Chapter 6
Magnetic Heads

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6.1 Introduction

Figure 6.1 shows how rapidly the areal density of hard disk drives (HDD) has been increasing over the past 20 years [1]. Several critical innovations were necessary to bring about such rapid progress in the field of magnetic recording [2]. One of the most significant innovations from the viewpoint of material improvement was the electrodeposition of permalloy ($Ni_{80}Fe_{20}$), which was introduced by IBM in 1979 as the core material of a thin-film inductive head to increase the magnetic recording density [3]. After the introduction of the magneto-resistive (MR) element as the read head and the electrodeposited permalloy as the write head by IBM in 1991 [4], the rate of increase in the recording density of HDDs jumped from 30% per year to 60% per year. Recently, a giant magneto-resistive (GMR) element has been used for the read element instead of the MR element. The rate of increase in the recording density jumped to over 100% per year in 1999, which is an *incredible* rate of increase. Since 2002, however, the rate of increase has decreased to 30%; thus, new innovations are required to maintain the rate of increase. In 2004, the practical use of perpendicular magnetic recording instead of longitudinal magnetic recording was announced [5]. This system is a critical innovation for developing high-performance HDD systems with high-recording density. The design of the magnetic recording head was changed because of the change of the recording system.

The development of a new magnetic recording head with higher performance and smaller dimensions is a key requirement for realizing high-density magnetic recording. Furthermore, to meet the demand for the rapid increase in magnetic recording density, the soft magnetic film in the core must have low magnetostriction, λ_s, high electrical resistivity, ρ, high thermal stability, low film stress, and high corrosion resistance, as well as high saturation magnetic flux density, B_s. The recording heads, using higher magnetic materials with high value of B_s can write to a high-H_c

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T. Osaka et al. (eds.), *Electrochemical Nanotechnologies,*
Nanostructure Science and Technology, DOI 10.1007/978-1-4419-1424-8_6,

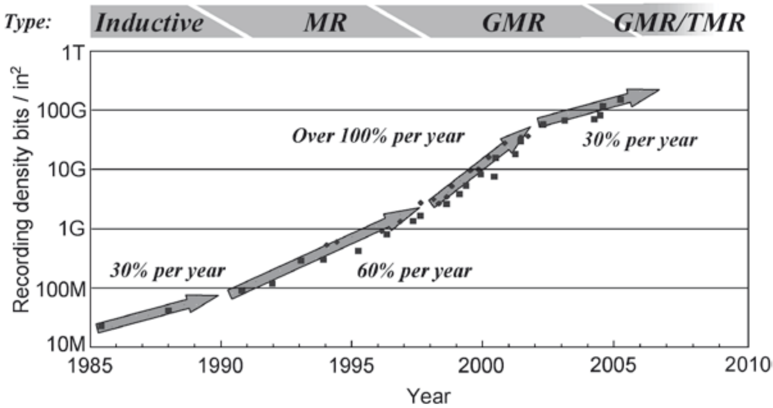
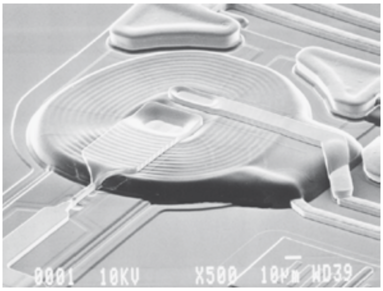
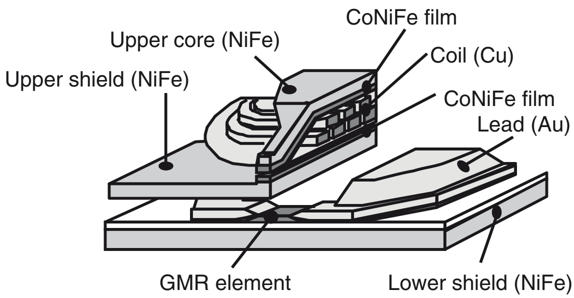


Fig. 6.1 Areal density of hard disk drives has been increasing over the past 20 years [1]

Fig. 6.2 SEM image and a schematic of a GMR head [1]





medium because of the high magnetic field generated. On the other hand, for higher-frequency recording, the soft magnetic film should have higher resistivity while maintaining a high value of B_s to suppress the eddy-current loss. Therefore, B_s and ρ of the soft magnetic thin film used for the recording head should be much higher than those of the conventional $Ni_{80}Fe_{20}$ permalloy, for which $B_s = 9–10$ kG and $\rho = 15–20$ μΩcm. So, permalloy with the composition of $Ni_{45}Fe_{55}$ was used instead of $Ni_{80}Fe_{20}$. Recently, CoNiFe has been used instead of permalloys. However, the development of a new magnetic recording head with smaller dimensions is strongly required for realizing a higher-density magnetic recording device. An SEM image and a schematic of a GMR head are shown in Fig. 6.2 [1].

