Future directions in electroplated materials for thin-film recording heads

by P. C. Andricacos
N. Robertson

The need for recording heads to write on high-coercivity media at high frequencies has created new requirements for the write-head material that cannot be met by $Ni_{80}Fe_{20}$, the nickel–iron alloy traditionally used in the fabrication of the device. Electroplating through a mask, the method of choice for depositing nickel–iron alloys, makes it possible to pattern and orient the magnetic film more readily than by other methods. We review here research performed mostly in the United States and in Japan to develop electroplated magnetic materials that can meet the new challenges of data storage technology. High-iron nickel–iron alloys ($Ni_{45}Fe_{55}$) have higher magnetic moment and resistivity than their low-iron counterparts and are increasingly being used in head fabrication. The addition of impurities in a controlled manner has been shown to produce drastic improvement in the properties of electroplated materials. And technology has been developed to fabricate laminated materials by electroplating from a single plating solution. Despite these advances in the electrodeposition of magnetic alloys, more research is required for electroplating processes to meet all of the challenges of data storage technology.

Introduction

Electroplating has been a process of major significance in the fabrication of thin-film recording heads, which are important components in magnetic recording hardware. The development of electroplating processes for nickel–iron alloys, such as $Ni_{80}Fe_{20}$, enabled thin-film recording heads to become technologically viable [1, 2]. With the introduction of thin-film inductive heads and, later, magnetoresistive (MR) heads, the disk-drive field has been able to sustain rapid growth. Today, a disk drive available to the individual consumer has over 1 GB capacity compared to 10 MB at the introduction of personal computers just 15 years ago.

In this paper we discuss the impact that the change from inductive to MR technology will have on write-head materials. We then summarize results obtained by several investigators who have attempted to extend electroplating technology to meet the new material requirements. Finally, we describe the deposition and properties of

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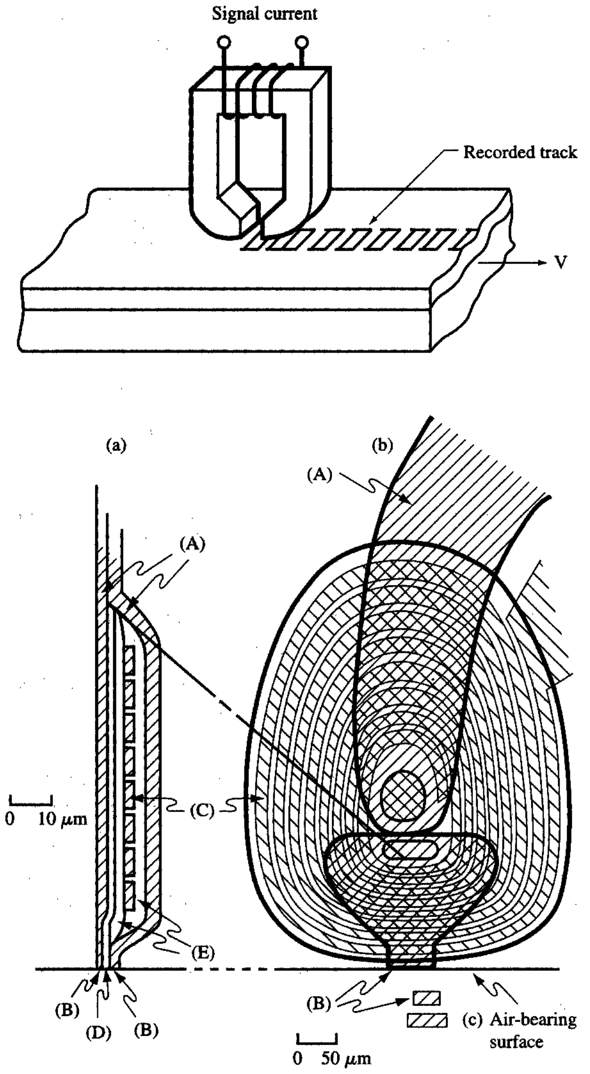

Figure 1

(Top) Schematic representation of the recording process (reprinted from Reference [4] with permission). (Bottom) Simple inductive recording head showing cross section (a), planar view (b), and structure at the air-bearing surface (c) (magnetic layers A, pole tips B, conductor turns C, gap layer D, insulator layer E) (reprinted from Reference [5] with permission).

an electroplated CoFeCu alloy developed in IBM to meet some of these requirements as an example of the methodology followed in this area of materials research.

Material requirements and directions in technology development

Electroplating offers several advantages as a process for magnetic-material deposition: Films can be electroplated with excellent magnetic properties and low stress at high rates of deposition; and plating cells are relatively inexpensive with a large installed manufacturing base. As a material additive process, electroplating allows for easier definition and control of small features such as yokes and pole tips in recording heads; on the other hand, the application of subtractive processes is seriously hampered by the lack of methods for selective materials etching. Reactive ion etching, a process of great popularity in semiconductor manufacturing, has not been found viable in thin-film head fabrication for that reason. One is left with ion milling, a process that requires thick photoresist to protect defined features, thereby increasing the complexity of the lithographic patterning. Electroplating through a mask [3] offers solutions to these patterning problems; hence, it is universally accepted as a thin-film head fabrication process.

In inductive read/write head design, a flat copper coil is linked to a magnetic yoke structure of two halves, each composed of a magnetically soft material. To write on magnetic media, current that flows through the copper coil generates a magnetic field, which is in turn focused on the media by the yoke structure. During read-back, the yoke structure collects magnetic flux from the media, generating an electric current in the coil. This process is schematically illustrated in **Figure 1**. Bit size in advanced commercial products with an areal density of 1.0 Gb/in.^{2} is 3.5 μm by 0.18 μm. The material in the poles must serve the dual purpose of effectively writing bits on the media as well as reading this information. Plated NiFe (of 80:20 nominal composition) is an excellent material for this application.[1] Its properties, as shown in **Table 1**, meet inductive-head requirements. It has a relatively high saturation magnetization [$4\pi M_s$ of about 10 kilogauss (kG)], low coercivity H_c to prevent formation of remanent states, and low anisotropy field H_k to make high-permeability devices. The magnetostriction coefficient λ is close to zero, thereby rendering device performance independent of stress. The high Ni content provides excellent corrosion resistance.

