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Technical Note 247

SURVEY OF MAGNETIC THIN FILM MATERIALS

GEORGE W. REIMHERR

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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A Survey of Magnetic Thin Film Materials

by

George William Reimherr

This survey lists the materials reportedly made as a magnetic thin film, along with some of their properties and potential applications. Research activity using the less-frequently mentioned magnetic film materials is noted. About 200 references are cited.

1. Introduction

The growth of activity in magnetic thin film research is indicated by the increasing number of papers published in this field. For example, the Magnetic Materials Digest series 1/ lists 26 papers in 1958, 33 in 1959, 70 in 1960, 131 in 1961, and at least 180 papers in 1962 that concern magnetic thin films. Much of this activity, both for research and for practical applications, has been with the nonmagnetostrictive 81Ni-19Fe permalloy composition. However, a sizable activity has concerned other compositions, particularly as fabrication techniques become better known.

This survey lists some of the properties, interesting features, and proposed applications of the various magnetic film materials. Research activity with the lesser-mentioned magnetic film materials is included.

2. Structure and Magnetic Properties of Materials Reported as a Magnetic Thin Film

The Key to Table I

The following items represent the various column headings of Table I, in the order of their appearance. All values (except Curie temperature) are given for about 20° C.

1/ References (100) through (103).

1. Materials. These are the materials reportedly made in the form of a magnetic thin film. In a few cases, the source composition rather than the film composition is given; these cases are noted by the words "source composition." - Magnetic films are prepared by a variety of techniques, including vacuum evaporation, electrodeposition, electroless deposition, and sputtering. Substrates are generally of glass or of metal such as aluminum, copper, gold, etc., although such materials as mica, MgO, NaCl, etc., are also used.

2. Structure. The structure type is listed, along with the lattice constants (a, c).

3. Curie temperature. Units are in degrees Celsius (°C).

4. M_s. This is the saturation magnetization, defined (in the cgs-emu system) as $\frac{B - H}{4\pi}$ for very large H.

5. H_c. This is the coercive force reported for the material as a magnetic thin film. Specific examples are sometimes given in cases where a typical range of values is not readily available.

6. H_k. This is the anisotropy field of the film. (See remarks for H_c, above.) A few materials have no magnetic anisotropy and are therefore listed as isotropic.

7. K_1. This is the crystalline anisotropy constant of the material.

8. λ_s. This represents the saturation magnetostriction of the polycrystalline material.

9. References. The reference sources are listed in parentheses (1) ... (201). The selected bibliography appears at the back.

3. Other Abbreviations

1.	Å	Angstrom unit
2.	(b)	value measured on bulk material [2]
3.	bcc	body centered cubic
4.	cc	cubic centimeter
5.	(f)	value measured on film material [2]
6.	fcc	face centered cubic
7.	hcp	hexagonal close packed
8.	hex	hexagonal
9.	H_w	wall coercive force
10.	oe.	oersteds
11.	ref	reference
12.	temp	temperature
13.	wt.	weight
14.	µsec.	microseconds
15.	~	about, approximately

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[2] In Table I, values given for the lattice constants, Curie temperature, and M_s, were generally measured on the bulk material; values for K_1 and λ_s were measured on bulk (b) or on film (f), while values of H_c and H_k were measured on the film material. Values measured on the bulk material for the lattice constants, Curie temperature, M_s, K_1, and λ_s, are generally considered applicable to the thin film also[3] except possibly (for the ultra-thin film --- < ~ 30 Å thick). However, values given for H_c and for H_k are unique to the thin film, because of their strong dependence on how the film is made.

[3] Although this has not been verified in every case.

Table I. Structure and Magnetic Properties of Materials Reported as a Magnetic Thin Film

Note to Accompany Table 1

To convert the given cgs-emu values to the International System (SI),

(1) Multiply the number of oersteds by 79.58 (= 1000/4π) to express H in amperes per meter, (2) Multiply the value of the magnetization in gauss by 0.001257 (= $4\pi\ 10^{-4}$ to obtain the magnetic polarization (intrinsic induction) in teslas.

Material	Structure	Curie Temp. (°C)	M_s (gauss)	H_c (oe.)	H_k (oe.)	K_1 (ergs/cc)	λ_s
1a Iron - bcc	bcc a = 2.861 Å (1) (2)	770 (1) (3)	1714 (1) (3)	values from ~10 (4) up to several hundred (5) see comments also	----	$+4.5\mathrm{x}10^5$ (f) (6) $+4.6\mathrm{x}10^5$ (b) (3) $+4.9\pm0.1\mathrm{x}10^5$ (f) (4)	$-7\mathrm{x}10^{-6}$ (7) (8)
1b Iron - fcc	fcc a = 3.588 Å at room temp. (9)	Néel temp. uncertain; see comments		see comments			
2a Nickel (fcc)	fcc a = 3.517 Å (2) a = 3.524 Å (10)	358 (1) (3)	484.1 (1) (3)	10 to 35 (11) another ref: (12), Fig. 6	example: 4 to 12 (13)	$-3.6\mathrm{x}10^4$ to $-4.5\mathrm{x}10^4$ (f) (6) $-4.6\mathrm{x}10^4$ (f) (14) $-5.5\mathrm{x}10^4$ (b) (15)	$-34\mathrm{x}10^{-6}$ (7) (8) (16)
2b Nickel (hcp)	hcp a = 2.66 Å c = 4.29 Å (2)			see comments			
3a Cobalt (hcp)	hcp a = 2.514 Å c = 4.105 Å (2)	phase change occurs below Curie temp.	1422 (3)	examples: 35 (17) 40 (18)	----	$5.3\mathrm{x}10^6$ (b) (3) general ref. for bulk: (19)	$-70\mathrm{x}10^{-6}$ (b) (3) ref. for polycrys. cobalt: (20)
3b Cobalt (fcc).	fcc a = 3.554 Å (2) a = 3.56± 0.01 Å (21)	1130 (1) 1131 (3)	(~1420) ref. for temp. above 500°C: (19)	----	----	ref. for bulk: (19) ref. for films: see comments	see comments

Material	Structure	Curie Temp. (°C)	M_s (gauss)	H_c (oe.)	H_k (oe.)	K_1 (ergs/cc)	λ_s
4 Gadolinium	hcp a = 3.622 Å c = 5.748 Å (22)	16 (1) (3) 17 (23) (24)	0 (paramagnetic at room temp.)	----	----	ref. (25) (b)	some mention in ref. (26)
5 MnBi	hex. a = 4.287 Å c = 6.126 Å (27)	360 (3) (27)	620 (3)	high, probably several thousand; see section on magnetic thin film papers.	----	$9.1x10^{6}$ (27) other ref.: (28)	$800x10^{-6}$ (27) other ref.: (28)
6a 81Ni-19Fe	fcc a = 3.54 Å (1)	~ 585 (1)	~ 800 (1)	0.5 to 5.0; typically $0.5H_k$ to $0.9H_k$ (29)	2.5 to 5.0; typically ~3. (29)	$-1.6x10^{3}$ (f) (6)	nearly nonmagnetostrictive alloy (b);(f) (29)
6b 50Ni-50Fe	fcc a ~ 3.58 Å (1)	~ 500 (3)	~ 1270 (1) (3) (30)	example: ~10 to 20 for 45% permalloy films (18)	----	$33x10^{-3}$ (b) (1)	$\sim 26x10^{-6}$ (30)
6c 3Ni-97Fe	bcc a~2.862 Å (1)	~ 770	~ 1735 (1)	14.5 to 16 (32) 15 (rod) (33) 9 (waffle-iron) (31)	magnetically isotropic alloy (31) (32)	----	should be near zero
7 Ni-Fe-Al	ref.; (1), p 386 for the phase diagram.	----	----	see section on thin film papers			

Material	Structure	Curie Temp. (°C)	M_s (gauss)	H_c (oe.)	H_k (oe.)	K_1 (ergs/cc)	λ_s
8a 80Ni-17Fe-3Co (source composition)	fcc (1)	~590 (1)	~835 (1)	3.9 (29) 5.0 (34)	6.0 (29) 5.5 (34) 2.5 to 3.0 oe. are possible (35)	----	nonmagnetostrictive film (29)
8b 57Ni-13Fe-30Co (source composition)	fcc (1)	~760 (1)	~1000 (1)	see ref. (36)	30 (36)	----	nonmagnetostrictive film (36)
8c 48.6Ni-2.8Fe-48.6Co (source composition)	fcc (1)	~830 (1)	~1000 (1) ~1030 (37)	10 (H_w) (37)	30 (37)	----	zero magnetoelastic sensitivity (37)
8d 45Ni-30Fe-25Co (perminvar) (approx. source composition)	fcc (1)	~720 (1) 715 (3)	~1260 (1) 1230 (3)	example: 6.9 to 7.5 (38)	example: 38-42 (38)	believed to be small - (1) p 571	$12x10^{-6}$ (b) (1)
9 Ni-Fe-Cr	fcc (1) (39)	ref.: (1), p 149	ref.: (1) p 150	~1 (H_w) (39)	~1 to 6 (39)	----	----
10 Ni-Fe-Cu	ref.: (1), p 154	ref.: (1) p 155	ref.: (1) p 156	----	----	----	----