6.2 Thin-Film Head

6.2.1 Mechanism of Magnetic Recording

Figure 6.3 shows system of magnetic recording of HDD. A recording bit is a small area of the recording layer, and the bit is magnetized. The magnetized bit pattern is made by magnetic flux, which is formed by an exciting current in the coil of the recording head. The recording bit is read by the read-head element by measuring the magnetic flux from the recording layer on the medium, which is rotated. Ferromagnetic material is used as the core of the magnetic-electric converter. Generally, soft magnetic materials that have high permeability (μ) and low coercivity (H_c) are used. Contact heads, which are in contact with the medium, and flying heads, which are not in contact with the medium, can be used for the magnetic recording. Magnetic tapes and floppy disks use contact heads, and HDDs use flying heads. The distance between the surface of the flying head and the medium is less than 10 nm, and the distance is maintained by an air flow between the medium and the slider on which the head is installed.

6.2.2 Thin-Film Inductive Head

A magnetic recording head that uses magnetic flux flowing from and into the coil for read–write operations, is called an “inductive head”. Figure 6.4 shows a schematic illustration of an inductive head.

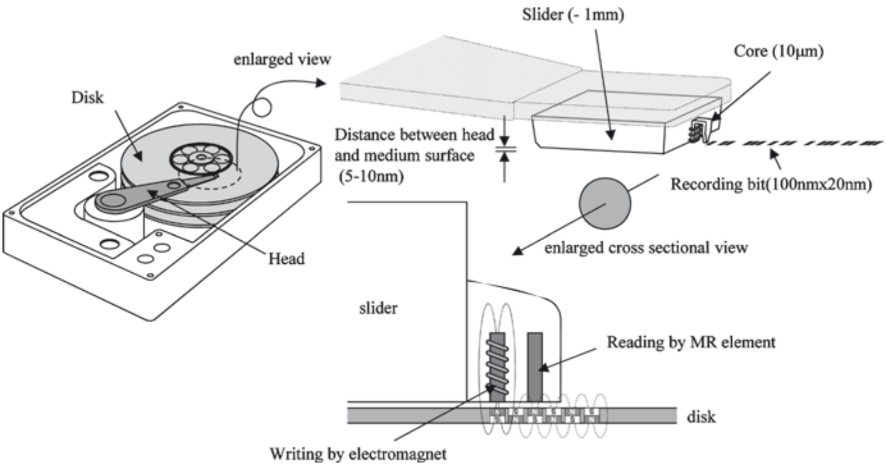


Fig. 6.3 System of magnetic recording of HDD

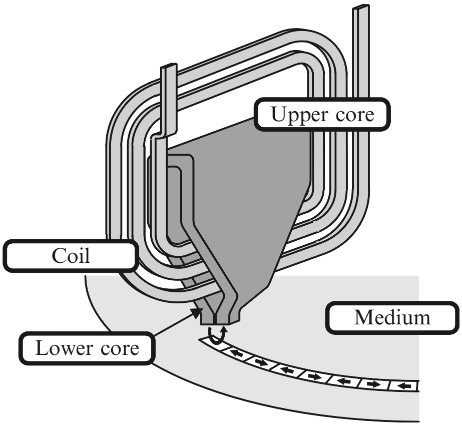


Fig. 6.4 Schematic illustration of an inductive head

In the case of bit writing, the magnetization of a small area of the magnetic layer is changed to produce a recording bit by the leakage of magnetic flux through a gap of the core, resulting from magnetic flux produced from coils by an exciting current. In the case of bit reading, an electric signal generated by electromagnetic induction in the coil is read by measuring the leakage of magnetic flux through the coil from the gap to the core. In 1960, inductive heads with a ferrite core and Cu wire coils were used. In 1979, a thin-film inductive head was developed by IBM Corporation [3], and the recording density increased rapidly as a result of this innovation. The development of the earlier inductive heads had involved the machine-tooling of the ferrite and the manual twisting of Cu-wire. However, the thin-film inductive head was not developed mechanically but by sputtering, evaporating, and plating. Since the core and the coil were produced by a thin-film process involving photolithography without using machine tools, a thin and fine core and coil could be realized. Thus, the read–write characteristics improved rapidly, and the rate of production increased dramatically. Since the core material was changed from ferrite to a metal-thin film, a high B_s was achieved. As a result, the read–write characteristics improved dramatically and the magnetic flux available for writing increased. During that time, soft magnetic permalloy ($Ni_{80}Fe_{20}$) thin film became the core material in practical use. The B_s values of ferrite and $Ni_{80}Fe_{20}$ permalloy are 3–5 kG and B_s = 9–10 kG, respectively. A variety of methods have been used for realizing the head core.

6.2.3 *Magnetoresistive (MR) Head*

In 1991, IBM Corporation developed an MR head for practical use: a thin-film head with magnetoresistive element. The magnetoresistance effect is the phenomenon in which the resistance of a magnetic material changes with the magnetic field. The effect is also called an anisotropic magnetoresistive effect (AMR) to distinguish it from the giant magnetoresistive effect (GMR). The MR device in the head is used for reading, and a common inductive head is used for writing. A head in which a soft magnetic thin

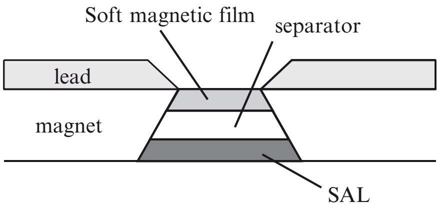


Fig. 6.5 Structure of an MR element

film is used, both as a lower core and an upper shield of the MR element, is called a merged-type MR head. Figure 6.5 shows the structure of an MR element.