With the recent introduction of MR heads, the read-back function of the head is now performed by an MR sensor. MR head technology has allowed areal densities in disk drives to increase at a rate of about 60% per year. The inductive portion of the head is now used for only the write portion of the data-recording operation. This change in the function of the inductive portion of the head, combined with an increase in performance parameters such as areal density and data rate, has created a demand

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[1] The actual composition used in devices may deviate slightly from the 80:20 nominal composition depending on factors such as stress susceptibility and domain configuration [6, 7].

Table 1 Plated materials with high saturation magnetization.

Material	*Coercivity* H_c (Oe)	*Anisotropy field* H_k (Oe)	*Magnetostriction coefficient* λ	*Saturation magnetization relative to* $Ni_{80}Fe_{20}$
$Ni_{80}Fe_{20}$	0.3	2.5	−0+*	1
$Ni_{45}Fe_{55}$	0.4	9.5	+	1.6
NiFeCo	1	6–10	−0+	0.8–2.4
NiFeCoB	0.6	14		1.5
CoNiFeS	1	20	+	1.7
CoFe	3	7–14	−0+	1.9
CoFeB	1	"	"	"
CoFeCr	0.3	20	−	1.7
CoFeNiCr	0.5		+	1.7
CoFeP	1	15	−0+	1–1.5
CoFeSnP				
CoFeCu	1	13–18	−0+	1.7–2.2
CoB	1	40		1.2
CoFeB (*e*-less)	1	15		1.2

* λ can be negative, zero, or positive depending on alloy composition; specifically for NiFe, λ is negative below about 19 wt.% Fe and positive above about 19 wt.% Fe.

for materials with improved properties with respect to the traditional $Ni_{80}Fe_{20}$ system.

Areal density is a combination of track density, or how close tracks can be placed to each other in the radial direction of the disk, and linear density, or how close bits can be placed one after the other. Linear density is defined by a combination of the properties of the recording head and media, the spacing between head and disk, and signal-processing electronics. A key property is the ability to record a transition (or bit) in the media and maintain it at a stable state. In the limit, the smallest bit length a that can be sustained in the given media [8] is

$$a = M_r d / 2\pi H_c\,,$$

where M_r is the magnetization of the media, d is the thickness of the media, and H_c refers to the coercivity of the media. One of the key methods of obtaining shorter transitions is to increase the coercivity of the media. Since H_c is a measure of the field required to reverse the magnetization direction of a bit, the recording head must generate a higher magnetic field to write effectively on the high-coercivity media. This magnetic field is determined by parameters such as head geometry and spacing between head and disk, as well as by the saturation magnetization of the magnetic material in the head poles. An increase in media coercivity requires an increase in the saturation magnetization of the head material beyond that of the conventional $Ni_{80}Fe_{20}$ system.

A consequence of higher areal densities is higher data rates. In combination with the increase in disk rotation speeds, a substantial compound growth in data rate has been obtained during the past few years. The top-performing disk drives in the market now have data rates of the order of 16 MB/s. The increase in data rates places further requirements on the writing process by requiring faster switching of the magnetic material in the poles. Switching of the magnetic field in the pole material causes the formation of eddy currents, which produce a field opposing the externally applied field. Eddy current formation is one of the most significant mechanisms by which the effective permeability of a material is affected by high-frequency device operation. Skin depth δ is the thickness of the outer core of the material that can carry magnetic flux unimpeded by eddy currents. Skin depth depends on the resistivity ρ ($\mu\Omega$-cm), frequency of excitation f (MHz), and permeability μ of the material according to [9]

$$\delta = 1.6(1000\rho/f\mu)^{1/2}.$$

For a $Ni_{80}Fe_{20}$ film in a disk drive operating at 40 MB/s (200 MHz), δ is 0.27 μm. This indicates that only 10% of the material in a 3-μm-thick pole tip carries magnetic flux successfully at 200 MHz. High-frequency operation can thus dramatically decrease head performance. Increasing the resistivity of the write-head material or using a multilayer material with high-resistivity (magnetic or nonmagnetic) interlayers are among the potential approaches to counterbalance the effect of eddy currents.

The above examination of trends in magnetic recording technology allows us to conclude that advanced materials for write heads should possess the following properties: high saturation magnetization to be able to write on high-coercivity media; low coercive force to prevent remanent states; optimal anisotropy field for high permeability; close to zero magnetostriction to render device operation independent of stresses; high resistivity (or ability to be deposited as multilayers) to suppress eddy current formation; and excellent corrosion resistance.

These magnetic materials requirements, especially when combined with issues such as ease of manufacturing, pose a serious technological challenge. Corrosion resistance and manufacturing complexity can be as important as magnetic properties. Electrodeposition has provided satisfactory solutions to these requirements; electroplating through a mask has enabled facile patterning of the magnetic film combined with relative ease of manufacturing. Many researchers in the field have naturally turned toward electrodeposition to satisfy the new data-recording requirements.

Electroplated materials with high saturation magnetization

It was recently demonstrated [10] that increasing the Fe content of electroplated NiFe alloys from about 20% to about 55% causes an increase in both the moment and the resistivity of the alloy without significantly affecting other requirements such as corrosion resistance or ease of manufacturing. Magnetic properties remain about the same as in the case of $Ni_{80}Fe_{20}$ (Table 1) with the exception of magnetostriction, which acquires a relatively large positive value. Although a large positive magnetostriction would disqualify the material for use in read–write heads, causing instabilities in the read function, it does not prevent its use in write-only heads. The high-Fe version of NiFe is thus gradually replacing $Ni_{80}Fe_{20}$ in write-head fabrication.

One of the most widely studied high-magnetic-moment materials is the ternary NiFeCo alloy. Investigations with NiFeCo alloys have been conducted for at least three decades [11, 12], most recently in Japan. Apart from the capability of increasing the saturation magnetization of the binary NiFe system by Co addition, NiFeCo alloys are readily plated from electrolytes whose composition differs from that of a NiFe plating bath only by the addition of a Co^{2+} salt, usually a sulfate or chloride.