Material	Structure	Curie Temp. (°C)	M_s (gauss)	H_c (oe.)	H_k (oe.)	K_1 (ergs/cc)	λ_s
11 Ni-Fe-Mo (some specific examples noted)	fcc (1)	ref.: (1) p 135 example: 460°C for 4-79 permalloy (3)	ref.: (1), p 136 example: ~690 Gauss for 4-79 permalloy (3)	0.7 (17) 0.6 to 4.3 (40)	2.2 to 50 (40) ~1.0 for 2% Mo-permalloy (29)	nearly zero for 4-79 Mo-permalloy (29)	nearly nonmagnetostrictive for 4-79 Mo-permalloy (29)
12 Ni-Fe-P	----	----	----	0.1 to 1.4 (41) see section on thin film papers	0.9 to 1.4 (41)	----	films are generally nonmagnetostrictive (41)
13 Fe-Al (22 to 25 atomic % Al)	bcc a~2.89 Å (1) (42)	ref.: (3), p 5-172; (43), p 837; (44)	~950 (1)	----	----	ref.: (b) (43)	----
14a 50Fe-50Co (source composition)	bcc a~2.85 Å	980 (3)	~1950 (3)	----	----	-70×10^{-3} (3)	67×10^{-6} (1)
14b 5Fe-95Co	----	~1090 (1)	~1460 (1)	high coercivity (29)	values about 10 times that of 81Ni-19Fe films (29)	----	(small) ref.: (1), Fig. 13-92
15 Ni-Cu	fcc (f) (45) ref.: (1), p 309	ref.: (1), p 308-310 also (46)	ref.: (1), p 310; (46)	----	----	ref.: (1), p 573; (3), p 5-190	----

Material	Structure	Curie Temp. (°C)	M_s (gauss)	H_c (oe.)	H_k (oe.)	K_1 (ergs/cc)	λ_s
16 Ni-Pd	fcc (f) (45)	ref.: (3), p 5-173		----	----		ref.: (b) (47)
17 Ni-alloys (other)			see section on thin film papers				
18 Co-Cu			see section on thin film papers				
19 Co-Ni	hcp or fcc; ref.: (1), p 277	ref.: (1), p 277	ref.: (1), p 279	may be high, e.g., 100 to 200; see e.g., (48), Fig. 5	----	ref.: (b)+(f): (6) other ref.: (b) (49)	ref.: (1), p 672; see comments
20 Co-P	hex. (50)	----	see comments	50 to 1300 (51) further ref.: (52)	----	----	----
21a Co-Ni-P (low coercivity electroless films)	----	----	some discussion in (53)	values from 0.3 to ~100 noted (53)	values from 2.0 to ~25 noted; (uniaxial) (53)	----	----
21b Co-Ni-P (high coercivity electrodeposited films)	hcp + fcc mixture (54) (55) (56) hex (57)	----		values from ~300 (56) to ~1000 (58); see comments 400 to 1000 (59)	isotropic in the film plane (54) (55) (56) (58) (60)	high (57)	uncertainty exists (54) see comments

Material	Structure	Curie Temp. (°C)	M_s (gauss)	H_c (oe.)	H_k (oe.)	K_1 (ergs/cc)	λ_s
22 Ferrite Films; data given for a typical example: $NiFe_2O_4$ (film)	cubic; a = 8.34 Å (61) inverse spinel	585 (3)	270 (3)	example; minimum value 40 (62)	----	-63×10^{3} (3)	-26×10^{-6} (3)
23 Garnet Films; data given for a typical example: $Y_3Fe_5O_{12}$ (YIG) (film)	cubic a = 12.374 ±0.005 Å (63)	278 ± 2 (63)	~138 (64)	this film type is mentioned in reference (65)		$\sim 7.1 \times 10^{3}$ (66)	-2.22×10^{-6} (67)

4. Additional Comments

The following are a series of comments to supplement the data of Table I.

1a. Iron - bcc

Ironfilms occasionally require fairly large drive fields for magnetization reversal. Coercive forces of several hundred oersteds are not uncommon, and values approaching 1000 oe. have been reported (68). Reincke (69), however, exceeds this. He prepared single crystal films of iron by evaporation onto heated rock salt crystals. Two films of 25 - 30 Å reportedly showed rectangular hysteresis loops and a coercive field of 4000 oe. A smaller coercive field of 1700 oe. was found in 2 other films 75 to 100 Å thick (70).

Various authors have commented on the oxidation of iron thin films; for example,

> Knorr and Hoffman (71) found that upon removal from the vacuum system, their iron films displayed a bright, shiny, metallic appearance, and have retained this luster for 2 years. This results from the oxide layer that quickly forms on pure iron. Electrical resistivity measurements indicated that most of the oxidation occurs immediately upon exposure to atmospheric pressure, with very little further oxidation occurring.

Rosette and Hoffman (72) noted an increasing amount of oxidation with decreasing film thickness, in their iron films. This oxidation occurred in spite of a coating of MgF_2. Koenig (73) found that iron films deposited on substrates held at 300°C did not oxidize appreciably when exposed to the atmosphere. Possibly a thin, passivating oxide layer is formed at the film surface that prevents further oxidation (74).

Single crystal iron films can be grown onto the (001) surface of either NaCl or MgO crystals. The lattice misfit of iron on NaCl is 28%, whereas it is only 4% in the case of iron on MgO (15). The orientation of crystallites is almost perfect for iron on MgO when the substrate is held above some critical temperature during the deposition (75). However, the orientation of iron films on NaCl is poor over the entire temperature range from 20 °C to 500 °C (75). A mixture of orientations occurs when iron films are grown on the cube faces of rocksalt (12). The mode of epitaxy of iron on MgO is given by

$$(001)_{Fe} \parallel (001)_{MgO}$$

$$[100]_{Fe} \parallel [110]_{MgO}$$

Therefore, the (001) plane of iron, which contains 2 easy axes of magnetization, coincides with the plane of the film (76).

1b. Iron-fcc

1. The face-centered cubic form of iron (γ-iron) is stable in the temperature range between 910 °C and 1390 °C (77). There is a volume increase of ~ 1% as bcc iron changes to fcc iron at 910 °C (78). The transformation temperature drops continuously with increasing pressure, down to 605 °C at 100,000 atmospheres (79).

2. It is difficult to study the magnetic properties of fcc iron at low temperatures because of the phase change that would occur. However, 2 approaches to keep iron in the fcc phase at low temperatures have met with some success.

One method is to alloy the iron with certain other metals, such as chromium and nickel as in stainless steel. This widens the stability range and preserves the structure to very low temperatures. However, the other elements, particularly the chromium, may affect the measured values of Neel temperature (77).

The other approach is to form a metastable γ phase by precipitating iron from a solid solution in certain materials - e.g., in copper, where iron precipitates as an iron-rich fcc phase coherent with the copper matrix. Further details appear in the literature (9) (77).

3. The magnetic properties of fcc iron may be summed up thusly:

a. At high temperatures, γ iron is paramagnetic in its region of thermodynamic stability and obeys the Curie-Weiss relation (77).

b. Neutron diffraction studies gave no evidence of an ordered magnetic state at either room temperature or at 77 °K (9).

c. At very low temperatures, γ iron is antiferromagnetic. The exact Néel temperature is uncertain, with estimates varying from ~8 °K (9) up to 67° ± 2 °K (77).

2a Nickel-fcc

1. A noncrystalline film of nickel may be formed.

a. Electroless nickel, formed by hypophosphite reduction from acid solution, is reportedly nonmagnetic and amorphous (59).

b. Films evaporated from high purity nickel onto glass substrates held at ambient temperatures were reportedly often amorphous (80); however, heating these films at 450 °C for 30 minutes resulted in the formation of the cubic structure.

2. Nickel films are apparently subject to oxidation. Mitchell (81), p. 356 remarked that a clean nickel surface will be oxidized to a depth of roughly 20 Å, even at low temperatures, when exposed to air --- probably whether or not it is protected by a film of silicon monoxide. Neugebauer (16) observed that the magnetization of his ultra-thin nickel films changed fairly quickly when he opened his vacuum system to air.

3. Sincle crystal nickel films can be grown epitaxially by vapor deposition onto (001) surfaces of NaCl or MgO crystals. The lattice misfit is 38% for nickel on NaCl, and 16% for nickel on MgO (15). The orientation of crystallites is almost perfect for nickel on NaCl, or on MgO, provided that the substrate is held above some critical temperature during the deposition (75).

Nickel films grown epitaxially on NaCl at elevated temperatures were shown to exist in a highly strained condition while on the substrate, resulting in a tetragonal distortion of the cubic symmetry of the film (10). Nickel films grown onto MgO were found very difficult to remove from the substrate (15).

The condition (mode) of epitaxy for nickel films on the cleaved surface of MgO crystals is the same as for fcc-cobalt (76).

2b. Nickel-hcp

Efforts to prove or to disprove the existence of a hexagonal phase in specially prepared nickel films have prompted a number of papers and comments. These are included in the section on magnetic thin film papers. Interestingly, Wyckoff (82) states that the cubic modification of nickel (β-Ni) can be made hexagonal (α-Ni) by annealing for several days at 170 °C. (Probably bulk nickel is meant.)

3a. Cobalt-hcp

1. The hcp phase of cobalt is stable below ~420 °C, while above this temperature, the fcc phase is the more stable one. However, both phases may appear in the same cobalt specimen. Prutton (83) notes that both phases have been detected in specimens of bulk cobalt, Williams and Sherwood (17) report that their cobalt film had approximately equal proportions of hexagonal and cubic crystals, with no preferred crystal orientation. Heavens (12) noted that his cobalt films, epitaxially grown on rocksalt crystals, generally consist of mixtures of the 2 forms, even when deposited at temperatures above 500 °C.

2. Cobalt is uniaxial at room temperature, with the c-axis being the easy direction of magnetization, and all directions in the basal plane being (~equally) difficult directions of magnetization. At higher temperatures (e.g., between about 245° and 325°C, ref. (84)), the directions of easy magnetization lie on a cone around the c-axis. At still higher temperatures, (~300°C), the preferred direction lies in the basal plane.

3. The crystalline anisotropy constant, K_1, is strongly temperature dependent. A 20°C rise in temperature above room temperature (which might occur during observation of the specimen in the electron microscope) may reduce K_1 by as much as 10% (85).