When the direction of the current that flows in a thin film is the same as the direction of magnetization of the thin film, the resistance of the film increases. On the other hand, when the direction of magnetization of a thin film and the direction of the current that flows in the film are perpendicular, the resistance of the film decreases. Since the voltage in an MR element changes upon changing the soft magnetic thin films in the MR element due to the leakage of flux from the recording bit on the recording layer, the recording bit can be detected. The output signal is proportional to the change in magnetic flux density with respect to time because the electromagnetic induction of the inductive head is used for writing. The relative speed of the head relative to the medium must be high. On the other hand, the output signal depends on magnetic flux density in the MR element. Thus, the relative speed of the head to the medium, i.e., the rotation speed, does not have to be high.

A request of properties of the inductive head could be altered because the read and write elements were divided. Since the intuitive element is not used as the read element, the high sensitivity of the inductive element is unnecessary. Therefore, the number of turns of coil could be decreased, and furthermore, the recording head could become smaller. The soft magnetic thin films with very low hysteresis loss, that is the films with very low coercivity, is not required. So, some soft magnetic films, except for commonly used permalloy, could be used for core materials. Now, high B_s soft magnetic thin films are in practical use for realizing high-recording density.

In 1999, a GMR head, applying a giant magnetoresistive effect instead of an MR element came into practical use. The GMR effect is of very high sensitivity compared with the MR effect, and this resulted in the rate of increase in recording density jumping to over 100% per year. In 2005, a TMR head applying the Tunneling Magnetoresistance(TMR) effect came into practical use. TMR and GMR heads have been in practical use ever since.

6.2.4 Development of Thin-Film Head

The process flow for the thin-film head is shown in Fig. 6.6 [6]. The Cu coils, Cu lead, Au pad, and the core of the soft magnetic thin films in the head are prepared by electrodeposition. These metal parts require a high-aspect ratio. Also, the method

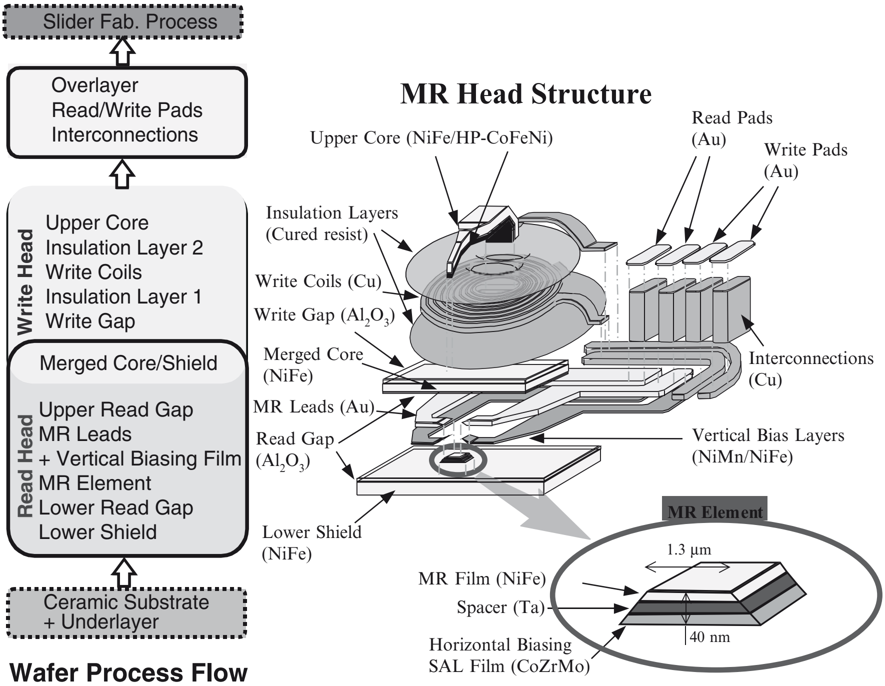


Fig. 6.6 Process flow for the thin-film head

of electrodeposition with photolithography is advantageous for selective deposition and the easy formation of thick films. In particular, the head core of the magnetic thin films is very fine with a width of less than 1 μm. Electrodeposition has a serious problem with the distribution of current density because the distributions of film thickness and metal composition occur often. pH modification near the deposition surface occurred by a side reaction that generated H_2. The alloy composition was changed markedly by this slight modification of pH during electrodeposition. In particular, the electrodeposition of NiFe alloy is very easily changed by pH modification during electrodeposition. Furthermore, obtaining a constant film composition is very difficult in Fe-based plating because of "anomalous codeposition". It is necessary to maintain a deviation of film composition of less than 0.1% because the magnetic properties of permalloy films depend on the film composition.