Anderson and Chesnutt [13] deposited alloys with high Co content and examined composition ranges at which zero magnetostriction is obtained. Thus they extended the work of Tolman [12], who studied alloys having low Co content. Anderson and Chesnutt reported that a $Co_{80}Ni_{10}Fe_{10}$ alloy (representative of the compositions of interest to them) has a $4\pi M_s$ value of 16 kG, a coercivity of 1.5 Oe, an anisotropy field of 10 Oe, high permeability, and near-zero magnetostriction. Later Chesnutt [14] fabricated integrated inductive-write magnetoresistive read heads with a pole thickness of 2.5 μm using CoNiFe as the write-head material and demonstrated superior overwrite performance compared to a head fabricated using conventional NiFe with a thicker pole of 4 μm. Chesnutt preferred the use of a CoNiFeB alloy plated from a bath containing dimethyl amine borane (DMAB) as the source of boron, B. As demonstrated earlier for NiFeB [15], the addition of B to CoNiFe causes a decrease in the coercivity from 1.5 Oe to 0.6 Oe, while the saturation magnetization as well as the anisotropy field remains unaffected. Chesnutt suggested that B improves the corrosion resistance of CoNiFe, but did not present systematic data.

Sano et al. [16] were similarly concerned with the attainment of zero magnetostriction in CoNiFe alloys. In order to decrease the anisotropy field, which was 3–5 Oe for plated NiFe but had increased to more than 10 Oe for plated CoNiFe, a magnetic field was applied parallel to the substrate during plating and switched in orthogonal directions at a predefined frequency. This was in contrast to the unidirectional field employed by most investigators in this field to induce uniaxial anisotropy in the plated film. Sano et al. were thus able to decrease the CoNiFe anisotropy field to 6 Oe by appropriate selection of switching frequency and field strength. The resulting CoNiFe film had all the advantageous properties of the binary NiFe system (including low anisotropy and near-zero magnetostriction), with the added advantage of higher saturation magnetization. However, Chesnutt [14] found that the photoresist baking steps that follow the deposition of the magnetic material in head fabrication cause the anisotropy field to revert to the high value that is obtained if a unidirectional magnetic field is applied during the deposition. He therefore recommended that no orienting field be used during the baking steps. Sano et al. also discussed the addition of fourth elements to CoNiFe alloys: These elements included B to decrease coercivity and In, Sb, or Bi to raise the "heat-resisting property of the CoNiFe alloy."

Omata and co-workers [17–20] prepared FeNiCo films by both rf-sputtering and electrodeposition and examined magnetic as well as structural properties over a wide range of compositions. Their electroplated films were Fe-rich (typical composition was $Fe_{45}Co_{20}Ni_{35}$), with film properties that were satisfactory except for a highly positive magnetostriction, which was viewed by these investigators as sufficient reason to prevent the utilization of these materials in the fabrication of heads. In an attempt to decrease the magnetostriction, they introduced Cr as a fourth element; they determined that small amounts of Cr (typically 5 at.%) cause a substantial decrease in the magnetostriction. In order to introduce Cr in the deposit, they had to plate at high current densities which in turn roughened the deposit, leading to the need for pulse plating. Total elimination of Ni and an increase in the Co content (typically $Co_{90}Fe_8Cr_2$) produced films with negative magnetostriction and high saturation magnetization.

Shinoura et al. [21] studied NiFeCo alloys with intermediate Fe (25–35 wt.%) and Co (30–50 wt.%) content. Magnetically soft films were found in the entire range of compositions; however, magnetostriction remained positive. The authors conducted detailed annealing studies at 300°C and higher and correlated changes in the microstructure of the deposit to changes in the magnetic properties. Most notably, a substantial decrease in coercivity observed in several cases was correlated to a mixture of fcc and bcc crystalline faces in the film. Impurity analysis revealed the existence of S (560 ppm), C (850 ppm), and H (20 ppm). They were attributed to the electrolysis of a stress-relieving agent (saccharin) and a surface-active agent (lauryl sulfuric acid) in the plating bath. Since these agents appear to be used universally, similar impurities may exist in all of the electroplated films reported above.

The presence of impurities in electroplated magnetic films was recently explored by Takai and co-workers [22, 23]. Electroplating CoNiFe alloys from plating solutions containing thiourea resulted in the addition of higher amounts of S than those obtained by the use of saccharin. Alloys in the composition range $(Co_{73}Ni_{12}Fe_{15})_{99.10}S_{0.90}$–$(Co_{73}Ni_{12}Fe_{15})_{96.50}S_{3.50}$ were found to have lower coercivity and higher resistivity than CoNiFe alloys with lower amounts of S. These properties were attributed by the authors to the smaller grain size that is obtained in the presence of S. The alloys exhibited thermal stability; their anisotropy could be decreased by annealing in the presence of a magnetic field; and high-frequency permeability improved as a result of the increased resistivity. This work has shown that systematic exploration of impurities in electrodeposited films, an area where little understanding exists, can lead to improvements in material properties.

The work of Liao and Tolman [24, 25] provided substantial impetus to the quest for high-magnetic-moment materials and generated new directions in magnetic-alloy electrodeposition. Liao showed that the binary CoFe alloy (representative composition $Co_{90}Fe_{10}$) could be electroplated from sulfate baths with a coercive force of about 4 Oe, close to zero magnetostriction, a saturation magnetization of at least 19 kG, and high permeability. This is in contrast to vacuum-deposited CoFe, which has a coercivity of 18–20 Oe, much lower permeability, and higher magnetostriction. An additional advantage was that the Co:Fe ratio in the CoFe film closely resembled the Co^{2+}:Fe^{2+} concentration ratio in the bath, promising improved process control potential; the corresponding ratios for NiFe plating favor Fe deposition, thereby introducing process complexities in NiFe plating.

We studied CoFe plating from an all-chloride electrolyte [26] and observed a strong dependence of coercivity on alloy composition. A minimum of 3 Oe was obtained at about 11.5 wt.% Fe. An increase of Fe content by 1% on either side of this composition caused the coercivity to double, with the dependence being slightly stronger in the low Fe composition. Detailed microstructural and X-ray analysis revealed that the coercivity minimum was associated with the coexistence of fcc and bcc phases; effects such as grain size contributed to the strong compositional dependence of the coercivity. It was recognized at the time that, although plated CoFe showed excellent promise, there was still room for improvement by lowering coercivity and improving corrosion resistance. It seemed appropriate to explore third-element additions (other than Ni, described above) to accomplish the task [27–29].