4. Grundy and Tebble (86), using a cobalt foil about 1000 Å thick, noted the change in domain pattern in a hcp crystal, between room temperature to about 300°C. These changes are related to changes in value and sign of the crystalline anisotropy constant, and to rotation of the easy axis of magnetization. Bates and Craik (87) reported finding complex closure domain patterns on the basal plane of a cobalt crystal.

3b. Cobalt-fcc

1. The fcc phase of cobalt is stable above ~420°C. In hcp cobalt, adjacent layers of atoms in (00.1) planes are displaced with respect to each other, but the pattern repeats every second layer. In cubic cobalt, the (111) planes are similar to those of the (00.1) planes of hexagonal cobalt, but the succession of planes is different so that in the cubic structure the pattern repeats after every third layer (1). The mechanism of the hcp-fcc crystallographic phase change is given e.g., in ref. (19), p 371. The similarity in the 2 structures goes hand in hand with the small heat of transition (1). Also, there is a fairly large temperature hysteresis in the phase transformation.

2. Magnetization curves of fcc cobalt crystals in the temperature range 500° to 1000°C were found to be similar to those for nickel, in that the crystallographic directions in order of increasing difficulty of magnetization are [111], [110] and [100], and the fields required to produce saturation are only of the order of a few hundred oersteds. The material became magnetically isotropic at ~1000°C (19).

3. There are few reports on the magnetostriction of cobalt at high temperatures because of experimental difficulties (88).

4. Films of fcc cobalt can be prepared by epitaxial growth onto a freshly cleaved Mg0 crystal heated above ~430°C. This fcc structure is retained at low temperatures as long as the film stays on the substrate (76).

The mode of epitaxy of fcc cobalt on Mg0 is the following:

$$(001)_{Co} \parallel (001)_{Mg0}$$

$$[100]_{Co} \parallel [100]_{Mg0} \qquad (76)$$

The easy directions of magnetization of fcc cobalt crystals are <111>; no change was observed over the temperature range from room temperature to ~500 °C (86). However, in the case of fcc cobalt films on cleaved Mg0, the mode of epitaxy coupled with the thinness of the film causes the easy direction to rotate from the [111] direction to the minimum energy direction in the plane of the film - viz., [110] (76).

5. Doyle (21) observed biaxial anisotropy in the film plane of his fcc cobalt films. His values for K, the biaxial anisotropy constant, varied for different films from $-4.1 \pm 0.6 \times 10^5$ to $-6.2 \pm 0.9 \times 10^5$ ergs/cc, in fair agreement with the value of $-7.1 \pm 0.7 \times 10^5$ ergs/cc obtained by Rodbell (89) from ferromagnetic resonance. Doyle notes that K, the observed anisotropy constant, is not necessarily K_1, the fourth-order crystalline anisotropy constant (21).

4. Gadolinium

1. Gadolinium displays a broad and diffuse transition from the ferromagnetic to the paramagnetic state, with a consequently ill-defined Curie temperature near 300 °K (25). Recent studies (23) indicate that long range magnetic order disappears at 290 °K, in confirmation of previous measurements of magnetization, specific heat, and resistivity. However, the zero-field magnetization arising from short range order disappears only at ~300 °K, in agreement with expansivity and x-ray measurements (ibid).

2. Gadolinium displays a fairly large, strongly field-dependent apparent magnetocrystalline anisotropy that persists to temperatures at least 30 °C above the Curie temperature (25).

3. The easy direction of magnetization near the Curie temperature is along the c-axis, while at lower temperatures (near 77 °K), the basal plane becomes the preferred orientation of the magnetization (90). A recent investigation of a gadolinium single crystal by neutron diffraction indicated that it has magnetic moments aligned parallel to the c-axis above 248 °K, while below this temperature, the moments make an angle with the c-axis which reaches a maximum of 75° at 195° K and approaches 30° at 4° K (91).

4. A compound of gadolinium and bismuth, $Gd_4 Bi_3$, reportedly has a Curie temperature of 340 °K (24) -- appreciably above that of gadolinium.

5. Bitter patterns of ferromagnetic domains on a $(11\bar{2}0)$ face of gadolinium single crystal, taken at -5 °C, were recently reported)92). Bitter patterns of domains on gadolinium are difficult to obtain in this region of temperature, and none had previously been reported.

5. MnBi

1. The intermetallic compound MnBi (manganese bismuthide), at room temperature, has a magnetostriction which is the highest that has been found in any material except cobalt ferrite (28).

2. The anisotropy at room temperature is quite large -- about twice that for cobalt (1) -- but decreases rapidly with decreasing temperature (28).

3. The easy direction of magnetization lies along the c-axis of the hexagonal crystal, down to a temperature of ~84 °K. Below 84 °K, the magnetic moments may rotate to positions in the basal plane, though studies indicate this rotation to be incomplete (27).

4. In bulk form, MnBi is a permanent magnet material (Bismanol) having both high coercive force and high energy product. The bulk material reportedly corrodes easily when exposed to the atmosphere (93). Magnetic films of MnBi reportedly do not deteriorate when exposed to the atmosphere. These films have been suggested as a medium for high density information storage (94).

6a. 81Ni-19Fe Permalloy

1. Permalloys are a series of high permeability nickel-iron magnetic alloys. Two regions of composition are of particular interest -- the 50% nickel region, because the induction is at a maximum (thereafter decreasing with increasing nickel content), and the 81% nickel region, because of its low crystalline anisotropy and zero magnetostriction.

2. Most past research on magnetic films for use in computer memories has been confined to the 81Ni-19Fe composition, largely because of its nonmagnetostrictive property. This property is desirable for practical applications so that stresses applied to the film-bearing substrate by mechanical or thermal means do not adversely affect the magnetic properties of the films (29).

3. When 81 permalloy,~1000 Å thick, is deposited onto a glass microslide or cover-glass surface (free from scratches and other gross imperfections) at a uniform substrate temperature of 300 °C, a value of H_k ranging from 2.5 to 5 oersteds can be had, with an

angular dispersion, α_{90}, of 3 degrees or less (29). H_c typically varies from 0.5 H_k to 0.9 H_k, depending on various geometrical factors and deposition parameters (ibid).

4. In order to obtain zero magnetoelastic strain sensitivity in Ni-Fe films, the melt must be 83:17 or 81:19, depending whether an alumina or silica crucible is used (37). This indicates one reason why results vary between different research groups.

5. Permalloy films, protected from oxidation with a layer of Krylon (a proprietary acrylic ester resin solution) have been kept at room temperature for years without changes in H_c or H_k (29). However, very little work has been published on the effects of elevated temperatures and weak fields, under vacuum or in air (ibid). Early findings in an aging study designed to determine the reliability of thin nickel-iron films of 81%-19% composition appears in reference (99).

6. The orientation of crystallites is almost perfect for permalloy on NaCl when the substrate is held above some critical temperature during the deposition (75).

6b. 50Ni-50Fe Permalloy

1. Compared to 81Ni-19Fe, the 50Ni-50Fe permalloy composition has higher values of saturation magnetization, coercive force, and crystalline anisotropy. It also has appreciable magnetostriction.

2. The possibility of having appreciable compositional variation between the magnetic film and the starting material should be noted (18). In addition, permalloy compositions below ~ 50% nickel begin to show second phases.

3. The coefficient of expansion of ordinary microscope slides, which is probably in the range 8 - 10 x 10^{-6} per degree C, compares well with that of the 50Ni-50Fe alloy, which is about 9.7 x 10^{-6} at comparable temperatures (18).

6c. 3Ni-97Fe

1. Evaporated or plated permalloys tend to be anisotropic; however, experiments with the composition 3Ni-97Fe indicate that it could be electroplated onto a flat copper substrate with essentially isotropic properties (31).

2. A thin organic coating is used to protect the iron-rich magnetic film from corroding (33).

7. Fe-Ni-Al

Alloys containing nickel, iron, aluminum, perhaps cobalt, and perhaps small percentages of copper and/or titanium, form the class of permanent magnet materials known as alnicos. Some compositions are listed in, e.g., (3), p5-188.

8a. 80Ni-17Fe-3Co

1. This ternary alloy composition had been referred to as "gyralloy" in earlier publications (34).

2. The specific use of 3% cobalt (by weight) is reportedly a compromise between increasing values of H_k, and decreasing easy axis angle skew, with increasing cobalt content (34).

8b. 57Ni-13Fe-30Co

This ingot composition lies within the so-called "perminvar region" (1), Fig. 5-79 -- i.e., the region of Ni-Fe-Co compositions for which the typical perminvar characteristics can be developed.

8c. 48.6Ni-2.8Fe-48.6Co

Films made from this melt composition reportedly have small angular dispersion (37).

8d. 45Ni-30Fe-25Co

1. An alloy consisting of 25% cobalt, 45% nickel, and the balance, iron, corresponds to the usual perminvar composition (1). However, note that a wide range of alloy compositions in the Ni-Fe-Co system can exhibit perminvar properties (1), Fig. 5-79.

2. Perminvar characteristics include the following:

a. A low but constant initial permeability up to an induction as high as 1000 gauss or more, and virtually no hysteresis loss in this region (95).

b. A wasp-waisted, constricted, or perminvar hysteresis loop at intermediate values of drive field. The perminvar loop is usually a minor loop; when the major loop is traced, the constriction is absent or greatly reduced in magnitude (95). The perminvar loop may be modified or often eliminated by proper heat treatments.

8e. Ni-Fe-Co (other)

Cobalt, when added to nickel-iron alloys, raises the value of H_k, but generally lowers the value of H_c in the concentration range 0 to 30% cobalt in the film, and Ni/Fe ratio = 4.9 (48), Fig. 6. (Also see section on magnetic thin film papers.)