This serious problem was solved by two new plating developments: the paddle plating cell system and the frame plating method. Figure 6.7 shows a schematic illustration of the paddle plating cell system [7]. This method of plating surfaces allows the formation of films with constant composition because the plating solution near the deposition surface is agitated by a "paddle". This agitation also removes bubbles on the deposition surface and unwanted products formed during electrodeposition. Effective agitation suppresses pH modification during electrodeposition, thus ensuring a constant film composition. Figure 6.8 shows the process

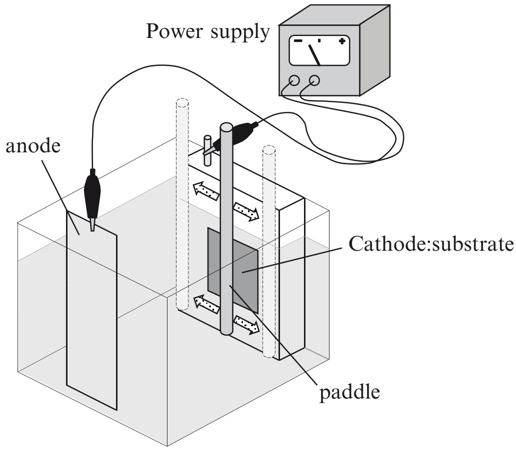


Fig. 6.7 Schematic illustration of the paddle plating cell system

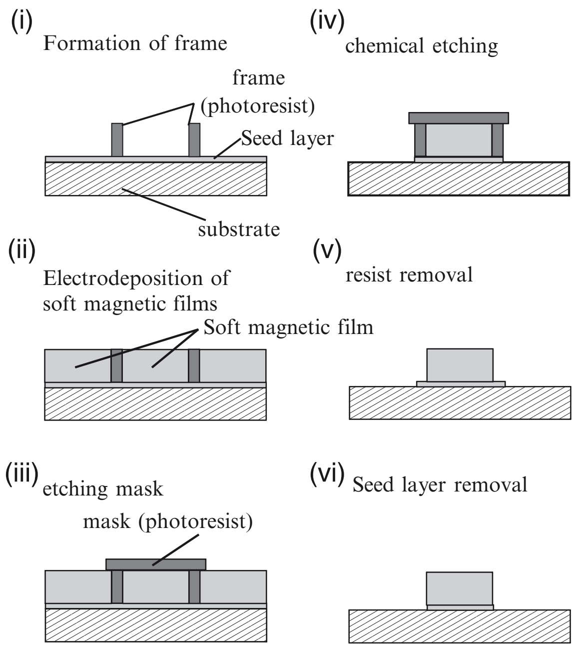


Fig. 6.8 Process flow of the frame plating method

flow of the frame-plating method [8]. This method suppresses the distribution of the current density on a fine pattern. In this method, a line resist pattern called a "frame" is used to suppress the distribution of current density at the edge of the pattern. After electrodeposition, the metal pattern in the frame pattern is covered with a resist pattern. The film deposited outside the frame pattern is removed by chemical etching. Thus, a metal pattern is obtained inside the frame pattern. Since a resist pattern having a narrow width and a small area is used, distribution of current density can be suppressed. The composition of the film pattern is consistently uniform, so that permalloy with homogeneous magnetic properties can be obtained. These methods have been widely used for development of the other soft magnetic films, such as CoNiFe and CoFe.

6.3 Design of High-Performance Soft Magnetic Films

6.3.1 Theoretical Concept of Soft Magnetic Properties

Because of the requirement of new soft magnetic thin films with a high value of B_s and high resistivity, high-performance soft magnetic thin films are overviewed. Only Ni, Co, Fe, and their alloys and some of their oxides show ferromagnetism at room temperature, and Fe has the highest magnetic moment of a single element. Materials with soft magnetic properties have a low value of H_c and a high μ. H_c, and the grain size are related by the following equation: [9]

$$H_c = \frac{{K_1}^4 D^6}{A^3 M_s} \tag{6.1}$$

where, K_1 is the constant of magnetocrystalline anisotropy, D is the crystal grain size, and A is the exchange stiffness constant. M_s and K_1 mainly depend on the composition of metals in the film. From this equation, decreasing the grain size is an effective means of obtaining soft magnetic properties for films with high magnetocrystalline anisotropy. On the other hand, K_{eff} is given by the following equation:

$$K_{eff} \propto \frac{K}{n} \tag{6.2}$$

where, K is the constant of magnetocrystalline anisotropy, and n is the number of crystal grains. This equation shows that an increase in the number of grains, that is, a decrease in the grain size, is an effective means of obtaining low K; therefore, decreasing the grain size is very effective for obtaining soft magnetic thin films.

6.3.2 Design of Soft Magnetic Thin Films with High B_s

Since the 1980s, many researchers have discovered new, soft magnetic materials with high values of B_s . Figure 6.9 shows the composition – B_s and H_c diagrams for CoNiFe bulk ternary alloy published by Bozorth [10]. Fe has the highest magnetic moment of a single element, and $Fe_{60}Co_{40}$ is the magnetic alloy with the highest