Liao [27] described the fabrication of read/write heads using a CoFeB alloy with the B content varying between 0.1 and 2 wt.%, and Fe content varying between 7 and 12 wt.%. Plating was performed using a conventional bath to which dimethyl amine borane (DMAB) and sodium citrate were added; the pH was held at 3.5. Boron addition caused a decrease in coercivity down to 1 Oe, while other properties remained the same as the properties of the binary CoFe alloys. In order to decrease the anisotropy field (thereby increasing permeability), Liao applied a magnetic field during plating in orthogonal directions at predefined frequencies; by this method, the anisotropy decreased by a factor of almost 2 and the permeability increased proportionately. Another third element, Cr, was codeposited with CoFe [28]. The ternary CoFeCr system (Cr content of about 3 wt.%) was reported to be more corrosion-resistant than its binary counterpart; it also had lower coercivity (down to 0.3 Oe) and about three times the resistivity of conventional $Ni_{80}Fe_{20}$, making it attractive for high-frequency applications, where the high resistivity prevents formation of eddy currents. Low coercivity was also reported by Shinoura et al. [29], who plated CoFe in the presence of additives (such as naphthalene-1,3,6-trisulfonic acid and 2-propynl-ol) and attributed the low coercivity to the incorporation of unspecified amounts of S in the CoFe deposit.

Hironaka and Uedaira [30] studied CoFeP and CoFeSnP alloys electroplated by pulse-plating techniques. Although incorporation of P caused a drastic decrease in the saturation magnetization of the alloys, Sn incorporation (of about 7 wt.%) improved their corrosion resistance. The alloys were magnetically soft, while the magnetostriction coefficient depended on composition.

Electroless plating has also been used for depositing magnetically soft ($\leq$1 Oe) films (e.g., [31–35]). Osaka et al. reported on electroless deposition of CoB and CoFeB alloys in the presence of an external magnetic field; coercivities below 1 Oe were obtained, but values for the anisotropy field were quite high (e.g., 25 Oe for a $Co_{92}Fe_2B_6$ alloy), causing a decrease in permeability. Also, the plating baths used for these depositions were operated at high pH and high temperature; thus, their compatibility with masking materials used in head fabrication requires investigation.

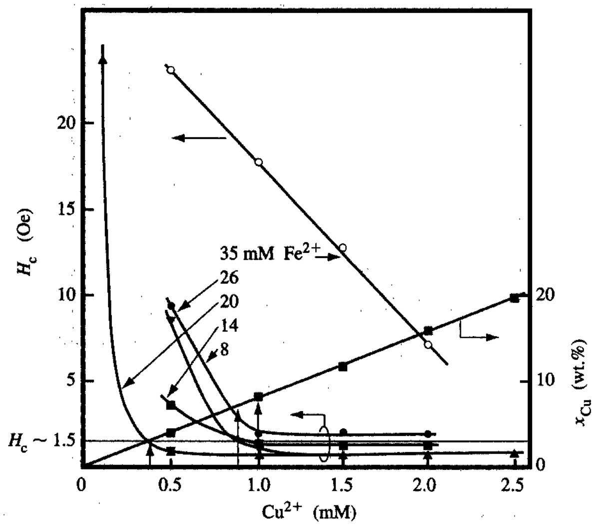

Figure 2

Dependence of CoFeCu coercivity (left ordinate) and Cu content (right ordinate) on the Cu^{2+} concentration in the plating solution. Numbers on curves show the concentration of Fe^{2+}. The bath Co^{2+} content was 0.2 M in all cases. All salts were sulfate salts. Other bath components included Na–acetate (0.07 M), boric acid (0.4 M), a stress-relieving agent, and a surfactant. Plating was done at a current density of 6 mA/cm^2 in a paddle cell. A horizontal line is drawn at an H_c value of 1.5 Oe. All films with a coercivity below 1.5 Oe are magnetically acceptable. Given a value for Fe^{2+}, the intersection of the corresponding curve with the horizontal line defines the Cu^{2+} bath concentration and the x_{Cu} film content beyond which the film coercivity remains below 1.5 Oe. For example, given a bath with 20 mM Fe^{2+}, the intersection with the horizontal line occurs at about 4 mM Cu^{2+}; by extrapolation to the right ordinate, the Cu content of the film is about 3.5 wt.%. All films with higher Cu content have a coercivity of 1.5 Oe. The Fe content of the same film can be found from Figure 3.

Table 2 Equilibrium potentials of selected electrochemical reactions.

Electrochemical reaction	*Equilibrium potential* (V)
Cu^{2+}/Cu	0.34
H^+/H_2	0
Ni^{2+}/Ni	−0.23
Co^{2+}/Co	−0.28
Fe^{2+}/Fe	−0.44

We have recently studied the addition of Cu to the binary CoFe system with the intention of improving its magnetic properties. We have found that ternary CoFeCu alloys of a particular composition are magnetically soft and have a high saturation magnetization; moreover, they can be fabricated in laminated form from a single plating solution. The remainder of this paper describes the electrochemistry and properties of the CoFeCu system.

Electroplated CoFeCu alloys

The addition of Cu to CoFe and the observation that this addition leads to a decrease in coercivity in the ternary system resulted from our attempt to create a laminated CoFe/Cu film, since laminated films generally have lower coercivity than the parent magnetic film [36]. Because of the electrochemistry of the system [37, 38], a laminated CoFe/Cu film that was electroplated from the same bath is in reality a CoFeCu/Cu film; i.e., the plating process adds a small amount of Cu to the magnetic CoFe layer. It was therefore required that, prior to creating a laminated CoFeCu/Cu film, the magnetics of the ternary CoFeCu single-layer film be understood; this study led to the observation that low coercivity could be attained in the ternary system without lamination [39, 40].