9. Ni-Fe-Cr

Chromium is particularly effective in lowering the Curie points of nickel-iron alloys, especially when the nickel content is high. This fact is often used in making non-magnetic alloys for special purposes (1).

11. Ni-Fe-Mo

1. Since molybdenum has a melting point that is so much greater than that of nickel and iron, it is very difficult to control the preparation of alloys of these three elements in thin films (29). Blois (18) discussed the probable compositions of evaporated films as compared to that of the starting material. In the case of 4-79 moly-permalloy (4Mo-79Ni-17Fe) maintained at 1600 °C, the theory indicated that the nickel would evaporate about 50% faster than the iron, but the molybdenum would scarcely evaporate at all. However, his results with Ni-Fe alloys indicated that the difference in composition between the film and the melt may be considerably less than indicated by this theory.

Williams and Sherwood (17) report a chemical analysis of a 150 Å film obtained by evaporating the alloy 5%Mo, 79%Ni, 16%Fe, using a helical tungsten filament, and a pressure of $\sim 10^{-5}$ mm Hg. The resulting film composition was 7%Mo, 57%Ni, 36%Fe.

2. Attempts to electroplate 4-79 moly-permalloy films have been disappointing (29).

3. Moly-permalloy films reportedly showed room-temperature ferromagnetism even at a composition estimated at 60% molybdenum (40). This is quite different from that reported for bulk, where the induction in high fields, at room temperature, decreases uniformly with increasing molybdenum content, and approaches zero at about 15% molybdenum (1), p. 136.

4. The composition 5Mo-79Ni-15Fe-$\frac{1}{2}$Mn, known as supermalloy, results in the highest permeability, lowest coercive force of any commercially produced material (7).

12. Ni-Fe-P

A few comments concerning the properties of Ni-Fe-P films appear in the next section on magnetic thin film papers -- e.g., reference (96).

13. Fe-Al

1. A tutorial description of the ordering processes in the aluminum-iron system is noted in reference (42), p. 144. A model is shown which indicates that, at the alloy composition corresponding to the formula Fe_3Al, for slowly cooled alloys, the centers of alternate small cubes of the bcc lattice are occupied almost completely by aluminum atoms, with the other positions in the lattice being occupied almost completely by iron atoms.

2. Although only one reference to aluminum-iron thin films has been noted, there have been a fairly large selection of papers concerning the properties of bulk aluminum-iron specimens. Interested readers may refer to, e.g., references (43) or (44) for bibliographies.

3. The composition Fe_3Al, containing 25 atomic percent aluminum, corresponds to about 13.83% aluminum by weight.

14a. 50Fe-50Co

1. A number of papers in the literature mention use of magnetic thin films of iron-cobalt. Two compositions are singled out for special mention here: 50Fe-50Co because it corresponds to the permendur composition, and 5Fe-95Co because of its reported use in a magnetic storage device.

2. The highest value of saturation induction for any magnetic material, 24,600 gauss (1), occurs at about 35% cobalt, 65% iron; however, the plot of saturation induction versus cobalt content is rather flat over the range 30% to 50% cobalt.

3. Supermendur is an alloy containing 2% vanadium, 49% cobalt, and remainder, iron. This is an improvement over the 50-50 alloy in everything except maximum induction (7).

4. See comment for 14c., Fe-Co (other).

14b. 5Fe-95Co

1. Iron-cobalt alloy films, such as 5Fe-95Co, oxidize even more rapidly than do films of 81-permalloy, unless they are protected by encapsulation. This occurs even for films 2000 Å thick (29).

2. An alloy composition 96.5%Co, 3.5%Fe, is reportedly nonmagnetostrictive (29).

3. A phase change from hexagonal to fcc occurs at about 95%Co, 5%Fe, at 200 °C (1), p. 15.

14c. Fe-Co (other)

Fairly large values of magnetostriction exist in the iron-cobalt alloy system. In moderately high fields, there is an unusually large expansion of 60 to 90 x 10^{-6} in alloys containing 40-70% cobalt. (A λ of 130 x 10^{-6} was observed in specimens of hard rolled tape containing 70% cobalt, 30% iron (1), p 664). The magnetostriction drops to near zero at near 90% cobalt.

19. Co-Ni

1. The magnetic properties of the cobalt-nickel alloys reportedly have no interesting peculiarities (1); they are rather the result of mixing 2 elements that are similar chemically and different magnetically, in that one has almost three times the saturation magnetization of the other.

2. Magnetostriction: See comment 2 in section 21b, (Co-Ni-P).

20. Co-P

1. The phosphorus content of these films may often be rather small; e.g., Sallo and Carr (51) used a phosphorus content in the deposit in the range of 2-3%. Fisher (97) had about a 4% phosphorus content in his cobalt coatings.

2. The following results were reported (51): The 60-cycle hysteresis loop of the electrodeposits at all coercivities within the test range (50 to 2000 oe) showed a squareness ratio (B_r/B_m) of about 0.5. Remanence values were about 5500 gauss for a 400 oe. deposit; however, full saturation may not have been reached.

21. Co-Ni-P

Films of Co-Ni-P can conveniently be divided into 2 categories. One category, designated as "21a", consists of electroless films which, (it turns out), usually have low values of coercive force. The other category, noted as "21b", consists of electrodeposited films which, though of similar composition, are known to possess very high coercivities (53). A recent bibliography of papers concerning Co-Ni-P films appears in reference (53).

21b. Co-Ni-P

1. Smaller flux outputs were obtained from both the Co-Ni-P and the Co-P deposits than would be expected from the chemical composition (51).

2. Bate and Speliotis (54), in discussing their hard films of Co-Ni-P, mention that the state of knowledge of magnetostriction even in bulk alloys of Co-Ni is chaotic.

3. The addition of phosphorus to Co-Ni alloys reportedly increases H_c of the deposit (48), Fig. 5.

4. These Co-Ni-P films, as well as the Co-P films, are usually relatively thick films, compared to typical permalloy memory films.

22. Ferrite Films; 23. Garnet Films

Tutorial articles on ferrites and garnets, and their actual or potential applications, are available in the literature -- e.g., (98).

5. Research Activity Using the Less Frequently-Mentioned Magnetic Thin Film Materials

This section describes some of the work published using the less frequently mentioned magnetic thin film materials. All categories are included except 1a, (Iron-bcc); 2a, (Nickel-fcc); 3a, (Cobalt-hcp); and 6a, (81Ni-19Fe). The latter-mentioned materials receive frequent mention in the literature; e.g., in the Magnetic Materials Digest series (100), (101), (102), (103), the writer noted about 46 papers mentioning iron films, 88 mentioning nickel films, and 26 mentioning cobalt films (some possibly fcc-cobalt). Tutorial type articles dealing mainly with 81-permalloy thin films are available in the literature - e.g. reference (104).

1a. Iron-bcc

See introductory comments to this section.

1b. Iron-fcc

Hasse (105) obtained very good thin (10 Å) epitaxial films of fcc iron by evaporating iron onto the (100), (110), and (111) faces of heated copper single crystals (100).

Koritka (106) reported that he was able to make γ-iron films up to 80 Å thick, stable at room temperature.

2a. Nickel-fcc

See introductory comments to this section.

2b. Nickel-hcp

Bonnelle and Jacquot (107) found by electron microscopy and diffraction, a hexagonal phase on annealing vacuum deposited nickel films (102). Trillat et al (108) made general observations concerning the transformation of fcc nickel to the hexagonal form. The hexagonal form reported by Bonnelle and Jacquot is questioned, since the lattice constants of Ni_3C and Ni_3N are so close to that found for hexagonal nickel, as seen below (70):

Material	a	c
Ni (hex) ?	2.63 ± 0.01 Å	4.32 ± 0.02 Å
Ni_3C	2.628	4.306
Ni_3N	2.660	4.304

Thin films of nickel reportedly were transferred from the fcc lattice into the hcp lattice as a result of fast neutron irradiation (109). All irradiated samples showed great changes in magnetic properties. The magnetic properties disappeared for the samples that completely transformed into the hcp structure. Gaertner (110) prepared nickel layers by cathodic sputtering. When atmospheres of spectroscopically pure nitrogen and tech. argon were used, x-ray diffraction lines of hexagonal Ni_3N appeared; however, these lines were not present in such layers formed in spectroscopically pure argon atmosphere. In the last case, the nickel lattice constant is 3.52 Å, which is that of pure nickel (70). The results suggest (102) that the extra electron diffraction lines, sometimes found in sputtered nickel, are probably caused by Ni_3N, and not by hexagonal nickel as reported earlier.

Morimoto and Sakata (111) evaporated nickel films with mean thickness about 10 Å, onto amorphous substrates. The evaporation and heat treatment were carried out in the diffraction camera. Although all diffraction patterns of these nickel specimens showed a fcc structure, anomalous neighbors of the hcp type were also found in the nickel crystallites.

Several investigators reported failure in efforts to find a hexagonal phase in nickel thin films. These include Neugebauer (16) who prepared thin nickel films (< 100 Å) in ultra high vacuum (~ 10^{-9} mm Hg.); Heavens (12) who grew epitaxial nickel films on rocksalt, and Adamsky and Sears (80) who prepared amorphous nickel films by evaporating pure nickel onto glass substrates held at ambient temperatures; however, they (80) note that no effort was made to study extremely thin films where possibly a hexagonal nickel structure is stable.

3a. Cobalt-hcp

See introductory comments to this section.

3b. Cobalt-fcc

L. Reimer (112) prepared thin cobalt layers by electrodeposition onto a copper surface. Electron diffraction showed the layers to have a purely cubic structure. A maximum in coercive force was found at 20° and at -190°, for thicknesses of 200 and 300 Å respectively. The corresponding coercive forces were 350 and 600 oe (70).