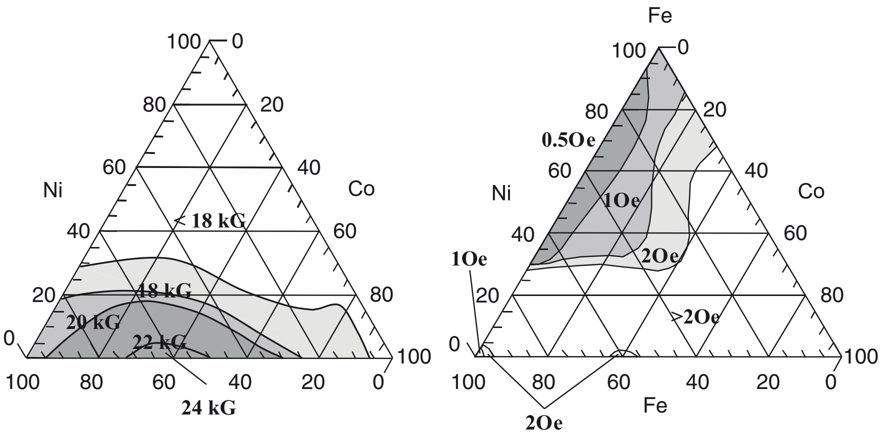


Fig. 6.9 The composition – B_s and H_c diagrams for CoNiFe bulk ternary alloy

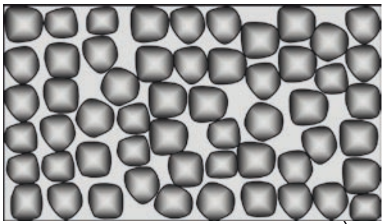


Fig. 6.10 Design of a microstructure for soft magnetic films with a high B_s value. Small and fine grains that have a high B_s, such as Fe, are included in the thin films

known B_s value of 24 kG. However, these materials do not show the soft magnetic properties that only $Ni_{80}Fe_{20}$ and $Ni_{45}Fe_{55}$ films have. Therefore, the CoFe- and Fe-based alloys have been studied with the aim of obtaining new soft magnetic materials. Figure 6.10 shows the design of a microstructure for soft magnetic films with a high B_s value. The ideal high-B_s soft magnetic film has small and fine grains having high B_s value. Various techniques for forming high-B_s soft magnetic thin films are shown below.

The films are in amorphous state under the as-deposited condition; however, if they are annealed above the crystallization temperature, nano Fe or CoFe grains are deposited, and other components inhibit the grain growth. This basic concept is used for the preparation of Fe-based nano-crystalline alloys, such as Fe-Cu-M (M = Nb, Zr, Hf, Ta)-Si-B; (B_s = 12–13 kG) [11] and Fe-M (M = Ta, Nb, Hf)-N(C) (B_s = 15–16 kG) [12]. These films are mainly prepared by sputtering or evaporation. Rapidly quenched ribbons such as Fe-Cu-M (M = Nb, Zr, Hf, Ta)-Si-B (B_s = 12–13 kG) [13] are formed by the same technique. Furthermore, sputtered CoAlO, FeAlN, and

Fe(CoFe)HfN [14, 15] alloys with granular structure are reported to be high-B_s and high-ρ materials with $\rho = 150–3{,}500$ μΩcm.

The film contains an impurity to inhibit grain growth during film deposition. Therefore, the film is in the nanocrystalline state under as-deposited condition. The additive is used during electrodeposition, whereas during electroless deposition, codeposited atoms from the reducing agent are used as the inhibitor. This basic concept is used for the preparation of electrodeposited CoFe (18–19 kG) [16] and CoNiFe (16–19 kG) [17–21]-based alloys, and electroless-deposited NiFeB (7–10 kG) [22, 23], CoB (14 kG) [24], CoFeB (16–18 kG) [25, 26], and CoNiFeB (15–20 kG) [27]. Electrodeposited CoNiFe with a very high B_s value of 20 kG is also reported [28–33]. This film has a bcc-fcc mixed crystalline structure; therefore, it is suggested that crystal grains with different crystalline structures act as the inhibitors. Furthermore, Fe-M-N (M = Mo, Rh, Zr, Ta, Al) films prepared by sputtering have higher B_s values of nearly 20 kG [34], and sputtered granular oxide soft magnetic thin films, such as Fe-M-O (M = Mg, Al, Hf) [35, 36], Co-M-O (M = Al, Zr, Cr) [37, 38], CoFe-M-O (M = Al, Mg, Hf) [39], formed without annealing have very high B_s value of 16–20 kG. Recently, CoFeN [40, 41] and CoFeAlO [42] were reported to have the highest B_s value of 24 kG. These films have a nanocrystalline structure in the as-deposited state, and grain growth was inhibited by very small amount of metal nitride.

The film contains an intermediate layer as the inhibitor for grain growth during film deposition. Fe/FeC and Fe/CoNbZr, multiplayer films have been produced with such an intermediated layer [43].

6.3.3 Design of Soft Magnetic Thin Films with High B_s and High ρ

Since 1995, new, soft magnetic materials with high B_s and high resistivity have been discovered. Co-based amorphous alloys (CoTaZr, CoNbZr, CoPdHf, etc.) have high B_s values of 11–14 kG and a high ρ of 100–200 μΩcm compared with the values for permalloy. However, the B_s value of these Co-based amorphous alloys is not sufficient to realize high-density recording. Therefore, fine grain-based soft magnetic thin films are required.

