressive. If the basic through-mask plating process described in the preceding section were used, even the relatively short exposure of the unprotected edges to remove a seed layer of less than 1000 Å left would have left undesirable "rat bites." With the full encapsulation provided by the plating frame process, the smooth, as plated edge was retained even though the plating frame process called for removing the full 2 µm or so thickness of the excess permalloy that created the pseudo-continuous layer. (Figure 20.) The complete encapsulation was particularly useful in later work where laminated permalloy (multilayers of permalloy interspersed with layers of non-magnetic material) was used for the yoke and pole tips. [42]

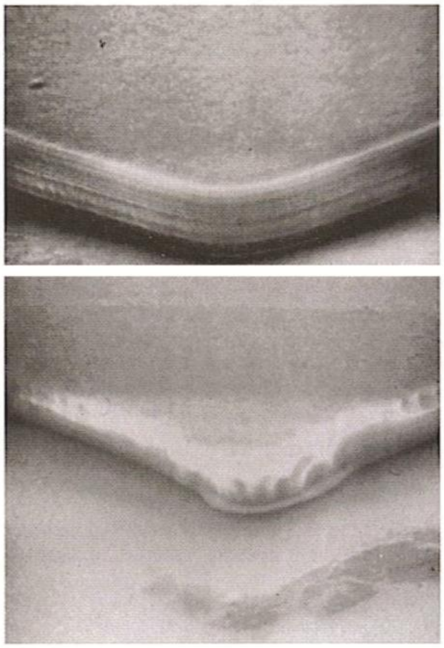


Figure 20. The SEM micrograph in the upper photo shows the extremely well-defined, smooth edges of a 90° corner in a 2 µm thick permalloy pattern plated using a resist frame. The lower SEM shows the same structure produced by conventional chemical etching using a resist pattern on the top surface. The imperfections on the edges that result from conventional etching serve as nucleation sites for undesirable domain walls.

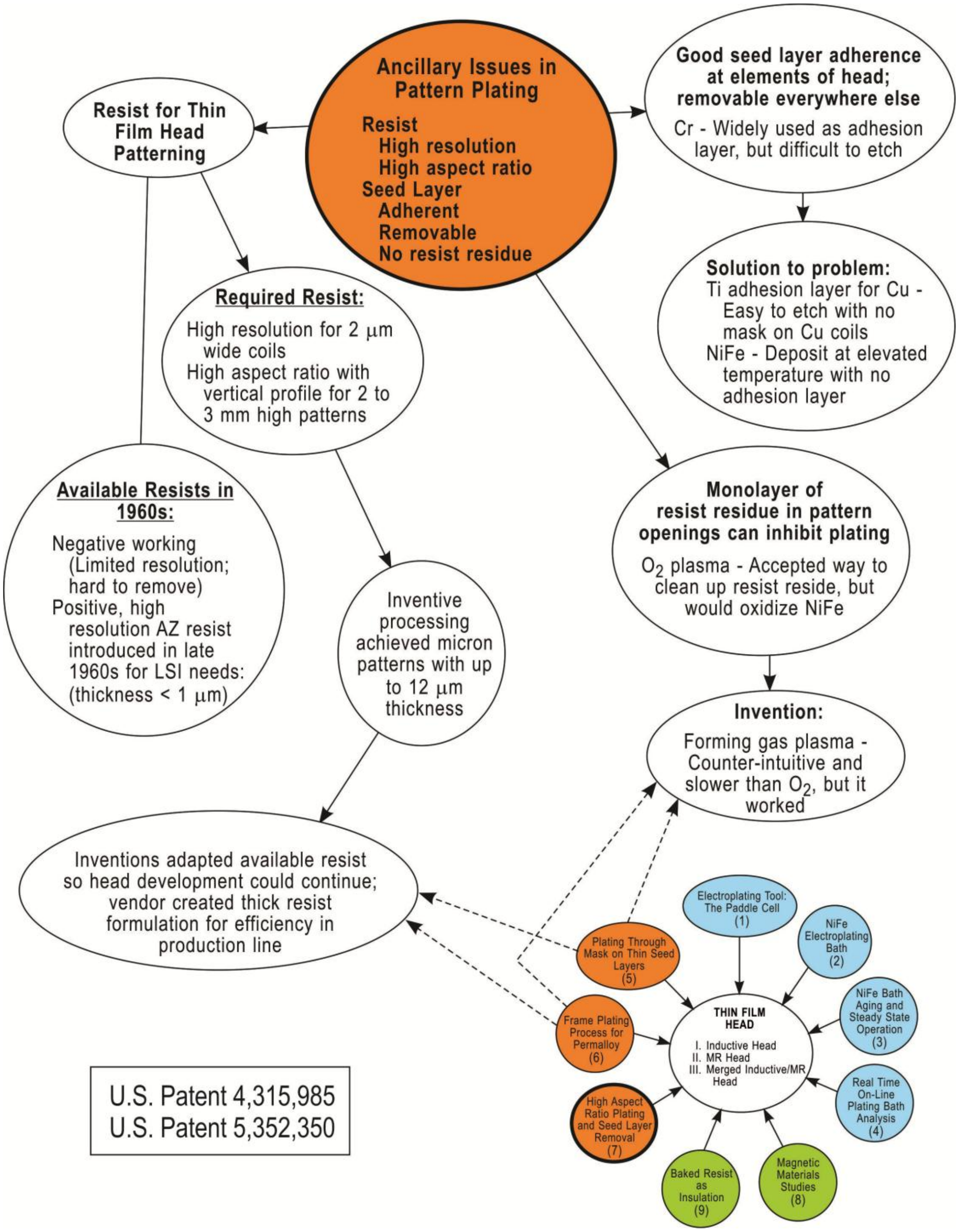


Figure 21. Inventive resist processing was necessary for work on the thin film head to move forward. There were also a few issues unique to the head that had to be resolved.