O.S. Heavens (12) found that cobalt films prepared on rocksalt generally consist of mixtures of hcp and fcc structures, even when deposited at temperatures above 500°C. Frait (113) made ferromagnetic resonance measurements on thin cobalt films that were vacuum deposited onto unheated glass slides. The line width and other resonance parameters were obtained as functions of film thickness. An fcc structure was found for films 600 and 1200 Å thick.

Tannewald and Weber (114) measured the exchange constant A, and exchange integral J, and their temperature dependencies, in evaporated cobalt films, using spin wave resonance. At room temperature, $A = 1.30 \times 10^{-6}$ erg/cm, and J = 155k (ergs). The results are compared with data obtained by other methods. The cobalt films showed a predominantly cubic structure, a uniaxial anisotropy of ~ 23 oe in the plane of the film, and a g factor and saturation magnetization close to that of the bulk.

Rodbell (89) prepared single crystal fcc cobalt films on Mg0 substrates. Standard ferromagnetic resonance techniques were used to determine the magnetocrystalline anisotropy parameters K_1/M and K_2/M over the temperature range 4.2 - 850°K.

Morimoto and Sakata (111) made structure studies of ultra-thin nickel films and cobalt films formed on amorphous substrates. These films, of average thickness 10 to 20 Å, are not continuous, but consist of small crystallites. The results for cobalt films deposited on 20°C substrates implied a possible mixture of hcp and diamond structures. Heating these films tended to favor the hcp structure. Cobalt films deposited on substrates at 450°C showed fcc type diffraction patterns that did not change when the films were cooled to room temperature.

Sato et al (76) observed a checkerboard domain pattern on a single crystal fcc-cobalt film epitaxially grown on a heated M_g0 substrate.

Grundy and Tebble (86) examined the domain structure in thin cobalt foils at temperatures above room temperature. The foils were 1000 Å thick, and contained both fcc and hcp phases. At higher temperatures, the domain pattern in the fcc regions was in agreement with anisotropy measurements.

Doyle (21) extended the Stoner - Wohlfarth coherent rotation model to the case of biaxial anisotropy, and compared some of the predictions with experimental results observed on fcc single-crystal cobalt films. The films were prepared by epitaxial evaporation onto the (100) face of single-crystal MgO slabs held at $\sim 400^\circ$C. Torque and rotational hysteresis measurements on these films yield some results in disagreement with the theory. It is concluded that the magnetization reversal process in single-crystal cobalt films is not coherent, and that noncoherent rotations or wall motions must be investigated.

4. Gadolinium

Holmes and McClung (115) prepared evaporated films of iron, nickel, cobalt, and gadolinium. Faraday rotation measurements for iron, nickel, and cobalt are reported. However, the gadolinium films did not show any rotation at temperatures as low as 77°K.

Wilburn (116) evaporated Er, Yb, Ho, Tb, Gd, and Tm on quartz and glass substrates as optical film surfaces. Vacuum evaporation techniques are discussed. Optical properties of these metals are presented (70).

Auphan (117) reported measurements of the Kerr magnetooptic effect made on thin films of gadolinium overcoated with a protective film of silicon monoxide. He observed that the effect diminished with temperature somewhat more slowly than expected (102).

Schüler (118) describes briefly the construction of an all-glass electron diffraction camera. It was found possible to obtain pictures of the clean surface of thin gadolinium films evaporated at a residual gas pressure of 10^{-9} mm Hg. inside the camera, and to follow the oxidation process taking place at somewhat higher pressure.

Schüler (119) lists measurements of the longitudinal Kerr effect on thin gadolinium films, prepared and measured in ultra high vacuum.

Schüler (120) presents a study of magnetoresistance in thin evaporated gadolinium films. The films were prepared in ultra high vacuum, and the temperature dependence of the resistivity was measured between 80°K and 450°K. Results are compared to that reported for bulk.

Schüler (121) examined the spin ordering effects in the electrical resistance of thin films of Gd, Dy, and Tb.

Lambeck et al (122) report the detection of the Faraday effect in thin evaporated layers of gadolinium. Hysteresis curves were obtained with the help of the Faraday effect and the Kundt constant.

The dc voltage generated across the surface of a thin magnetic film during ferromagnetic resonance provides a new and sensitive means of studying ferromagnetic resonance phenomena (123). Juretschke (124) reported on further studies of this effect, using thin films of nickel and of gadolinium.

A report (90) dated April 1963, noted that efforts to make thin film single crystals of gadolinium had not yet proven successful.

5. MnBi

Thin films of MnBi were reported (125) (126) in which the c-axis of the hexagonal crystallites (which is also the axis of easy magnetization) tends to be normal to the plane of the films. The films, ~1000 A thick, gave an optical rotation of ~ 5° for transmitted light, providing good visual contrast for observing the domains by means of the Faraday effect (95). It is possible to write magnetically on these films with a fine permanent-magnet probe, and to read the writing with the polarized-light technique.

Mayer (127) (128) suggested that writing could be done by heating a small region of the MnBi film above the Curie point, using an electron beam. On cooling, the fringing field from the surrounding film would cause this region to have a reversed magnetization. This process is called "Curie point writing". The direction of easy magnetization must be normal to the plane of the film; however, this is possible despite the large demagnetizing fields.

Mayer (94) found that writing speeds corresponding to 3 x 10^4 bits/sec., and information densities corresponding to 10^5 bits/cm^2 were achieved in first experiments using Curie point writing on MnBi films. Considerably higher writing speeds (10^6 bits/sec.) and some increase in information density (10^6 bits/cm^2) should be feasible (ibid). Readout is possible by use of the Kerr magneto-optic effect, or the Faraday effect, or electronically, by electron mirror microscopic methods. Two major difficulties were encountered with MnBi films (93). One difficulty is that of erasing, since this requires the application of several thousand oersteds. The other difficulty is the poor reproducibility in the preparation of these films -- e.g., films may turn out to be nonmagnetic, or to have, at least in part of the film, the direction of magnetization in the plane of the film, rather than normal to it. At least 2 papers (93), (129) have been concerned with the problem of reproducibility.

Chen and Gondo (130) examined the magneto-optic Kerr rotation and the crystalline anisotropy energy of MnBi films over the temperature range 84 °K to 300°K.

6a. 81Ni-19Fe

See introductory comments to this section.

6b. 50Ni-50Fe

This material was used occasionally in research on magnetic thin films. Blois (18), in his classic paper on the preparation and properties of thin magnetic films, noted the effects of annealing on the coercivity of a series of 50Ni-50Fe films. Rubinstein and Spain (131) prepared a film from a 50Ni-50Fe ingot for their studies of cross-tie walls in thin films. Fuller and Hale (132) mention use of a 50Ni-50Fe alloy film in their paper concerning the use of transmission electron microscopy to observe the magnetization pattern in magnetic thin films. Kirenskii et al (133) observed the domain configurations in films of Fe, 50Fe-50Ni, and 80Ni-17Fe-3Mo with the Kerr effect, from -15°C to 650°C (103). Fuller and Rubinstein (134) proposed methods using domains at a high density in a continuous film for storing information in compact, large-capacity memories. A wall-film interaction experiment is described using a multi-layered structure consisting of a relatively high coercive force (14 oe.) 50Ni-50Fe film, separated from a low coercive force (2 oe.) 80Ni-20Fe film by a film of MgF_2.

6c. 3Ni-97Fe

Kolk and White (33) discuss the effects of various deposition parameters on the resulting magnetic properties of 3Ni-97Fe thin film electroplate. Optimum magnetic properties were achieved for use in the Rod magnetic memory device.

Bobeck (31) reported use of this alloy composition in part of the cubic waffle iron memory device. When the 3Ni-97Fe material is electroplated to a thickness of 0.05 thousands of an inch, it has a coercive force of 9 oe., a squareness ratio of 0.95, and a switching coefficient (S_W) of 0.8 oe-µsec.

7. Fe-Ni-Al

Hodges (135) reported on a study into the influence of directional ordering on the anisotropy of magnetic thin films. Although most of his work appears to have been with aluminum iron alloy thin films, he observed that the anisotropy of permalloy films could be governed by an oblique incidence aluminum beam, and that the easy axis so formed could be made to lie orthogonal to the direction of an applied annealing field.

A typical example is mentioned in which a permalloy film containing near 3 atomic percent aluminum, had an equivalent anisotropy field aligned by the aluminum beam, of 22 oe., with an easy axis direction coercive force of 0.9 oe..

8a. 80Ni-17Fe-3Co

A number of papers have appeared recently mentioning use of Ni-Fe-Co films evaporated generally on an aluminum substrate,[4] from a starting ingot composition of 80%Ni, 17%Fe, 3%Co, by weight.

Bradley (34) considered the properties that magnetic films should have, in order to function successfully in computer memories. Particular importance is attached to reducing the easy axis dispersion. His considerations suggest use of this nonmagnetostrictive composition on an aluminum substrate as a possible compromise solution to the problem.

Leaver and Prutton (136) reported on inhomogeneous coherent magnetization rotation in these films. Leaver (137) noted the dependence of the easy axis dispersion on film thickness. He found the dispersion of these films remains at ~ 1°, for film thicknesses between 2000 Å to 6000 Å, if a substrate temperature of 150°C was used (103).

Mossman and Williams (35) note that a principle factor in the failure of magnetic film storage elements is skew of the easy axis. Since the skew varies from one film element to another, they investigated the way in which such variation affects the performance of storage cells. One effect noted is that the films may become more sensitive to small disturb pulses.

Leaver and Prutton (138) proposed a theory of reversal which is in qualitative but not quantitative agreement with experimental data obtained on Ni-Fe-Co films (70).