Figures 6.11 and 6.12 show microstructure designs for soft magnetic films with high values of B_s and high ρ. In Fig. 6.11, the ideal soft magnetic film, with a high B_s and a high ρ, has small and fine grains with a high B_s value, surrounded and separated by a high-ρ region. Sputtered (Co,Fe,CoFe)-M-O (M = Al, Mg, Hf, Cr, Zr) [35–38] alloys with a granular structure have been reported to be high-B_s and high-ρ materials with ρ values of 150–3,500 μΩcm. Using Al–O and Mg–O for grain boundary, these films have a high B_s and high resistivity because Fe or Co grains are separated by the insulating grain boundary of Al–O and Mg–O. High-ρ soft magnetic thin films prepared by electro- and electroless deposition have also been reported. The high value of ρ was realized by the codeposition of impurities such

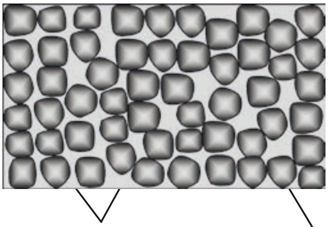


Fig. 6.11 Design of a microstructure for soft magnetic thin films with high B_s and high ρ. Fine grain with high B_s is separated by high ρ materials

Fig. 6.12 Design of a microstructure for soft magnetic thin films with high B_s and high ρ. Soft magnetic film is separated by intermediate layer with high ρ

as Mo, Cr, and S; however, the details of this mechanism by which a high value of ρ has been achieved have not been reported.

In Fig. 6.12, the film contains an intermediate layer for suppressing the eddy current loss. Insulators such as SiO_2 and Al_2O_3 are widely used for the intermediate layer, and the formation of films such as FeAlN/Al_2O_3 [44], FeTaN/AlN [45], have been reported. Soft magnetic thin films with high resistivity and a low B_s value are used for the intermediate layer instead of an insulator, because of the small decrease in value of B_s. Fe(Fe-C)/CoNbZr [43, 46] and FeRhN/CoZrCr [47] films have also been reported.

6.4 High-Performance Soft Magnetic Alloy Films Prepared by Electrodeposition

Soft magnetic thin films with high B_s and/or high ρ prepared by electrodeposition are shown in Fig. 6.13. Soft magnetic films prepared by electroless deposition are also discussed in this section.

6.4.1 NiFe Alloy and NiFe-Based Alloy Films

Electroplated permalloy films for use as thin-film heads are based on the technology of magnetic wire memory developed in the 1950s. Ever since IBM applied the

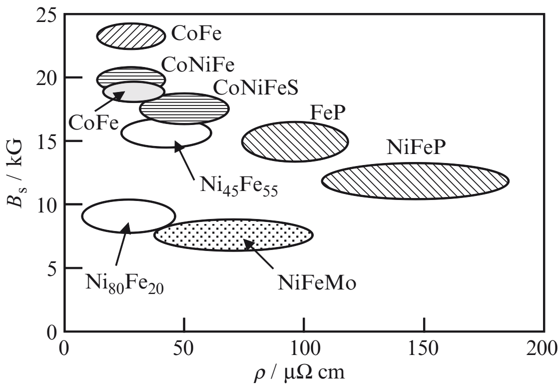


Fig. 6.13 Soft magnetic thin films with high B_s and/or high ρ prepared by electrodeposition

electroplated $Ni_{80}Fe_{20}$ permalloy to the thin-film head, electrodeposited permalloy films are being widely used , even though alternative soft magnetic films are available with high values of B_s [3]. This is because the electrodeposited permalloy film has several advantages, such as a high B_s (=10 kG), high permeability (3,000–5,000), near-zero magnetostriction, and high corrosion resistance. However, it is difficult to prepare the electrodeposited NiFe alloy films because their magnetic properties are very sensitive to the composition. Furthermore, maintaining constant composition is very difficult because of the serious problem of Fe-based plating, known as anomalous co-deposition [48–50]. Romankiw solved this problem by using the paddle plating cell system and the frame plating method [7, 8].

Though $Ni_{80}Fe_{20}$ permalloy has superior properties for magnetic recording head core, the film has low resistivity (20 μΩcm). Therefore, some researchers have reported permalloys with high resistivity, such as Moco-deposition permalloys [51]. Reports also indicate that an increase in the resistivity can be achieved by co-deposition with metalloid-forming elements, such as sulfur, carbon, or phosphorus [52, 53]. The inclusion of impurities is said to result in an increase in resistivity. $Ni_{45}Fe_{55}$ permalloy had been widely used for write head core because the film has high B_s value (14–16 kG). $Ni_{45}Fe_{55}$ permalloy co-deposited Mo or Cr is also reportedly in use [54].

6.4.2 CoNiFe Alloy Films

CoFe alloy has a high B_s value; and $Co_{90}Fe_{10}$ bulk alloy shows both a high B_s (=19 kG) and a low H_c (<2 Oe) [16]. There have been several reports on the preparation of soft magnetic CoFe films and the development of a magnetic recording head using CoFe alloy. However, CoFe alloy has poor corrosion resistance; thus, CoNiFe ternary alloy has been the focus of research because of its high value of B_s and high