4.3.3. Ancillary issues in pattern plating

The thin film head program faced a few problems that had not previously been addressed in microelectronic fabrication. (Figure 21.) One problem was the lack of a suitable, commercially available high resolution resist. High aspect ratio resist was just coming on the market in the late 1960s, but that resist was aimed at the semiconductor industry, where thin layers of resist were preferred. Another problem was insuring good adhesion of the seed layer to the underlying structure. LSI technology used Cr as an adhesion layer, but Cr was difficult to etch, and the etchants were not necessarily compatible with the materials in the head. Finally, there was the matter of insuring a clean surface for plating, where even a monolayer of resist residue could inhibit plating or result in the formation of nodules due to non-uniform nucleation of the deposit. The solution on the semiconductor line was to use an oxygen plasma to remove any residue; this approach would only make matters worse in magnetic head fabrication by oxidizing the permalloy.

Resist for through-mask plating

When the use of through mask plating to build a thin film head was first conceived, there was, as noted above, no commercially available resist that could produce the required plate through masks. Photolithographic processing was done primarily with negative working resists, the best of which were limited to patterns wider than 3 µm in resist coatings thinner than 1 µm. (The separation between turns of the coils was 2 µm; the thickness of the resist had to be at least 3 µm so that the 2 to 3 µm of plated copper would not mushroom over the top of the resist.) In the late 1960s Shipley [43] introduced a positive resist, AZ-1350, that was claimed to produce 0.5 µm lines, but no experimental data on the use of this resist had yet been published [44]. This resist was intended for use as an etch mask in LSI fabrication and was therefore optimized for the thin resist coatings (less than 0.5 µm) preferred for this application.

A reliable source of photoresist was necessary for the work in developing a manufacturing process for the head to proceed, and, except for the thickness limitation, the AZ resist was the only promising option. The simple approach of multiple coatings did not work because the solvent in the next coat of resist dissolved most of the previous layer. Ultimately a combination of spin, drying and bake procedures were invented that could use the AZ resist to produce up to 12 µm thick, high resolution resist patterns with near vertical walls. As the thin film head moved closer to becoming a product, GPD contracted with Shipley to formulate a version of the resist that was optimized to provide the thick resist patterns needed for head manufacturing. Although the resist processes that were invented to produce thick resist patterns using AZ-1350 resist were not used in the final production process, their invention played an indispensable role in allowing the development work on the head to continue.

An adherent, removable seed layer

This and the following section offer examples of why each device must be regarded as a unique structure and how the choice of materials and fabrication processes are intertwined in optimizing the final product.

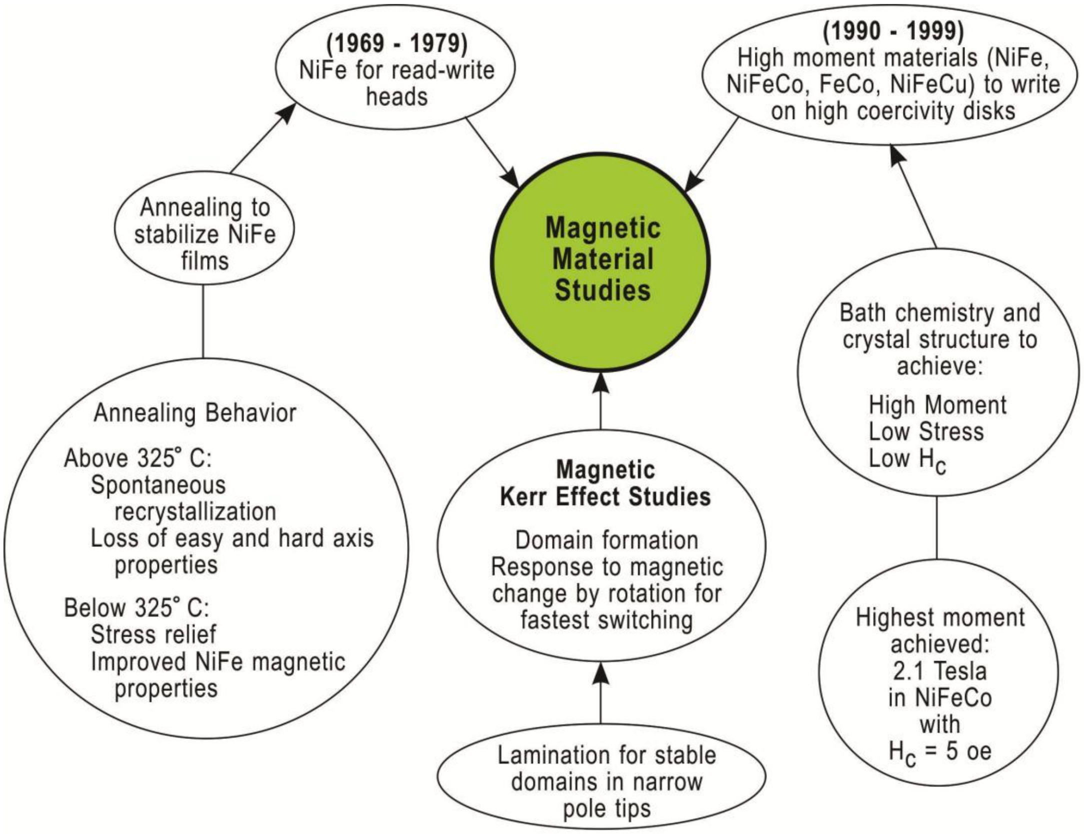
Since the seed layer becomes part of the final structure, adherence to other parts of the structure was an important consideration. A thin layer of chromium was typically used to promote adhesion between a dielectric surface and copper or other metals that had marginal adhesion to the dielectric. Etching chromium, however, entailed a somewhat complex etching process. Substituting a few hundred angstroms of titanium for the chrome provided equally good adhesion for the copper and was readily removable with HF. The use of titanium as an adhesion layer was a break-through in electronic device fabrication that came about when it was realized that titanium, because of its reactivity, readily formed good adhesion to dielectrics and thus could serve as a good transition-layer between the substrate and the deposited metal. Titanium was particularly useful as the adhesion layer for the copper coils because titanium was readily etched in dilute HF. Because the CuF that formed on the copper had an extremely low solubility product, the coils were protected by an insoluble CuF layer that prevented any removal of Cu during this etch step. Occasionally, some traces of seed layer were seen between the turns after this etch step. This residue did not cause any performance problems with any of the lab devices, but the wet etch step was replaced by ion milling on the manufacturing line to eliminate any chance of residue in the product.