Fuller and Lakin (139) performed wall-wall interaction experiments. They used vacuum deposited, double-layer films of 100 Å thickness, prepared from 80Ni-17Fe-3Co material, and separated by a 100 Å layer of carbon. The multifilm structure was thin enough so that transmission electron microscopy could be used to see domain walls in both films simultaneously.

Bonyhard (140) used this ingot composition in his investigation of the switching behavior of thin ferromagnetic films at liquid helium temperatures, using fast pulse techniques.

8b. 57Ni-13Fe-30Co

Tickle (36) prepared films evaporated from ingots of this composition (by weight) in the development of a domain wall motion

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[4] Use of a thick, high conductivity substrate has many advantages. However, 2 disadvantages are considered in reference (199).

shift register. He defined the nucleation factor as the ratio of the writing field (the minimum field required to introduce reverse domains into a saturated film) to the shifting field (the minimum field required to move the walls of an already existing domain). A large nucleation factor is desirable for this application; however, this is difficult to achieve with permalloy films (ibid). The Ni-Fe-Co composition provides a reasonably large nucleation factor for the shift register application while still providing zero magnetostriction.

8c. 48.6Ni-2.8Fe-48.6Co

Crowther (37) considered 2 methods for achieving higher bit densities in magnetic thin film memories. One approach uses conventional Ni-Fe films in a paired film structure which has quasi-flux closure in both the easy and the hard axis directions. The other, more direct approach simply uses a film with a higher coercive force and no magnetoelastic sensitivity, such as the above (melt) composition.

A slightly different melt composition -- approximately 47%Ni-3%Fe-50%Co -- was mentioned in another paper which considered this problem (141). These films also featured H_c = 10 oe., H_k = 30 oe., low angular dispersion, and essentially zero magnetostriction.

8d. (Perminvars)

Perminvar films were used occasionally in research on magnetic thin films. Conger and Essig (142) presented a theory correlating the ferromagnetic resonance line width with the reversal time of thin films, for reversing fields greater than a certain critical value. Experimental results with film compositions of 80Ni-20Fe; 48Ni-30Fe-22Co; and 85Co-15Fe gave support to the theory.

Williams and Sherwood (17) examined domain patterns in thin films deposited from 43Ni-34Fe-23Co perminvar onto a heated substrate in the presence of a magnetic field. Gomi et al (143) studied domain patterns on films prepared by evaporating perminvar (45Ni-30Fe-25Co) on unheated substrates, in the absence of an external magnetic field.

Heidenreich and Reynolds sought to correlate the microstructure of magnetic thin films with their magnetic uniaxial anisotropy. Results indicated (144) that both bulk and thin film perminvars and permalloys contain oxygen atoms condensed along (111) planes when they also exhibit a uniaxial anisotropy (83). These faults form preferentially with their normals parallel to the induced anisotropy (83).

8e. Ni-Fe-Co (other)

Wolf (145) discussed the electrodeposition of alloys of the Ni-Fe-Co system. Solutions from which these metals are deposited are described and the role of their constituents discussed. The variation of magnetic properties with cobalt content is shown. Results indicate that the magnetostriction coefficient depends only on the Ni-Fe ratio in the films.

Bradley (34) presents some quantitative data on vapor deposited Ni-Fe-Co films. The zero magnetostriction composition is plotted for increasing cobalt content, running from 81Ni-19Fe at 0% cobalt content, to about 45Ni-10Fe at 45% cobalt content. H_k values rise linearly with increasing cobalt content up to 35% cobalt (thereafter leveling off) while the Ni:Fe ratio is maintained to keep zero magnetostriction.

Bruyere et al (146) studied a new type of magnetic interaction between 2 ferromagnetic thin films separated by a third metallic, non-magnetic thin film. This coupling tends to bring the magnetization of the ferromagnetic materials parallel. The coupling depends upon the materials and the thickness of the intermediate material. Non-magnetostrictive alloys, such as 45Ni-10Fe-45Co or 52Ni-13Fe-35Co, were used for one of the films in the multifilm structure.

Massenet (147) described experiments on multilayer evaporated thin films with a structure FeNi-Mn-FeNiCo, and FeNi-Mn. There was strong evidence of a ferromagnetic - antiferromagnetic exchange coupling between the FeNi film and a transition layer at the FeNi-Mn interface obtained by mutual diffusion of Mn and FeNi at 300° C. A 52Ni-13Fe-35Co composition was mentioned.

9. Ni-Fe-Cr

Cohen (39) prepared vacuum deposited Ni-Fe-Cr films on heated glass substrates. The Cr content ranged from 0 to $\sim 5\%$, while the Ni:Fe ratio ranged from 78Ni-22Fe to 90Ni-10Fe. For all Ni-Fe ratios, the anisotropy field H_k, the magnetization M, and the wall coercive force H_w decreased monotonically with Cr content, while angular dispersion and electrical resistivity ρ increased with Cr content. The variations of M and ρ with Cr content were consistent with bulk data (ibid).

10. Ni-Fe-Cu

Wolf (148) examined the effect of increasing copper content in Ni-Fe-Cu films, on the properties of the films. The magnetization at room temperature is plotted against increasing copper content. A linear decrease in magnetization is shown, similar to the quenching effect noted in bulk Cu-Ni.

11. Ni-Fe-Mo

Williams and Sherwood (17) observed domain patterns on evaporated films of iron, nickel, cobalt, and several alloys, including Ni-Fe-Mo. Kirenskii et al (149) studied the magnetization in molypermalloy and the magnetic anisotropy of cobalt films (102).

Kim and Rodichev (150) measured the wall velocity in iron and in Ni-Fe-Mo films for cases in which the entire film switched in one jump. A plot of wall velocity versus applied field resulted in a straight line with a positive intercept on the field axis. In the case of Ni-Fe-Mo, the slope was 3.432×10^4 cm. sec.$^{-1}$ oe.$^{-1}$, with an intercept of 3.8 oe. (103).

Kirenskii et al (151) studied the domain structure of Ni-Fe-Mo films in the temperature range - 100° to 700°C. They found no appreciable change in domain structure, but the nucleation field and the saturation field were found to increase with decreasing temperature (103).

Eckardt (152) prepared Ni-Fe-Mo films by normal incidence of Ni-Fe vapor, but angular incidence of Mo vapor. The resulting films showed anisotropy in the plane and perpendicular to the flux of Mo vapor (103).

Telesnin et al (153) made pulse switching measurements on Mo-permalloy films (103).

Ahn and Beam (40) prepared molybdenum-permalloy films using two evaporating sources; one contained 83Ni-17Fe by weight, and the other contained pure molybdenum. Intrinsic film properties measured at Mo concentrations up to 6% - 8% indicated reductions of M, H_c, H_k, and dispersion. However, at high Mo concentrations, oblique incidence produced strong anisotropies.

12. Ni-Fe-P

Freitag et al (96) discussed the magnetic properties of ternary alloy Ni-Fe-P films as a function of their composition and thickness. They prepared essentially nonmagnetostrictive films, 1200 Å thick, and 3 x 3 inches in area, with coercivities of 2 oe. and anisotropy fields at 3.5 oe. The Ni-Fe atomic ratio corresponding to zero magnetostriction increases from approx. 4.0 in the absence of phosphorus, to about 5.5 at 3.2 wt.% phosphorus, for films about 1200 Å in thickness. They noted an improvement in magnetic properties when the phosphorus content was 1% to 2% by wt.; however, at higher phosphorus content, the magnetic properties deteriorated.

Kriessman et al (41) considered methods that would result in a low power, thin film memory. One approach is the use of film compositions that have lower values of anisotropy field, H_k, hence require smaller values of drive current. They reported use of essentially nonmagnetostrictive Ni-Fe-P electrodeposited films, ~ 200 Å thick, having H_k values ranging from 0.9 to 1.4 oe., compared to 3 to 4 oe. for films in present magnetic film memories.

Matcovich et al (154) describe a memory system presently under development. The magnetic film spots consist of an electroplated Ni-Fe-P alloy, 5 mils in diameter, and a few hundred Å thick. The reported values of H_c and H_k are about 2 oe. and 1 oe., respectively; switching is completed in 10 ns. with a word drive current of 35 ma.

13. Fe-Al

Hodges (135) prepared evaporated films of Fe-Al on glass substrates. Separate evaporating sources were used because of the difference in vapor pressure of iron and aluminum. The geometry of the evaporation was such that, when the iron was deposited at normal incidence, the aluminum was incident at ~ 30° to the substrate. The magnitude of the aluminum beam induced anisotropy was measured as a function of aluminum content in the film. A specimen containing an average chemical composition of 22.0 atomic percent aluminum had an anisotropy energy density of 1.5×10^5 ergs/cc. This compares with a maximum induced anisotropy of $< 1.8 \times 10^4$ ergs/cc in bulk Fe-Al, occurring at about the same 22 atomic percent aluminum composition (43). The results suggest that the easy axis dispersion found in large area films due to the geometry of the deposition, may be reduced by the use of suitably oriented aluminum beams incident over the film area during its deposition (ibid).

14a. 50Fe-50Co

Williams and Sherwood (17) prepared various magnetic thin film types, including a film made from a 50Fe-50Co alloy in their study of domain patterns on thin films. Heat treatment in a magnetic field established an easy direction of magnetization in the film.

14b. 5Fe-95Co

This composition is reportedly used in the Bicore memory device (29).

14c. Fe-Co (other)

Conger and Essig (142) used an 15Fe-85Co film in their studies of magnetization reversal in magnetic films.

Kolk and Orlovic (155) used thin films of iron, nickel, cobalt, and a 70Fe-30Co alloy, in their study of ways to increase the Kerr magneto-optic effect in thin films. They found that the magneto-optic rotation of magnetic films of thickness less than 500 Å is a function of the optical properties of the substrate as well as the optical constants of the magnetic material.