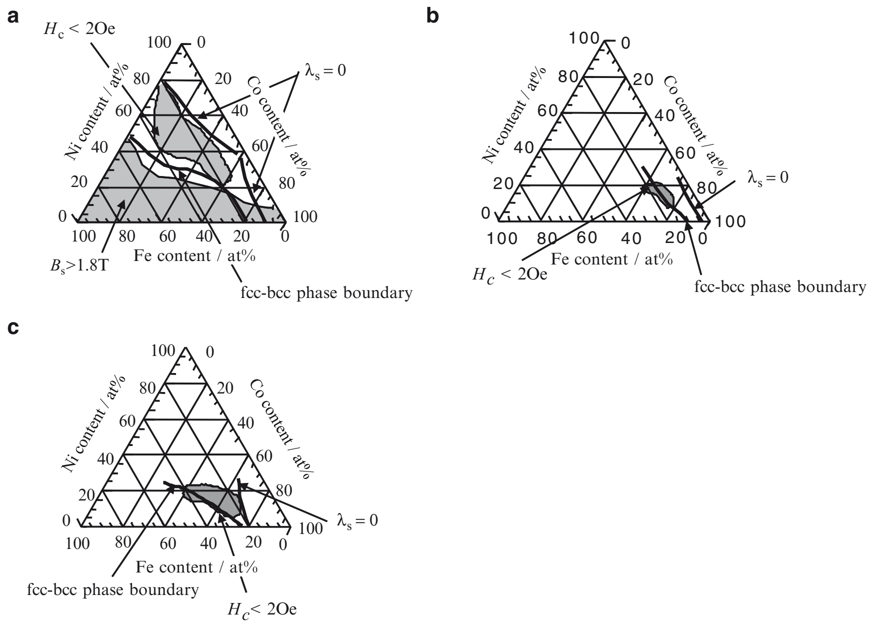


Fig. 6.14 Magnetic properties and fcc-bcc phase boundary of electrodeposited CoNiFe from saccharin bath (**a**), CoNiFeS from thiourea bath (**b**) and high B_s CoNiFe from additive free bath (**c**) [29]. © 1998 IEEE

corrosion resistance. For the composition used, CoNiFe alloys do not have a low H_c, and it is believed that the use of additives is necessary for decreasing H_c. Preparation of CoNiFe films deposited from the saccharin contained bath had been reported in 1994 [18]. There have been several reports on the preparation of CoNiFe soft magnetic thin films using the baths containing additives [17–19]. CoNiFe films prepared from the bath containing thiourea have a high $B_s = 17$ kG and low $H_c = 0.7$ Oe because of small grains cased by sulfur impurities from thiourea (Fig. 6.14) [20, 21]. The first CoNiFe soft magnetic thin films with the highest reported B_s value of 20 kG, and developed using a bath without additives were reported (Fig. 6.14) [28]. These new films had a fine bcc-fcc mixed crystal structure, and a low value of H_c was realized by this crystal structure (Fig. 6.15) [28–31]. This film has bcc-fcc mixed crystalline structure, and therefore, it is suggested that crystal grains with different crystalline structure from each other act as the inhibitor. Moreover, new heads using these high-B_s CoNiFe films show superior write performance compared with heads using conventional magnetic thin films [28, 30, 55, 56]. Therefore, some researchers have reported soft magnetic CoNiFe film with high resistivity. Mo-codeposition CoNiFe are also reported [57, 58]. Moreover, it has been reported that an increase in the resistivity can be achieved by co-deposition with a metalloid-forming element such as sulfur [20, 21] or carbon [59, 60]. It is suggested that the inclusion of impurities can result in an increase in resistivity [61].

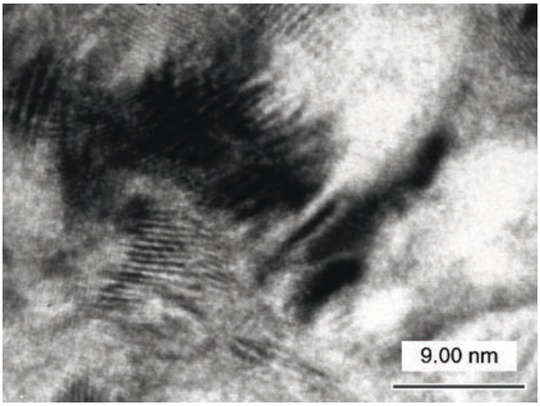


Fig. 6.15 High-resolution transmission electron micrograph of the electrodeposited high B_s CoNiFe thin film [28]

6.4.3 CoFe Alloy Films and its Preparation Technology

$Co_{35}Fe_{55}$ binary alloy is known as a material with B_s of about 24 kG, which is close to the limiting value achievable with ferromagnetic alloys. Several soft magnetic thin films with the highest B_s value of 24 kG have recently been prepared by using a dry sputtering process, e.g., NiFe/CoFeN/NiFe trilayer film [40, 41] and Co–Fe–Al–O granular film [42]. However, thin films containing only Co and Fe do not exhibit soft magnetic properties. Electrodeposited soft magnetic thin films of CoFe binary alloy with the highest B_s of 24 kG are now in strong demand. However, CoFe films with a value of B_s as same as that of bulk alloy cannot be obtained using the conventional electrodeposition method (Fig. 6.16) [62, 63]. To clarify the reason for the low B_s value of the electrodeposited CoFe films compared with that of the bulk alloy, the state of Fe ions was analyzed [62, 63]. As a result, the ratio increased dramatically after electrodeposition in the conventional bath and Fe^{2+} could be oxidized to Fe^{3+} at the potential of the anode during electrodeposition [64]. Thus, it is suggested that Fe^{3+} was produced by the anodic reaction. Moreover, the solubility product constant, K_{sp} of $Fe(OH)_3$ is very low, 66×10^{-38} [65]; therefore, Fe^{3+} must have formed $Fe(OH)_3$ at the surface during electrodeposition because the pH near the surface during electrodeposition increased to a value above 2.3. Thus, $Fe(OH)_3$ is *assumed* to be present in the outer shell of the deposit, and it is suggested that the adsorbed $Fe(OH)_3$ is included into the film, and that the inclusion causes the decrease in B_s value. Confirmation of the *presence* of Fe^{3+} is important for understanding the electrodeposition of Fe and Fe alloy films.