Any issues with an adhesion layer for permalloy were resolved when it was established that a permalloy seed layer had adequate adhesion by itself when deposited at an elevated temperature.

A clean interface for plating

An important requirement for through mask plating was a seed layer that was completely free of resist or any other residue. As little as 30 to 50 Å of residue could inhibit initiation of plating. Since resist development proceeded by the dissolution of resist where the resist had been made soluble by exposure through the mask, this problem become particularly acute for narrow, high aspect ratio patterns. The accepted technique to insure complete removal of resist residue in semiconductor fabrication was to burn off the residue by exposure to an oxygen plasma. This process could not be used with permalloy because the oxidation of the permalloy seed layer during resist clean-up led to erratic plating or even no deposit at all. The solution proved to be the use of a forming gas (8 to 12 % hydrogen in nitrogen) plasma. Although forming gas took about 5 times as long as oxygen to remove organic residue, it was also sufficiently effective in removing oxides from the permalloy surface to insure very uniform and reproducible plated deposits.

It should be noted that through mask plating provided easy, visual verification of a clean, low resistance electrical interface because any contamination of the surface would interfere with the deposition. If the plating looked good under the microscope, one could assume proper electrical contact at the seed layer interface without waiting for a final electrical test at the completion of the fabrication run.



U.S. Patent 4,003,768

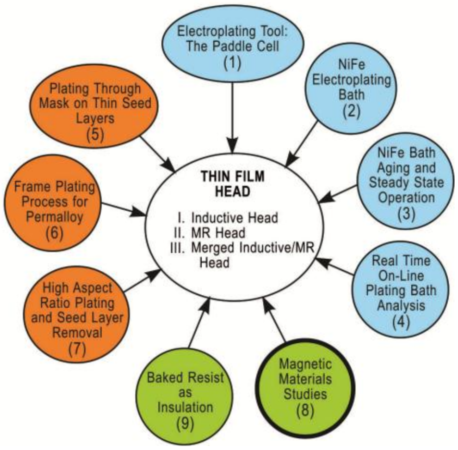


Figure 22. Research on magnetic materials was necessary to create the processes and materials for the original thin film heads and to meet the increasingly demanding requirements of new structures for higher density disk files.

4.4. Materials

4.4.1. Magnetic materials studies

The work on electroplating permalloy for thin film memories was the beginning of an extensive study of the magnetic properties of permalloy and their relation to the deposition and other processing steps that ultimately enabled the production of permalloy with magnetic properties precisely tailored to the requirements for the thin film head. (Left side of Figure 22.) Characterization of the deposits was done on continuous sheet films and included composition analysis, grain structure and orientation analysis, B-H looper measurements, and Kerr magneto-optic studies. Kerr studies were also used to examine the behavior of magnetic domains in various yoke structures.

Annealing studies established 250 ºC as the preferred temperature to stabilize the films by minimizing the dislocations and imperfections that were usually present in the as-plated films, thus relieving the tensile stresses in the deposit. Annealing was also used to tailor the magnetic properties of the films. Figure 23 shows the effects of various annealing cycles for a range of