Grycza (156) measured the Faraday effect of thin films of iron, nickel, cobalt, and an Fe-Co alloy. He found that the "equivalent magnetization" diminished rapidly at a critical thickness, as compared to that for bulk samples (70).

15. Ni-Cu 16. Ni-Pd

Nose (157), (158), (159), and Kimura and Nose (45) made spin wave resonance measurements on various nickel, Ni-Cu, and Ni-Pd (alloy) films. For Ni-Cu and Ni-Pd films, the exchange coupling constant, A, decreased monotonically with increasing content of Cu and Pd, to ~ 1/5 at 22% Cu, and 2/3 at 35% Pd, respectively. The exchange integrals, J, of these alloys were, however, nearly constant. The temperature variations of A and J are investigated for some Ni-Cu alloy films (159).

17. Nickel alloy films; miscellaneous

In addition to the nickel alloy thin films already mentioned, various other such films have appeared in the literature from time to time, generally for studies concerning other than magnetic properties. A sampling of these papers now follows.

> Fukano (160) prepared quenched single crystal films of Ni-Au alloy. He studied the structure changes prompted by various aging processes. (Some magnetic properties of bulk Ni-Au samples appear in reference (161)).
>
> Flechon and Ormancey (162) made resistivity measurements of P (2-12%) -- Ni films as a function of thickness, to provide a method for determining the P concentration (70).
>
> Goto et al (163) describes the manufacturing processes and the properties of vacuum deposited Ni-Cr alloy thin film resistors.
>
> Finnegan and Gould (164) studied Fe-Ni, Ni-Cr, and Pb-In alloys by the moving-plate technique, to determine deposition rates during vacuum evaporation to prepare homogeneous alloy films (70).
>
> Vaumoron and Colombani (165) reported on qualitative investigation on the evaporation of a nickel chromium mixture (thin film) (166).

18. Co-Cu

In the binary system Co-Cu, no thermodynamically stable solid solutions exist at any temperature in the concentration range between 12 and 95 at. % Cu (167). However, Kneller (167) reports the successful preparation of metastable solid solutions in the concentration range 40 to 85% Cu, by the simultaneous evaporation of Cu and Co onto a substrate kept cool enough to prevent decomposition. The metastable solid solutions were in the form of polycrystalline films ~ 1000 Å thick.

The thermodynamic equilibrium state (2 phases) could then be obtained by subjecting the film to high temperature vacuum annealing. Spin moment measurements are shown both for the metastable as-deposited alloy, and for the 2 phase system after annealing. The latter corresponds to an equilibrium mixture of Cu and 90Co-10Cu. S. Mader et al (168) prepared Co-Cu films 600 to 1000 Å thick, by the simultaneous evaporation of the 2 metals in vacuum. When alloys of 40-65% Cu were prepared by co-evaporation onto substrates at room temperature or at 80°K, the diffraction pattern always indicated a metastable single phase solid solution, in complete agreement with the magnetic studies of Kneller (167).

The structure of alloys prepared by the "vapor-quenching" technique mentioned above, were compared with that obtained by the rapid quenching of the liquid alloy solutions. The authors conclude that for Co-Cu (and for Cu-Ag), the method of vapor quenching onto a cold substrate is considerably more effective for the production of nonequilibrium phases than is the liquid-quenching method.

19. Co-Ni

Boyd (6) measured the crystalline anisotropy constant K_1 of epitaxially grown single crystal films of Ni, Fe, Ni-Fe, and Co-Ni alloys, using a sensitive torque balance. The resulting values of K_1 are compared with previously published data taken on bulk single crystals. The Co-Ni alloy films are not in good agreement as to the magnitude of K_1, but do show the same variation with composition (ibid).

L. Reimer (148, discussion section) mentioned experimenting with electrodeposited Co-Ni films on copper substrates. The films showed, at low cobalt content, a much higher content of twins.

Fuller and Sullivan (169) examined, both theoretically and experimentally, the magnetostatic interactions between 2 parallel Néel walls in 2 parallel planes (103). They mention use of a vacuum deposited multi-layer film consisting of a 50Co-50Ni film separated from an 81Ni-19Fe film by a film of MgF_2, in their experimental studies.

E. Hirota (170) reported use of a 90Ni-10Co alloy film, 1500 Å thick, in a spin wave resonance experiment.

20. Co-P

Sallo and Carr (51) discussed means of preparing Co-P electrodeposits having a wide range of magnetic properties. Studies of the crystalline structure of the deposit are given, along with an interpretation of the origin of the coercivity. Further studies of these high coercivity electrodeposits, as well as Co-Ni-P electrodeposits, appear in references (50) and (59). Both rod and platelet particles were found in the electrodeposits. The high coercive force was attributed to crystalline anisotropy in the case of the platelet structures, and to shape anisotropy in the case of the rod structures (59).

Fisher (97) studied the recording characteristics of Co-P films prepared by electroless deposition. Film thicknesses from 3000 Å to 56,000 Å were used. The hysteresis, saturation recording and surface characteristics are compared to commercial oxide tapes evaluated under identical conditions.

Allen et al (171) studied high coercivity Co-P electrodeposits as a magnetic recording medium in both contact and non-contact recording. Data are given concerning the packing density and signal output levels that can be expected from these coatings. Also discussed is the effect of coercive force and deposit thickness on these parameters.

21a. Co-Ni-P (low coercivity electroless films)

Sallo (172) (173) used films of nominal composition 35%Co, 63%Ni, and 2%P, (172) in the fabrication of a thick film, closed flux path memory device called "orthocore". Electroless deposition was used because it forms a uniform deposit over the complex geometry of the device. Coercive forces are low; values ranging from 0.2 oe. to more than 5 oe. are attainable.

Holmen and Sallo (53) prepared thin ferromagnetic films of Co-Ni-P by chemical (electroless) deposition. The effects of film thickness and composition on coercivity and anisotropy are discussed. Also mentioned are switching data, dispersion data, torque curves, and effects of various chemical parameters on film properties.

21b. Co-Ni-P (high coercivity electrodeposits)

1. Sallo and Olsen (57) reported a Co-Ni-P electrodeposit having a 60 cycle coercive force of 1000 oe. Electron micrographs showed oriented clusters of lamellar structures. The material was found to be hexagonal, with its easy direction of magnetization (c-axis) in the plane of the film. Various results are explained on the basis of a model which considers each lammela to be a single-domain

particle. Further studies into the origin of the high coercivity of these electrodeposits were also reported (50), (59).

2. Bate and Speliotis prepared hard magnetic films of Co-Ni-P by electrodeposition onto polished brass substrates (54), (55), (56). Some statistics on these Co-Ni-P films are given directly below:

Composition (wt. %)			Film Thickness	H_c	M_r	Reference
Co	Ni	P	(microns)	(oe.)	M_s	
85 :	14	1	0.020 to 3.	375 to 600	~ 0.70 to 0.80	54
78 :	20	2	0.025 to 5	400 to 800	~ 0.75 to 0.85	55
78 :	20	2	0.1 to 15	300 to 700	. . .	56
(balance)	20	2 to 3	0.1200	500 to 1000	0.90 to 0.95	58
85	14	1	0.05 to 0.2	300 to 550	~ 0.90	60

A combination of properties was reported in these high coercivity films that is difficult to explain in terms of existing theories of magnetization reversal. A unique mode of magnetization reversal was found in these films (60).

22. Ferrite Films

Brownlow et al (174) gave switching and hysteresis data for ferrite films of ~ 10 microns thickness. The films are considered for use as storage and logic devices.

Banks et al (175) prepared various composition ferrite films of 1000 Å thickness, by vacuum evaporation of the metals, followed by high temperature oxidation. They noted that in many respects the properties of the films are the same as those of bulk ferrites of similar composition.

Lemaire and Croft (176) prepared ferrite films using a spray technique whereby hot suspensions cf hydroxides are directed onto a heated substrate. They noted that coercive force decreased as film thickness increased.

Wade et al (177) made resonance isolators at 30 Kmc/sec., using chemically deposited films of nickel and nickel zinc ferrite about 35 microns thick, deposited onto alumina substrates (103). Heinz and Silber (178), using thin films of magnetite, Fe_3O_4, observed the d-c voltage that accompanies ferromagnetic resonance in a ferrite. The d-c voltage had previously been observed in thin metallic films.

Francombe et al (62) measured the Faraday rotation and displayed the "optical" hysteresis loops for $NiFe_2O_4$ and $CoFe_2O_4$ by using thin films of these compounds with thicknesses in the range 1000 to 8000 Å. These ferrites in bulk form are opaque even at small thicknesses (~ 2 mils), and therefore information on Faraday rotation or optical absorption spectra of these compounds had not previously been available (ibid).

Gleason and Watson (179) describe the experimental deposition apparatus, the procedure used to deposit the films, and the resulting properties of ferrite films of a nickel-zinc-cobalt composition, prepared by pyrohydrolytic deposition.

Wade et al (65) prepared various ferrite films and garnet films by deposition from chemical solutions. Preparation techniques, microwave measurements, and crystallographic structure studies are discussed for these films. Possible applications in millimeter-microwave ferrite devices are noted.

Ferrite thin films are considered in the development of thin film spiral inductors (180). An article by Schroder (181) concerns magnetic oxide thin films (166).

23. Garnet Thin Films

Occasional mention has been given to the preparation of garnet thin films (65), (175). Wade et al (65) note that their chemical deposition method has successfully made both spinel ferrites and garnet ferrites; the amount of the main phase generally ranged from ~ 90 to 100%, while second phases (mostly ferric oxides) when present, did not exceed 10%.