To understand the electrochemistry of these systems, it is necessary to examine the equilibrium potentials of the Cu^{2+}, Co^{2+}, and Fe^{2+} reduction reactions (**Table 2**). The passage of current through an electrolyte containing these ions in an uncomplexed or weakly complexed state causes the preferential deposition of Cu, since the potential of that reaction is the most positive. However, if the concentration of Cu^{2+} ions in solution is low, the Cu deposition reaction becomes diffusion-controlled; the current in excess of the diffusion-limited current for Cu deposition then goes to the deposition of Co and Fe. A portion of the current is also used for H_2 evolution; the current efficiency of the deposition processes is typically higher than 0.7.

The electrochemical mechanisms that govern CoFeCu plating have several consequences: The Cu content of the alloy is defined by the concentration of Cu^{2+} in the bath and by the level of agitation (or thickness of the diffusion layer); inherent in the system is the capability of generating laminated films, since pure Cu can be plated when the total applied current is lower than the diffusion-limited current for Cu deposition; finally, dependence of film composition on agitation translates to the need for uniform agitation both over the surface of the wafer (macroscale) and over the device topography (microscale).

We studied the dependence of magnetic properties of CoFeCu films on composition. Alloys of different composition were obtained by varying the Cu^{2+} and Co^{2+} content of the plating solution. The level of agitation was kept constant through the use of a paddle cell. Results are shown in **Figures 2** and **3**. It is evident that the addition of Cu causes a decrease in the coercivity of the film.

Combining results such as those shown in Figures 2 and 3 suggests that, for coercivity to be less than a certain amount (say 1.5 Oe), the composition of the CoFeCu alloy must be located in the shaded region of **Figure 4** [39, 40]. Typical easy-axis and hard-axis hysteresis loops for a CoFeCu film are shown in **Figure 5**, where they are compared with data for a NiFe film of equal thickness. Measurements of other magnetic properties over this composition range showed that anisotropy increases with increasing Cu content from a value of about 13 at 4 wt.% Cu to about 18 at 15 wt.% Cu. Saturation magnetization for the $Co_{85}Fe_{10}Cu_5$ was about 20 kG and decreased to about 18 kG for the $Co_{80}Fe_{10}Cu_{10}$ alloy. Magnetostriction was near zero as long as the Fe content was about 10 wt.%; it became positive at higher Fe content and negative at lower Fe content. Microstructural investigation revealed that Cu addition causes a decrease in the grain size of the film; this is probably the reason for the decrease in the coercivity [39]. The same mixture of fcc and bcc phases, found necessary to achieve a low-coercivity state for the binary CoFe alloy, was necessary for the ternary alloy as well; coercivity increased with alloys that were predominantly fcc (and had very low Fe content) or predominantly bcc (and had very high Fe).

Laminated films with CoFeCu as the magnetic layer and Cu as the nonmagnetic layer were deposited by the use of pulse plating (**Figure 6**). Because of the preferential occurrence of the Cu deposition reaction, pure Cu is plated when the applied current is less than the diffusion-limited current for Cu deposition. The current efficiency of this process is close to 1. When the applied current is higher, the ternary alloy is plated with a current efficiency of about 0.75. The number of laminations is obviously equal to the number of applied pulses. The method was first used in IBM by Romankiw and Olsen [38] for the NiFeCu/Cu system and has been extensively used by others in systems such as NiCu/Cu and CoCu/Cu [41]. A discussion of the effect of lamination on domain configuration and micromagnetics has been the subject of extensive investigations [36].

Recording heads were fabricated in which $Co_{85}Fe_{19}Cu_5$ replaced the $Ni_{80}Fe_{20}$ second write pole. Both poles had a thickness of 4 μm, while the gap thickness was 0.2 μm. Identical heads in which the second pole was 6-μm-thick $Ni_{80}Fe_{20}$ were fabricated in parallel for comparison. Measurements performed at low frequency using a disk with high coercivity (3800 Oe) showed that overwrite with the ternary alloy is clearly superior, demonstrating the advantage in using high-moment materials to improve recording performance. Corrosion and resistivity measurements showed no improvement of the ternary CoFeCu alloy over NiFe. More research is thus necessary for this material to be able to satisfy all requirements for future write heads.

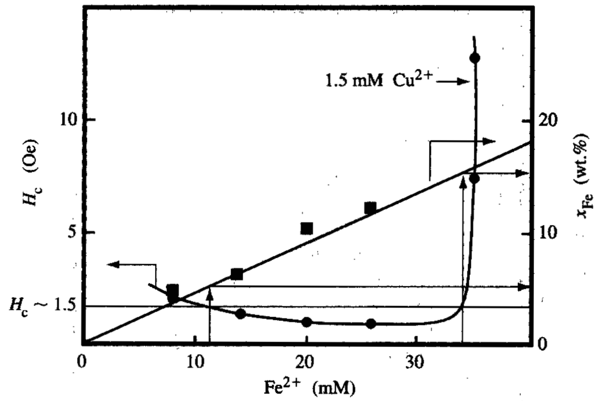

Figure 3

Dependence of CoFeCu coercivity (left ordinate) and Fe content (right ordinate) on the Fe^{2+} concentration in the plating solution; other conditions as in Figure 2. Given the weak dependence of coercivity on Cu^{2+} (see Figure 2), only one curve is drawn, corresponding to 1.5 mM Cu^{2+}. A horizontal line is drawn at an H_c value of 1.5 Oe. Baths with an Fe^{2+} concentration between about 12 and 33 mM yield films with lower coercivity that are magnetically acceptable. The Fe content of these films can be read off the right ordinate. A combination of the data shown in Figures 2 and 3 generates the diagram of Figure 4.

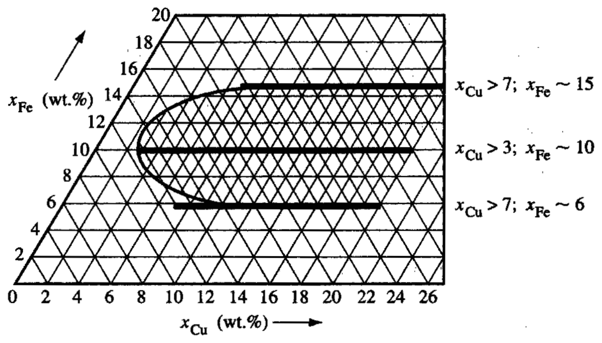

Figure 4

Composition range (crosshatched area) over which CoFeCu films have magnetically soft properties.