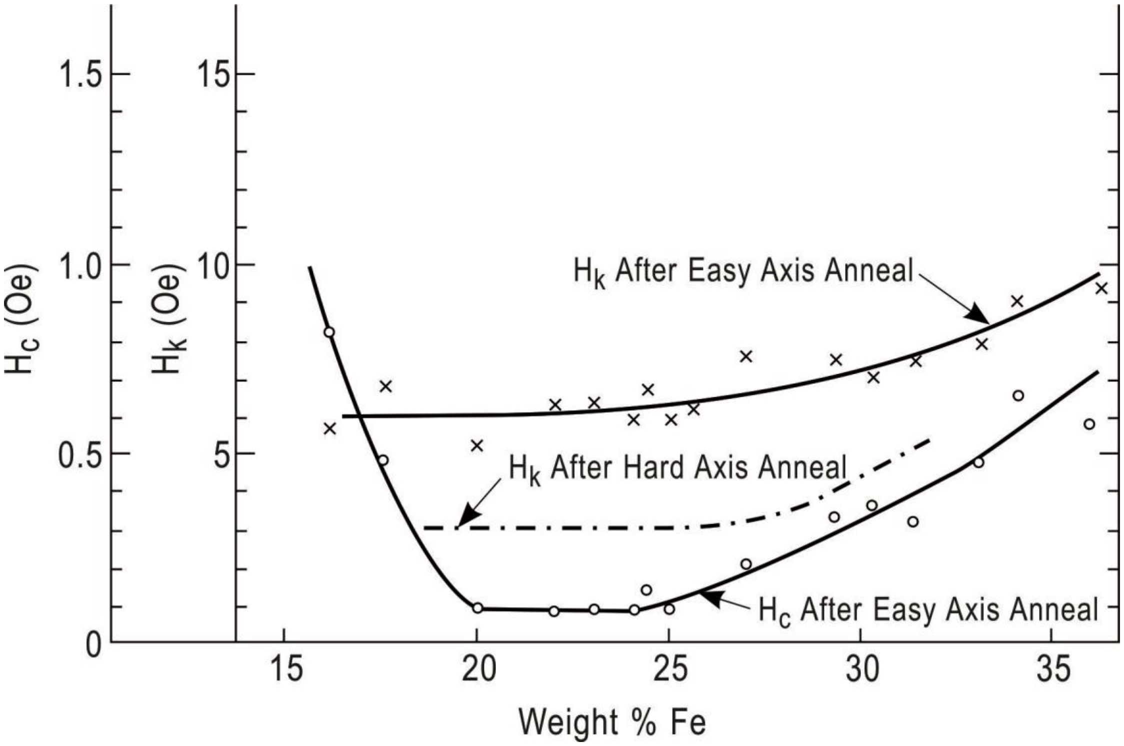


Figure 23. Annealing allowed magnetic properties to be tailored to specific requirements.

alloy compositions. An example of tailoring magnetic properties was the use of a hard axis anneal to reduce H_k, thereby increasing the permeability of the film. Another point to note in the figure is the sharp increase in coercivity (H_c) for Fe content below 20 wt%. This point highlights the importance composition control in attaining the required magnetic properties.

These studies continued as data storage technology advanced to achieve increasingly higher areal storage density. Higher density meant smaller magnetized spots on the disk, which in turn required higher coercivity media to insure stability of the data. As areal density increased, a point was reached where the 80:20 Ni:Fe permalloy of the first thin film heads with a saturation magnetization (M_s) of 1 Tesla could no longer write on media that had a coercivity greater than 300 oe, and yokes with higher M_s had to be produced and characterized. NiFeCo with $M_s = 2.2$ tesla and CoFe with $M_s = 2.4$ tesla were achieved and incorporated into the head fabrication process. (Right side of Figure 22.)

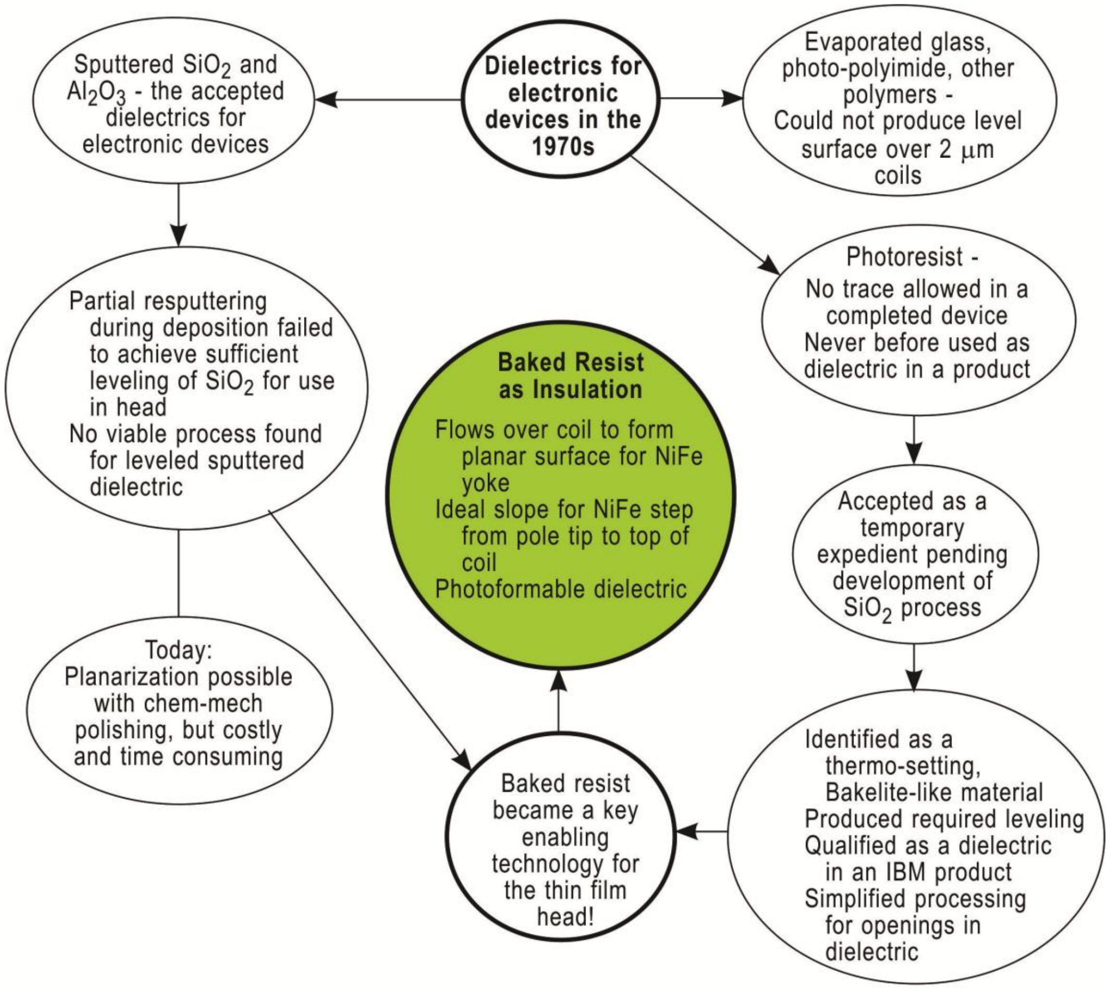
Details of the above studies are beyond the scope of this chapter. The reader is referred to chapters by Romankiw and Thompson [11] and by Andricacos and Romankiw [34] for extensive discussion of the magnetic properties and their relation to the plating solutions and to the operation of the heads. Annealing studies were reported by Anderson *et al* [42]. Lamination to achieve stable domains was described by Canaperi *et al* [45]. Work on high moment materials was reported by Cooper *et al* [46].