24. Other

Freitag and Mathias (48) discuss the effect of various preparation variables on the subsequent composition and magnetic properties of electrodeposited magnetic thin films. Magnetic materials mentioned include Ni-Fe, Ni-Fe-Co, Ni-Fe-P, Ni-Co, Ni-Co-P, Co-P, and quaternary alloys of nickel, iron, molybdenum, phosphorus, and arsenic.

Reference (182) titled: "Magnetic Tape Recording Materials" lists the physical and magnetic properties of some metals and alloys in powder and film form, as well as the physical and magnetic properties of some permanent magnet oxide powders.

Table II. Interesting Features and Potential Applications of Materials Reported as a Magnetic Thin Film.

Material	Interesting Features	Applications
1a. Iron-bcc	The high saturation magnetization of iron, coupled with its low cost (as bulk) makes iron an ideal constituent for many magnetic applications.	The ferromagnetic elements iron, nickel, and cobalt find applications as a thin film mainly in the form of alloys, rather than as the pure element itself.
1b. Iron-fcc	Uncertainty exists concerning its magnetic properties at low temperatures.	(not ferromagnetic)
2a. Nickel-fcc	Nickel films offer an uncomplicated structure (no phase change normally expected) and a low Curie point; its saturation magnetization is low, compared to iron.	See remarks for iron-bcc.
2b. Nickel-hcp	Research efforts have been directed largely towards proving or disproving the existence of a hexagonal phase in specially prepared nickel films.	....
3a. Cobalt-hcp	Cobalt (hcp) is a strongly uniaxial material at room temperature, with a large magnetocrystalline anisotropy. The easy direction of magnetization changes at higher temperatures.	See remarks for iron-bcc.
3b. Cobalt-fcc	The high temperature form of cobalt can exist as a thin film at room temperatures, under certain conditions.	....
4. Gadolinium	Gd displays some interesting properties: 1. an ill defined Curie temperature. 2. a relatively large and highly field-dependent crystal anisotropy at and above the Curie point. 3. a variation of easy direction of magnetization with temperature. 4. an unusuallylarge ferromagnetic Hall effect (183). 5. a compound with bismuth having a Curie point appreciably above that of Gd.	

Material	Interesting Features	Applications
5. MnBi	MnBi displays some interesting properties: 1. a strong ferromagnetism, although its constituents are not ferromagnetic. 2. very large values of magnetostriction and anisotropy at room temperature. 3. a variation of easy direction of magnetization with temperature. 4. extremely large magneto-optic Kerr rotations found at room temperature in oriented films (130). 5. an easy direction of magnetization perpendicular to the plane of the film.	Films of MnBi have been suggested as a medium for high density information storage (94).
6a. 81Ni-19Fe (81-permalloy)	This alloy film has the following properties: 1. zero magnetostriction. 2. fairly low crystalline anisotropy. 3. fairly low values of H_c and H_k. 4. a well developed uniaxial anisotropy with low dispersion. 5. a rectangular hysteresis loop 6. high permeability.	1. magnetic film memories. 2. magnetic film logic devices (see, e.g., ref. 184) 3. thin film parametric devices such as parametrons, parametric amplifiers, balanced modulators, and flip-flops (185). 4. sensitive field magnetometer (186). 5. variable delay magnetic strip line (187). 6. all-electronic compass (188)
6b. 50Ni-50Fe	This alloy film was used when higher coercive force values were desired than provided by 81-permalloy. Now this function appears to be taken over by the nonmagnetostrictive Ni-Fe-Co compositions.	....
6c. 3Ni-97Fe	This composition may be useful when magnetic isotropy is desired. It also provides a coercive force about an order of magnitude above that for 81-permalloy.	1. the magnetic rod memory device (33); (189). 2. the cubic waffle-iron memory device (31).
7. Ni-Fe-Al	Permalloy films containing aluminum were mentioned (135) in a study into the origin and control of the anisotropy in magnetic thin films.	....
8a. 80Ni-17Fe-3Co	Under the proper deposition conditions, this melt composition reportedly provides a nonmagnetostrictive film with lower easy-axis skew from element to element than is the case with films of 81-permalloy (29).	1. magnetic film store (190). 2. logic circuits (191).

Material	Interesting Features	Applications
8b. 57Ni-13Fe-30Co	Films made from this melt composition feature zero magnetostriction, and provide a reasonably large "nucleation factor" for the shift register application.	-domain wall motion shift register-
8c. 48.6Ni-2.8Fe-48.6Co	Films from this melt composition have higher wall coercive force values (~10 oe.), and no magnetoelastic sensitivity.	-mentioned in studies to achieve higher bit densities in magnetic film memories, while maintaining an open flux structure (37).
8d. 45Ni-30Fe-25Co (perminvars)	Perminvar characteristics are listed in the comments to Table I.	....
8e. Ni-Fe-Co (other)	The nonmagnetostrictive compositions in the Ni-Fe-Co system (see, e.g., ref. 34, Fig. 4) may be of interest when higher values of H_c, H_k are desired than are provided by the usual 81-permalloy composition. Some disagreement concerning nonmagnetostrictive composition exists at higher Cobalt contents--45 to 50% Co (37).	-mentioned for use in a proposed memory element (146)
9. Ni-Fe-Cr	In bulk, these alloys have been used where it is desired to have magnetic properties that change rapidly with change in temperature - e.g., temperature sensitive relays (1).	....
10. Ni-Fe-Cu	Copper additions have a quenching action on the magnetization of Ni-Fe films (148).	....
11. Ni-Fe-Mo	The combination of low magnetostriction and anisotropy of 4-79 molybdenum permalloy at room temperature should make it a very desirable film material (29).	.... reproduce head (200).
12. Ni-Fe-P	These films were developed to lower the drive current requirements of magnetic thin film memories, thereby making the films more compatible with molecular type integrated circuits (41). They provide rapid switching and zero magnetostriction.	-proposed as the memory elements in a low power, thin film memory (41), (154), (192).

Material	Interesting Features	Applications
13. Fe-Al	These films were examined to study the influence of directional ordering on their anisotropy (135). Bulk samples of similar compositions had previously displayed such influence on their induced anisotropy (43). (The uniaxial magnetic anisotropy of permalloy films near 80Ni-20Fe is thought to be due in part to directional ordering of the solute atoms as described by the Neel-Taniguchi theory (83).	....
14a. 50Fe-50Co	This alloy composition features very high saturation magnetization and high magnetostriction.	....
14b. 5Fe-95Co	....	-reportedly used in "Bicore", a NDRO storage device (29).
14c. Fe-Co (other)	Iron-cobalt alloys are of interest when high Curie points (see, e.g., Ref. 194) or high values of saturation induction are important. The alloy composition near 90% Co has low magnetostriction combined with a higher coercive force than 81-permalloy.	A higher coercive force material such as 90Co-10Fe was mentioned for possible use as the analogue storage element in a magnetic film adaptive linear decision array (193).
15. Ni-Cu 16. Ni-Pd	Nickel and copper are neighbors in the periodic table; one is ferromagnetic, and the other is diamagnetic. Palladium, on the other hand, lies directly below nickel in the periodic table. Therefore, Ni-Cu and Ni-Pd alloys may be interesting from a theoretical point of view. Spin waves apparently can be excited in thin nickel films only when stringent conditions are met during the deposition of the films; but, upon the addition of small quantities of impurities, such as Cu or Pd, the films produce spin wave spectra (195).	....
17. Ni-alloys (other)	These alloys were used in special purpose studies, etc.	....

Material	Interesting Features	Applications
18. Co-Cu	The successful production of metastable Co-Cu alloy films, in the 40-85% Cu range, showed that metastable alloys never observed in bulk materials may be produced as a thin film by the simultaneous deposition of the various metals onto a cold substrate.	....
19. Co-Ni	The most commonly used magnetic recording surfaces consist of either iron oxide particles dispersed in a binder, or continuous metallic films of cobalt and cobalt-nickel (196). These Co-Ni electrodeposits generally have coercivities of 200-300 oe. when used in serial storage devices, although a Co-Ni alloy having a coercive force of 500 oe. has been reported (51).	Electrodeposited Co-Ni alloys are widely used throughout the computer industry as the recording media in magnetic drum and magnetic tape memory systems (197).
20. Co-P	Results taken from tape and drum testing show improvements in recording properties relative to magnetic oxide coatings (171). These improvements correspond to those to be expected from thinner coatings having higher coercive forces (171).	These high coercive force alloys (200-700 oe.) may find use as the storage elements in drum, disc, and tape units (48). - potential use as a new magnetic tape medium (97).
21a. Co-Ni-P (electroless)	Electroless Co-Ni-P films can have magnetic properties that are similar to those of permalloy films (53).	-"orthocore" memory device (172). -Co-Ni-P films formed by electroless deposition possess magnetic properties that are potentially useful as memory elements (53).
21b. Co-Ni-P high coercivity electrodeposits	Electrodeposited Co-Ni-P films reported by Bate and Speliotis (54) (55) (56) (58) (60) show an unusual combination of magnetic properties, including: 1. high coercivity. 2. high ratio of remanent to saturation magnetization. 3. steep sided hysteresis loops. 4. magnetic isotropy in the film plane.	-high density recording on discs and drums (e.g., see (48), Fig. 7).-

Material	Interesting Features	Applications
22. Ferrite Films	Optical studies of the ferrite material in thin film form may be possible, by transmission, even though the material is opaque in bulk form.	1. potential applications in millimeter-microwave ferrite devices, e.g., circulators, masers, isolators, switches, variable attenuators, etc. (65). 2. memory or logic elements (174). 3. thin film inductors (180).
23. Garnet Films	Garnet materials, especially yttrium iron garnet, are characterized by a relatively narrow ferromagnetic resonance line width. This narrow line width is important in the design of practical devices (201).	Garnet in bulk may find use as delay lines at microwave frequency (198). Other possibilities include such microwave devices as switches, circulators, isolators, etc.

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