Summary

Electroplating of magnetic materials has found universal applicability in the fabrication of inductive thin-film heads, since it is an additive process and allows facile patterning of NiFe pole tips. The introduction of magnetoresistive

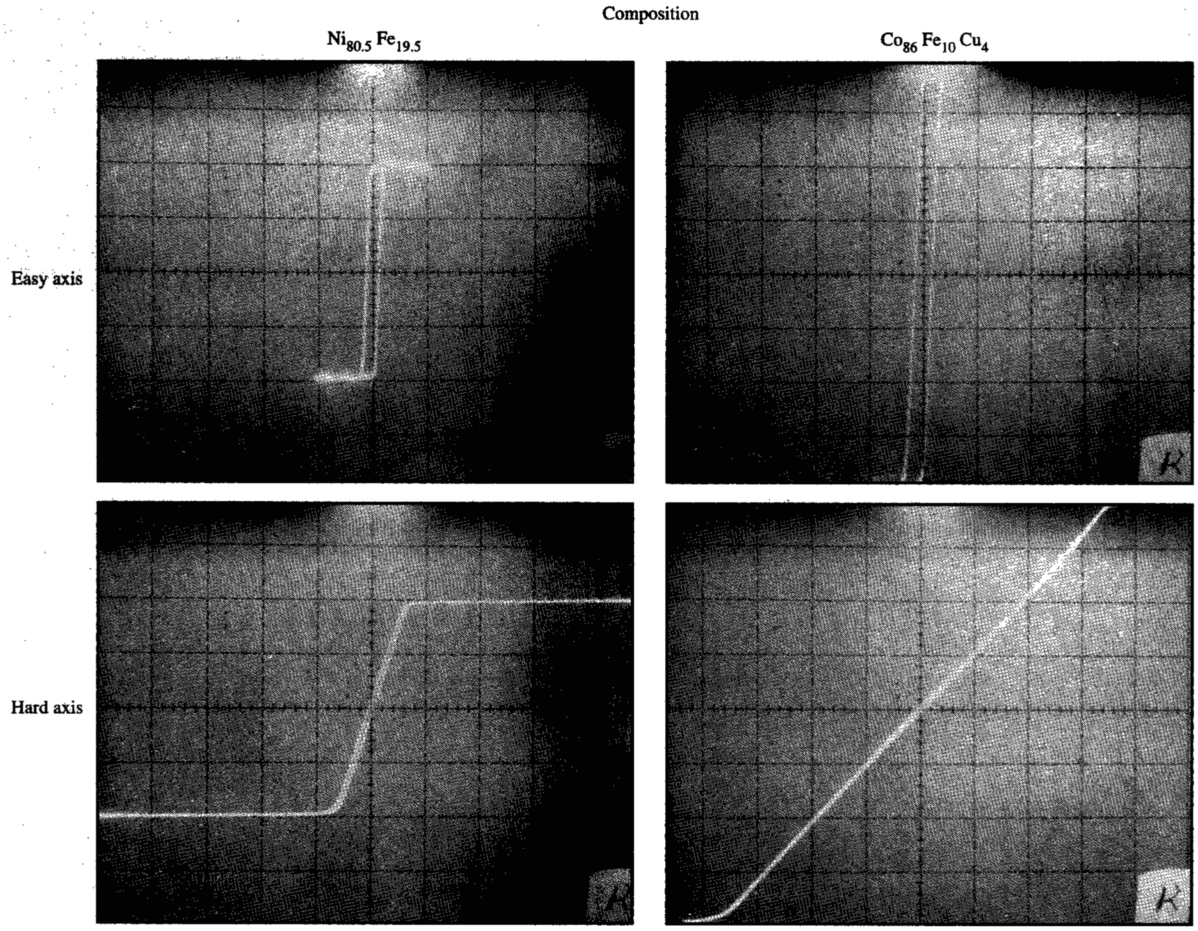

Figure 5

Hysteresis loops of $Ni_{80.5}Fe_{19.5}$ (left) and $Co_{86}Fe_{10}Cu_4$ (right) along the easy axis (top) and along the hard axis (bottom); a magnetic field of about 1000 Oe was applied during plating; the easy axis is parallel to the applied field; the hard axis is perpendicular to the applied field. In all loops, the abscissa is 5 Oe/division. The ordinate is in arbitrary units. Both films had the same thickness (2 μm).

technology for reading, and new requirements introduced in the writing process (such as the ability to write on high-coercivity disks at very high frequencies) pose a serious challenge to electroplating. A large amount of research is being conducted primarily in the United States and in Japan to face this challenge; results so far have yielded a variety of materials whose superiority to NiFe has already been shown. High-Fe NiFe alloys have higher magnetic moment and resistivity and are increasingly being used in device fabrication. Ternary CoNiFe alloys have been shown to possess similar properties. Significant advances have been made in the controlled addition of impurities to CoNiFe alloys by electroplating methods. This is a new area of electroplating research that promises improved control of deposit properties. Electroplating of ternary and quaternary alloys based on CoFe has yielded a variety of new materials, including CoFeCu, which has the additional advantage of allowing lamination with Cu from a single plating bath. However, the simultaneous satisfaction of all functional requirements, including corrosion stability in adverse environments and ease of manufacturing, has yet to be demonstrated.