A $Co_{35}Fe_{65}$ film was electrodeposited from a bath containing trimethylamineborane, TMAB to suppress the oxidation of Fe^{2+} in the plating bath. It is suggested that the addition of TMAB completely suppressed the formation of Fe^{3+} in the bath *before* and *after* the electrodeposition. As shown in Table 6.1, the $Co_{35}Fe_{65}$ thin film deposited from the TMAB bath exhibited a B_s value of 23 kG, which was higher than that of the film deposited from the conventional bath. It is suggested that $Fe(OH)_3$ inclusion was suppressed with the decrease in Fe^{3+} concentration.

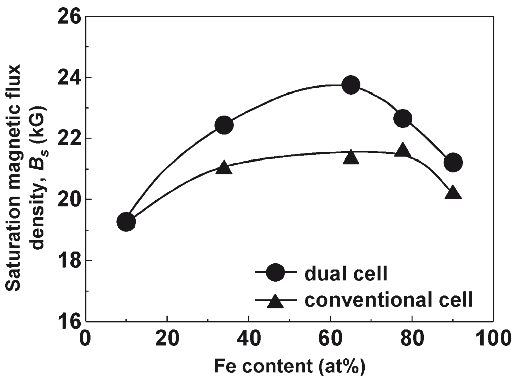


Fig. 6.16 B_s value of electrodeposited Co-Fe thin films as a function of Fe content

Table 6.1 B_s and H_c values of electrodeposited high moment CoFe thin films

	Conventional bath	TMAB bath	Bath used with dual cell system
B_s/kG	20	23	24
H_c/Oe	15	14	15

However, the B_s value of this film was still lower than 24 kG. This result is attributed to the presence of about 0.3% of boron in the film.

An improved electrodeposition cell system was investigated for suppressing the oxidization of Fe^{2+}. A separated compartment dual cell system was used, in which the anode and cathode cells were separated from each other but electrochemically connected using a salt bridge. A 0.1 mol dm^{-3} H_2SO_4 solution was used in the anodic cell. With this cell system, the oxidization of Fe^{2+} could not occur at anode because the anode cell did not contain any metal ions. From the result of iodometric analysis, it is seen that the concentration of Fe^{3+} ion did not increase after electrodeposition. As shown in Table 6.1, the B_s value of the $Co_{35}Fe_{65}$ thin film was about 24 kG, which was equal to that of bulk $Co_{35}Fe_{65}$ alloy. This result indicates that the film did not contain $Fe(OH)_3$ because of the low Fe^{3+} concentration. As shown in Fig. 6.16, the B_s values of the CoFe thin film with various Fe content were equal to that of bulk CoFe alloy. This result also indicates that the film did not contain $Fe(OH)_3$ because of the low Fe^{3+} concentration.

6.4.4 High-Performance Soft Magnetic Alloy Films Prepared by Electroless Deposition

Electroless deposition has been widely used for preparing magnetic thin films as described above. Note that this process is advantageous for depositing films onto a

Table 6.2 Magnetic and electrical properties of electroless-deposited soft magnetic thin films

Properties	Electroless-deposited films (at %)			
	$Ni_{70}Fe_{27}B_3$[a]	$Co_{96}B_4$[b]	$Co_{89}Fe_9B_2$[a]	$Co_{77}Ni_{13}Fe_9B_1$[a]
H_c/Oe	0.5	0.5	0.7	1.2
B_s/kG	10	14	16–18	15–17
μ [at 1 MHz]/–	1,000	400	650	600
H_k[as-deposited]/Oe	10	50	30	20
stability of heating/°C	400	300	400	–
ρ/μΩcm	40	–	30	40
$\lambda_s \times 10^{-6}$/–	+5.0	−1.0	+5.4	+2.0
Crystal structure	fcc	hcp	fcc	fcc

[a]Substrate: Cu(50 nm)/Ti(5 nm)/glass and Film thickness: 1.0 μm
[b]Substrate: Cu(50 nm)/Ti(5 nm)/glass and Film thickness: 0.7 μm

fine, selective area of a non-conductive surface. Magnetic and electrical properties of electroless-deposited soft magnetic thin films are shown in Table 6.2. Compared with electroless soft magnetic thin films such as NiFeP, CoNiP and CoP [66, 67] prepared from baths containing $NaHPO_2$ as the reducing agent, the films such as NiFeB [22, 23], CoB [24], CoFeB [25, 26] and CoNiFeB [27] prepared from baths containing dimethylamine-borane (DMAB) have higher B_s values, because of the difference in crystalline structure and codeposited elements between the two different classes of films. It is suggested that the formation of a fine crystalline microstructure or an amorphous-like phase results in a low H_c value, which probably is caused by the co-deposition of boron in the film. Soft magnetic thin films with magnetic properties similar to those of electrodeposited NiFe and CoFe can thus be obtained by electroless deposition using DMAB as the reducing agent. In particular, the CoNiFeB film has good magnetic properties and is suitable for use in a magnetic recording head. Electroless CoNiFeB films with high resistivity were also reported [68]. It is suggested that the inclusion of impurities such as carbon can result in an increase in resistivity.

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