4.4.2. Hard-baked resist as insulation

The accepted dielectrics in semiconductor technology around 1970 were SiO_2 and Al_2O_3. Both had excellent dielectric properties, could be readily deposited by physical vapor deposition processes, and could be patterned to serve as the insulator in the wiring layers of integrated circuit chips. SiO_2 had the added advantage that it could also be formed by oxidizing the silicon surface to provide insulation between the silicon and the interconnection wiring.

Because sputtered SiO_2 was an excellent and accepted dielectric, it was initially the unquestioned choice for the thin film head. (Figure 24.) However, the head had a quite different physical structure than LSI wiring and also had to meet structural constraints dictated by the magnetic behavior of its permalloy yoke. The interconnections on the chip were generally quite thin (~0.5 µm), and good edge coverage with a conformable SiO_2 layer was enough to insure good isolation between one level and the next. Although planarized insulation would be preferable (and work was underway to achieve planarization by resputtering during the SiO_2 deposition), the next metal layer could be patterned (with some difficulty) over the topography of the previous level.

The thin film head, on the other hand, was a 3-D structure with 2 to 3 µm thick permalloy yokes and copper coils and with 2 to 3 µm spaces between the turns of the coil. Most critical for the operation of the head was that the permalloy be deposited on a planar surface since studies of domain wall motion (Section 4.4.1.) had shown that any substrate topography could result in hang-up of the domain walls and therefore slow down or completely impede switching by the weak fields emanating from the very small bits on the disk. This constraint meant that the insulation over the coils had to have a planar surface to avoid any adverse effect on the upper



IBM Technical Disclosure Bulletin, Vol. 23, p.2584 (1980).

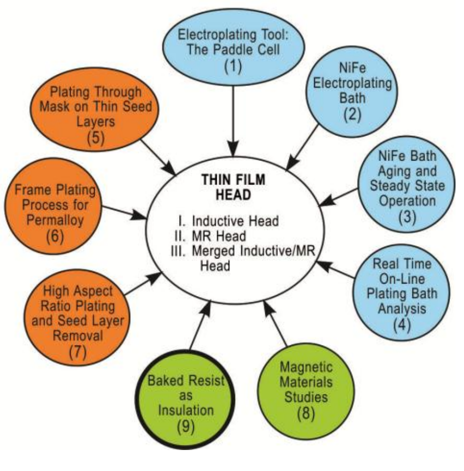


Figure 24. It took an open mind to accept the objective evidence that hard-baked photoresist was a better choice than SiO_2 or Al_2O_3 as the dielectric in the head.

yoke that was deposited over the insulation. Work in both the Research Division and in GPD was underway to use resputtering to achieve a planarized SiO_2 or Al_2O_3 surface over the coil structure. The Research group was also exploring the use of photosensitive polyimides. While some of these efforts showed progress toward a planarized dielectric, none had yet come up with a viable process for the insulation in the head.

As the design engineers were becoming increasingly frustrated by the lack of samples on which to test the performance of their designs, a lab observation suggested a temporary solution. The processing of AZ photoresist into a patterned mask for etching or for through-mask plating typically entailed a few baking steps in the range of 100 to 110 °C. When some parts were heated to 160 ºC, it was observed that the resist had flowed to form a smooth covering over existing topography. It was soon recognized by one of the authors (L.T.R.) that this flowed resist, which had lost its photosensitivity and was quite inert with respect to the etching and plating solutions used in head fabrication, could temporarily serve as the insulator in the head structure until a 'proper,' sputtered dielectric was developed. Appropriate application and bake procedures were developed to achieve leveled insulation over the coil structure, and the magnetics designers soon had completed heads to evaluate. (Figure 25.)