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References

1. A. Chiu, I. Croll, D. E. Heim, R. E. Jones, Jr., P. Kasiraj, K. B. Klaassen, C. D. Mee, and R. G. Simmons, "Thin-film Inductive Heads," *IBM J. Res. Develop.* **40,** 283 (1996).
2. P. C. Andricacos and L. T. Romankiw, "Magnetically Soft Materials in Data Storage: Their Properties and Electrochemistry," in *Advances in Electrochemical Science and Engineering*, Vol. 3, H. Gerischer and C. W. Tobias, Eds., VCH Publishers, New York, 1994, pp. 227–321.
3. L. T. Romankiw, "A Path from Electroplating Through Lithographic Masks in Electronics to LIGA in MEMS," *Electrochim. Acta* **42,** 2985–3005 (1997).
4. C. D. Mee and E. D. Daniel, *Magnetic Recording*, Vol. 1, McGraw-Hill Book Co., Inc., New York, 1987, p. 5.
5. R. E. Jones, Jr., "IBM 3370 Film Head Design and Fabrication," *IBM Disk Storage Technology*, IBM Corporation, GPD Technical Communications, 5600 Cottle Road, San Jose, CA, February 1980, pp. 6–9.
6. K. Ohashi, M. Ito, and T. Maruyama, "Effect of Plated NiFe Composition on Domain Configuration," *Proceedings of the Symposium on Magnetic Materials, Processes, and Devices*, PV 90-8, The Electrochemical Society, Pennington, NJ, 1990, p. 247.
7. R. D. Hempstead and J. B. Money, "Thin Film Head Having Negative Magnetostriction," U.S. Patent 4,242,710, December 30, 1980.
8. V. Brusic, J. Horkans, and D. J. Barclay, "Electrochemical Aspects of Thin-Film Storage Media," *Advances in Electrochemical Science and Engineering*, Vol. 1, H. Gerischer and C. W. Tobias, Eds., VCH Publishers, New York, 1990, pp. 249–287.
9. R. M. White, *Introduction to Magnetic Recording*, IEEE Press, New York, 1985, p. 20.
10. N. Robertson, H. L. Hu, and C. Tsang, "High Performance Write Head Using NiFe 45/55," *IEEE Trans. Magn.* **33,** 2818 (1997).
11. I. W. Wolf, "Electrodeposition of Magnetic Materials," *J. Appl. Phys.* **33,** 1152 (1962).
12. C. H. Tolman, "Non-Magnetostrictive Compositions of FeNiCo Films," *J. Appl. Phys.* **38,** 3409 (1967).
13. N. C. Anderson and R. B. Chesnutt, "Electrodepositing CoNiFe Alloys for Thin Film Heads," U.S. Patent 4,661,216, April 28, 1987.
14. R. Chesnutt, "Electroplated CoNiFe Alloy for Use in Integrated Inductive Magnetoresistive Recording Head," *J. Appl. Phys.* **73,** 6223 (1993).
15. M. C. Blakeslee, J. D. Olsen, and L. T. Romankiw, "Method of Electrodepositing a Low Coercive Force, Corrosion-Resistant Alloy of Nickel, Iron and Boron," U.S. Patent 4,440,609, April 3, 1984.
16. M. Sano, K. Mistuoka, M. Morijiri, S. Narishige, M. Hanazono, and T. Yoshidu, "Thin Film Magnetic Head Having Magnetic Film of CoNiFe Alloy," U.S. Patent 4,780,781, October 25, 1988.
17. Y. Omata, "Magnetic Properties of FeCoNi Films with High Saturation Magnetization Prepared by Evaporation and Electrodeposition," *IEEE Transl. J. Magn. Jpn.* **5,** 17 (1990).
18. Y. Omata, "Process for Producing a Thin Alloy Film Having High Saturation Magnetic Flux Density," U.S. Patent 5,011,581, April 30, 1991.
19. Y. Omata and N. Kaminaka, "Magnetic Properties and Electrodeposition of Fe–Co–(Ni and/or Cr) Alloy Films with DC or Pulse Mode Current," *Proceedings of the Second International Symposium on Magnetic Materials, Processes, and Devices*, PV 92-10, The Electrochemical Society, Pennington, NJ, 1992, p. 255.
20. Y. Omata, S. Mitani, T. Kai, A. Taniguchi, and S. Nakagawa, "Preparation and Soft-Magnetic Properties of FeCoNiCr Plated Films Having a Single Phase Structure and High Saturation Magnetization," *IEEE Transl. J. Magn. Jpn.* **5,** 956 (1990).
21. O. Shinoura, A. Kamijima, and Y. Narumiya, "Soft Magnetic Properties of Electrodeposited CoNiFe Films," *IEEE Transl. J. Magn. Jpn.* **9,** 118 (1994).
22. M. Takai, K. Hayashi, M. Aoyagi, and T. Osaka, "Electrochemical Preparation of Soft Magnetic CoNiFeS Film with High Saturation Magnetic Flux Density and High Resistivity," *J. Electrochem. Soc.* **144,** L203 (1997).
23. M. Takai, K. Hayashi, M. Aoyagi, and T. Osaka, "High Frequency Permeability of Electrodeposited CoNiFeS Films with High B_s and ρ," *J. Magn. Soc. Jpn.* **21,** supplement S2, p. 443 (1997).
24. S. H. Liao, "High Moment CoFe Thin Films by Electrodeposition," *IEEE Trans. Magn.* **MAG-23,** 2981 (1987).
25. S. H. Liao and C. H. Tolman, "Electrodeposition of High Moment Cobalt Iron," U.S. Patent 4,756,816, July 12, 1988.
26. J. W. Chang, P. C. Andricacos, B. Petek, and L. T. Romankiw, "Electrodeposition of Soft CoFe Alloys," *Proceedings of the Symposium on Magnetic Materials, Processes, and Devices*, PV 90-8, The Electrochemical Society, Pennington, NJ, 1990, p. 361.

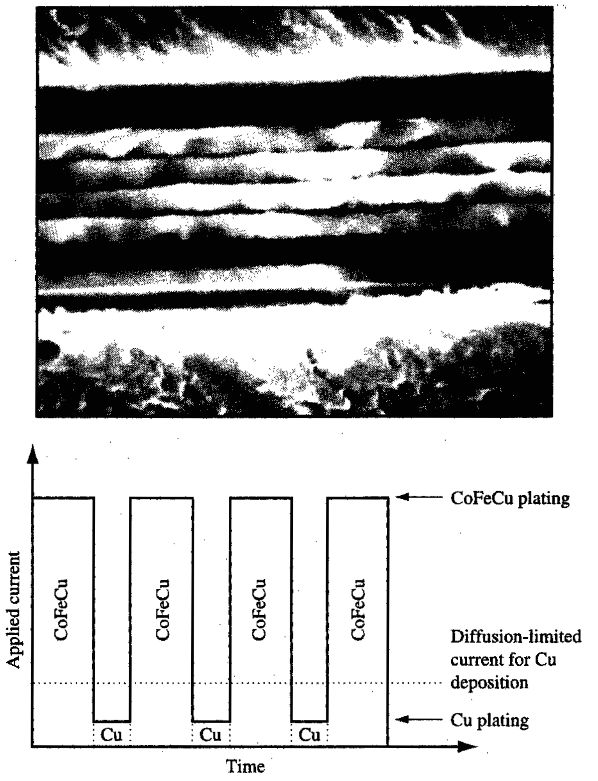

Figure 6

(Top) Cross section (magnified 20K) of a laminated CoFeCu/Cu film with four CoFeCu layers (approximate thickness 0.5 μm) and three Cu layers (approximate thickness 10 nm) plated by a pulsed current waveform shown schematically (bottom).