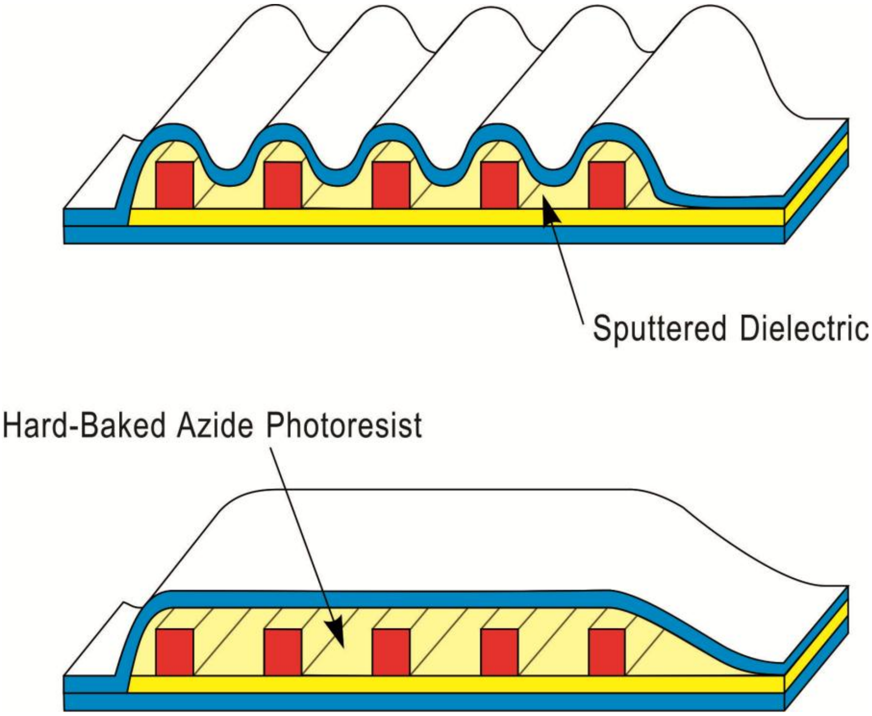


Figure 25. Hard-baked photoresist, originally used as a temporary expedient to complete the original laboratory versions of the thin film head, proved to be the ideal insulation between the coil and the yoke. This dielectric formed a planar surface over 2 to 3 µm high coils, provided a gradual transition from the top of the coil to the gap, and met all IBM's product assurance tests.

The heads with baked resist worked exactly as the head designers anticipated. As an added bonus, the leveled AZ resist fortuitously had the right surface tension and flow characteristics when heated to form the optimum angle for the transition from the top of the coil to the pole tip. While work on sputter leveling and on photosensitive polyimide continued in an intensive effort to get a ‘proper’ dielectric, a variety of experimental structures had been built and tested using the ‘temporary’ dielectric, baked resist, without encountering any problems in fabrication, in process development, or in the performance of the resist as a dielectric in the head. In fact, using baked resist simplified the fabrication process because the necessary openings through the insulation could be formed without the additional masking and etching steps that would be needed for sputtered SiO_2 or Al_2O_3. Also, the ranges of acceptable temperatures for reflow of the resist and for annealing and stabilization of the permalloy, were such that these process steps could be performed with no adverse effects on either the hard baked resist or the permalloy.

As all the other parts of the head fabrication process became ready for the production line, a process to produce a ‘proper’ insulator still eluded the researchers. The baked photoresist was the only workable insulator, and so the materials characterization group was asked to evaluate this material for use in the manufactured product. The results showed that the baked resist had similar characteristics to bakelite, a long accepted electrical insulator, and that it met all the requirements for the dielectric in the head. In spite of this objective qualification, the idea that device reliability required complete removal of all resist residue was so ingrained, that many engineers found it hard to believe that anyone would deliberately put photoresist or any organic insulator into a product. This issue was resolved by dropping any reference to resist and renaming the insulator as a “bakelite-like material”.

Perhaps the important lesson to be learned here is that engineers must keep an open mind as they move an invention from concept to manufacturing. The temporary use of hard-baked photoresist as an insulator allowed development work to continue on all the other steps in the manufacturing process even though no way had yet been found to incorporate the preferred dielectric. And the engineer, whose open mind realized that photoresist was a thermosetting polymer that, with proper baking, could become a fine dielectric, paved the way for an insulator that was a better choice for manufacturing than the originally planned SiO_2.

5. Concluding Thoughts

5.1. Fabrication technology – The key to a manufactured product

Having seen the many inventions that were necessary to manufacture the thin film head, it is obvious that the path for the thin film head’s becoming a product was unique to the thin film head. However, the perspective presented in this chapter also makes it possible to look back at this path to manufacturing and glean insights that are applicable to other inventions as they become valuable products. The time line in Figure 1 can serve as a guide to this review. Looking back to the end of the 1950s, it is seen that a smaller head was essential for magnetic data storage to remain a viable technology. Patents and theoretical analyses described appropriate structures, but there was no process that could build a structure with the dimensions needed for advanced disk drives. Without a process, there was no product.

The importance of the manufacturing process was further illustrated by the fact that each version of the thin film head – the inductive read/write head, the magnetoresistive read head, and the combined inductive read/MR write head – could each be described by the one particular patent covering the respective structure as listed for the center circle in Figure 9. However, these patents could not make a product without the many inventions shown in the outer ring surrounding this circle. The most fruitful path from invention to production is the path that recognizes at every step along the way that a viable manufacturing process is necessary for a successful product.

While future advances in data storage on magnetic disks seemed limited by the lack of a suitable fabrication process for the head, progress on the data processor and the internal memory of the computer was providing further examples of the importance of the manufacturing process. Looking back to the 1960s in Figure 1, one sees the beginning of the intensive effort that has brought continuing improvements in Large Scale Integrated circuit fabrication technology. In the area of memory, two different approaches – semiconductor memory and magnetic thin film memory – were pursued as a replacement for ferrite core arrays. Semiconductor memory, which used transistors, could be fabricated by the same LSI processes being developed for the processor chips. Furthermore, the memory circuits could be readily integrated with the processor on the same chip. The existence of LSI processes that could fabricate semiconductor memory, along with the widespread efforts launched in the 1960s to advance LSI technology, led to the choice of semiconductor memories for computers despite the fact noted in Section 2.2 that these memories had not yet achieved the performance of magnetic film memories. [6]

One of the authors (L.T.R.) had invented the through-mask plating process to build magnetic thin film memory structures more economically and with greater precision than was possible with photolithographic etch processes. As the bottom row of Figure 1 indicates, electroplating at that time was regarded as a shop art that could not meet the fabrication requirements for precision, micro-electronic parts. Most of the discussion on electroplating in this chapter reflects the work that was done during the magnetic thin film memory program at IBM in the 1960s. It was this work that provided the tools and the underlying science to transform electroplating into a precision fabrication technology and put IBM in the unique position of having an option other than LSI technology to manufacture the thin film head.

5.2. Matching product and process

As noted in Section 2.3 and highlighted in the time line for data storage in Figure 1, virtually all computer manufacturers by the end of the 1960s had programs to adapt LSI type processes to the manufacture of a thin film head. LSI technology was not an unreasonable starting point. The engineers who had the task of creating the head fabrication processes in IBM, and very likely at other companies, had a background in LSI type processing and were most comfortable in pushing a familiar technology to produce the head. Looking at existing technology and using it where appropriate is, of course, a proper and valuable engineering approach. But it is also essential that one have an open mind to objectively evaluate what the appropriate process is.

In the case of the thin film head, the difficulties IBM’s San Jose group encountered in forming the copper coils and the fact that no other manufacturer was able to develop a manufacturing process for a thin film in the ensuing decade that led to IBM’s announcement of its product were evidence that LSI technology was not appropriate for the thin film head. Objectively, the thin film head was a 3-D structure, whereas LSI technology was designed to build the relatively planar wiring on circuit chips. In fact, the magnetic thin film head was the first 3-D microelectronic device to become a manufactured product.

IBM was fortunate in that it had invented the plate-through mask process for its magnetic thin film memory program and thus was in a position to recognize that this technology could be used for head production. Through-mask plating was originally invented to form the 0.5 µm or so relatively thin metal elements in film memory structures to achieve more precise replication of the resist mask than could be obtained with subtractive etch processes. When faced with the challenge of head fabrication, an open-minded approach saw that, with a thicker resist pattern, through-mask plating could be extended to fabricate the thicker structures required for the head. LSI processes lacked such extendibility.

The match of product and process was further optimized by the interdisciplinary design of the head structure as describe in Section 3.2. By having the fabrication engineers working side-by-side with the design engineers, functional requirements of the head could be balanced against fabrication process capabilities to produce a testable device and, ultimately, the final product.

5.3 An interdisciplinary combination of science, engineering and intuition

The path to production of the thin film head entailed a balanced combination of science, engineering, intuition and even good luck. The approach that prevailed from the first prototype to the final product was to concurrently develop the fabrication tools and to engage in studies related to the materials, the process, process control, and process integration. It was preferable to use concrete data wherever possible, but the best engineering judgment was made when such data were not available. To expedite the transition of the head into production, the studies were done concurrently and carried just far enough to obtain the information required to control the process and build the head. When time permitted, or if new problems surfaced, further studies could be pursued. Where problems could be clearly defined and did not need head building capability, appropriate chemical engineering faculty members were contacted to get them and their students interested in carrying out the studies. Examples of such studies were the university studies of anomalous co-deposition cited in Figure 12 and the effect of uni-directional flow on convective transport in the small cavities of a plate-through mask by Alkire, Deligiani and Ju [47]. These studies, carried out in the 1980s and ‘90s, also exemplify work that could be deferred because the heads could be manufactured without the further understanding these studies provided.

Some of the inventions could not be planned but happened through a fortuitous confluence of events. Such were the circumstances that led to the invention of the tools and processes needed to reproducibly plate permalloy and tailor its properties to the requirements of the head. Researchers who were trying to electroplate permalloy films in the early and mid-

1960s for magnetic devices such as thin film memories were hard-pressed to get consistently reproducible magnetic properties in their deposits. In retrospect, the solution to this problem required the perspective of a chemical engineer who understood manufacturing processes, fluid flow in the plating cell, and chemical engineering unit operations; a materials scientist who understood the relation between the permalloy structure and its magnetic properties; and an electrochemist who understood the electroplating process and the metallurgical structure of the deposit. It is rare that a PhD scientist or engineer fresh out of graduate school should have such a broad background. When one of the authors (L.T.R, who subsequently invented the paddle cell, the procedures for reproducibly plating permalloy, and through-mask plating) applied for a position at the IBM T.J Watson Research Center, he had already earned a B.S. in Chemical Engineering, had industrial experience in the recovery of metals, and had just earned a PhD. in Materials Science. Fortunately, he had no formal training in electrochemistry. If he had such training, he would have been taught that through-mask plating with precise control of the properties of the deposited patterns was impossible.

Romankiw was hired, and he soon found himself trying to build magnetic thin film memory structures and facing the same difficulty in reproducibly plating permalloy that others had encountered. It was his multi-disciplinary background that led him to realize that several issues were contributing to the problem. Resolution of these issues as discussed in Sections 4.2 created the electroplating technology necessary to build magnetic thin film memory, but at this point it had no impact on the path of the thin film head to production. Those who were adapting LSI processes to build the head were focused on LSI technology; those who successfully built the thin film memory were not involved with head fabrication. The change that put the thin film head on the right path to production came from a remark during a visit to Yorktown by an engineer who was working on the LSI approach to the thin film head in San Jose. When he saw the film memory structure of Figure 5, he remarked, “You have a magnetic head here. All you have to do is put a gap in the permalloy.” This comment led to the first thin film head (Figure 6) and to Yorktown’s active participation in IBM’s thin film head effort. Once involved with the thin film head, the Yorktown group recognized that the plate-through-mask process was the only technology that could be extended to the 3-D requirements of the head and worked closely with the San Jose engineers to establish the process for head fabrication and to put it on the production line.

The preceding two paragraphs are included here not because the authors advocate waiting for a stroke of good luck – although it is important to have an open mind that can take advantage of good look when it happens. The paragraphs are included because the situations described illustrate the importance of an interdisciplinary approach. The problem of reproducibly plating permalloy was not resolved until the agitation in the plating cell, the current distribution in the cell, the chemistry of the plating solution, the plating parameters, and the post deposition annealing of the deposit were each addressed with the expertise of the respective disciplines. Precisely controlled electroplating of permalloy was not a process that could be implemented by electrochemists alone.