27. S. H. Liao, "Thin Film Core of CoFeB Alloy," U.S. Patent 5,168,410, December 1, 1992.
28. S. H. Liao, G. E. Roberts, and E. C. Darr, "Electrodeposited High B_s CoFeCr Thin Films for High Frequency Recording Applications," Paper GC-04, International Magnetics Conference, St. Louis, MO, 1992.
29. O. Shinoura, Y. Izumi, and Y. Narumiya, "Electrodeposited CoFe Soft Magnetic Films, *Abstract 2-43*, 42nd Meeting of the International Society of Electrochemistry, Montreux, Switzerland, August 25–30, 1991.
30. K. Hironaka and S. Uedaira, "Soft Magnetic Properties of CoFeP and CoFeSnP Amorphous Films Formed by Electroplating," *IEEE Trans. Magn.* **26,** 2421 (1990).
31. T. Osaka, T. Homma, N. Masubuchi, K. Saito, M. Yoshino, and T. Namikawa, "Preparation of CoB Soft Magnetic Thin Films by Electroless Plating," *IEEE Transl. J. Magn. Jpn.* **6,** 85 (1991).
32. T. Osaka, T. Homma, K. Saito, A. Takekoshi, Y. Yamazaki, and T. Namikawa, "Co-Based Soft Magnetic Films Prepared by Electroless Plating Method," *Proceedings of the Second International Symposium on Magnetic Materials, Processes, and Devices*, PV 92-10, The Electrochemical Society, Pennington, NJ, 1992, p. 267.
33. D. Kim, H. Matsuda, K. Aoki, and O. Takano, "Electroless NiFeB Alloy Plating Solution Using DMAB as a Reducing Agent," *Plating & Surf. Finish.* **83,** 78 (February 1996).
34. M. Takai, K. Kageyama, S. Takefusa, A. Nakamura, and T. Osaka, "Magnetic Properties of Electroless-Deposited NiFeB and Electrodeposited NiFe Alloy Thin Films," *IEICE Trans. Electron.* **E78-C,** 1530 (1995).
35. T. Osaka and M. Takai, "Study on Head Core Materials with High B_s by Plating Methods," *J. Magn. Soc. Jpn.* **21,** supplement S2, p. 433 (1997).
36. J. C. Slonczewski, B. Petek, and B. E. Argyle, "Micromagnetics of Laminated Permalloy Films," *IEEE Trans. Magn.* **24,** 2045 (1988).
37. J. M. Brownlow, "Electrodeposition of Thin Magnetic Films in the Ni–Fe–Cu System," *J. Appl. Phys.* **38,** 1440 (1967).
38. L. T. Romankiw and J. D. Olsen, "Electroplated Laminated Cu–NiFe Films from a Single Plating Bath for Inductive Recording Heads and Magnetic Shields," *Proceedings of the Symposium on Magnetic Materials, Processes, and Devices*, PV 90-8, The Electrochemical Society, Pennington, NJ, 1990, p. 339.
39. J. W. Chang, P. C. Andricacos, B. Petek, and L. T. Romankiw, "Electrodeposition of High M_s CoFeCu Alloys for Recording Heads," *Proceedings of the Second International Symposium on Magnetic Materials, Processes, and Devices*, PV 92-10, The Electrochemical Society, Pennington, NJ, 1992, p. 275.
40. P. C. Andricacos, J. W. Chang, W. J. Horkans, J. D. Olsen, B. Petek, and L. T. Romankiw, "High Magnetic Moment Materials and Process for Fabrication of Thin Film Heads," U.S. Patent 5,582,927, December 10, 1996.
41. T. P. Moffat, "Electrochemical Production of Single-Crystal Cu–Ni Strained-Layer Superlattices on Cu(100)," *J. Electrochem. Soc.* **142,** 3767 (1995) and references therein.

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Panos C. Andricacos *IBM Research Division, Thomas J. Watson Research Center, Yorktown Heights, New York 10598 (ndricac@us.ibm.com).* Dr. Andricacos is Manager of the Electrodeposition Technology group at the IBM Thomas J. Watson Research Center. He received B.S., M.S., and doctoral degrees in chemical engineering from Columbia University, where he is also an adjunct associate professor. As a postdoctoral research associate at the Lawrence Berkeley Laboratories, he worked on fuel cells and on the application of UHV techniques in the study of electrochemical reactions. While at IBM, he has worked on the application of electrochemical processes in storage, packaging, and C4 technology; he also played a key role in the development of copper electroplating for chip metallization. In 1993 he received the Research Award of the Electrodeposition Division, Electrochemical Society, for the development of novel techniques for the study of alloy electroplating.

Neil Robertson *IBM Storage Systems Division, 5600 Cottle Road, San Jose, California 95193 (robertsn@almaden.ibm.com).* Dr. Robertson is Senior Engineering Manager of the Thin-Film Magnetic Recording Head process development group at the IBM Almaden Research Center. The group conducts research in electrodeposited materials, lithography processes, and thin films for recording heads; most recently it has participated in the 5 Gb/in.^{2} technology demonstration, and it has transferred to manufacturing novel materials and device designs for IBM's next generation of products. Notable materials were those for the first new generation of high-moment plated materials as well as GMR materials. Dr. Robertson holds a B.S. degree from Cornell and a Ph.D. degree from the University of California, Berkeley, both in chemical engineering. He is a member of the Electrochemical Society.