The recognition that the structure of a magnetic thin film memory was a step removed from the structure of a magnetic thin film head illustrates another aspect of interdisciplinary involvement. The engineer from San Jose, looking at the thin film memory with the perspective

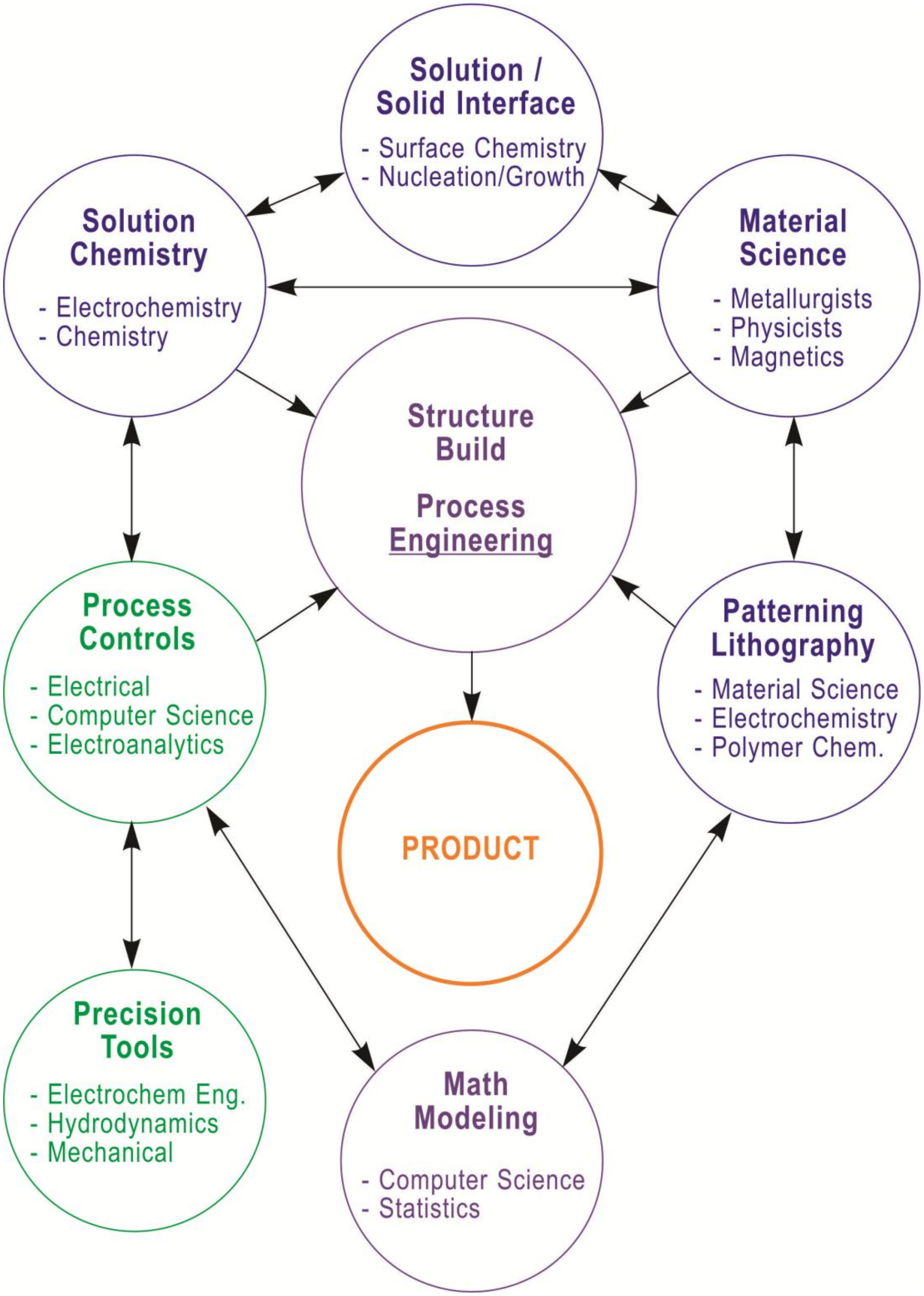


Figure 26. A graphic representation of the interactions among the many disciplines that were involved in bringing the thin film head into production.

of a magnetic recording engineer, was able to see a recording head structure within the memory devices and thus set the stage for extending the electroplating processes of film memory technology to head fabrication.

The manufacturing process for the thin film head entailed a carefully integrated set of inventions and process steps that spanned many disciplines. Some of the interdisciplinary connections among these disciplines were indicated in the circle charts of Section 4. An overview of the interdisciplinary approach that prevailed throughout the thin film head program from the design of the head to the manufacture of product is shown in Figure 26 [48]. Interchanges among the various disciplines allowed technical problems to be viewed from diverse perspectives and opened new windows to creative solutions. The interdisciplinary approach in combination with scientific studies, good engineering judgment, an open mind, and a bit of intuition defined the path to production for the thin film head and can serve as guideposts for bringing other inventions into production.

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Figure Sources

The following list acknowledges the sources of figures in this report that have been previously published, adapted from previous publications, or taken from on-line sources.

Figure 2 – http://media.almaden.ibm.com/images/RAMAC/photos/RAMAC.html (Accessed 7/15/2014).
Figure 3 – Composite created from photos cited in Reference [9].
Figure 5 – Reference [12].
Figure 6 – Reference [13].
Figure 8 – Adapted from Reference [34].
Figure 11 – Adapted from U.S. Patent 4,102,756 (Reference [20]).
Figure 13 – U.S. Patent 4,102,756 (Reference [20]).
Figure 15 – Reference [35].
Figure 16 – Reference [35].
Figure 17 – Adapted from Reference [34].
Figure 19 – Reference [34].
Figure 20 – Reference [34].
Figure 23 – Adapted from U.S. Patent 4,102,756 (Reference [20]).
Figure 26 – Adapted from Reference [48].

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