Magnetic Thin Films for Heads and Media

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OUTLINE

I. MAGNETIC PHENOMENA RELEVANT TO MAGNETIC RECORDING

II. MAGNETIC MEASUREMENT TECHNIQUES

III. THIN FILM DEPOSITION AND CHARACTERIZATION TECHNIQUES

IV. MATERIALS FOR THIN FILM HEADS

V. MATERIALS FOR THIN FILM MEDIA

VI. PERFORMANCE AND FUTURE OF RECORDING SYSTEMS

VII. REFERENCES

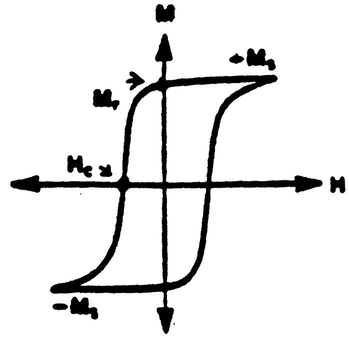
MAGNETIC PROPERTIES

Extrinsic

remanent magnetization M_r

coercivity H_c

permeability $\mu = \frac{B}{H}$



Intrinsic

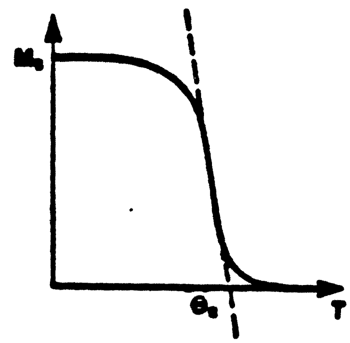
saturation magnetization, Ms

Curie temperature, Θ_c

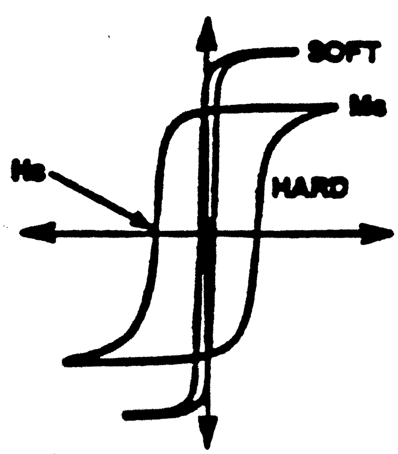
magneto-crystalline anisotropy, K_1, K_2

magnetostriction λ

$B = H + 4\pi M_s$



HARD AND SOFT MAGNETIC MATERIALS



Soft:

pure Fe

80 Ni: 20 Fe

Mn Zn ferrite

Fe N

Co Zr Nb

Al Fe Si

(SENDUST)

Hard:

Particles $\gamma-Fe_2O_3$

$BaO.6Fe_2O_3$

$SmCo_5$

Co Ni P-

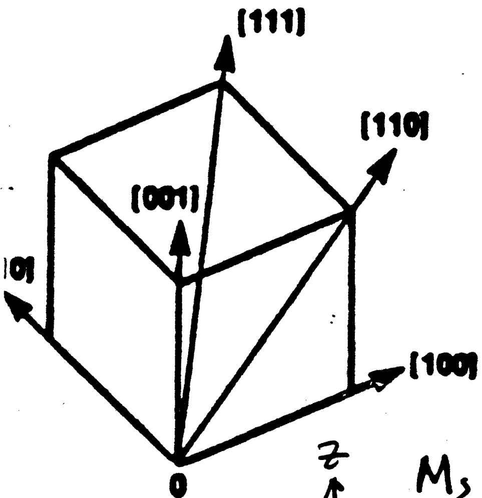
Co Cr/Cr

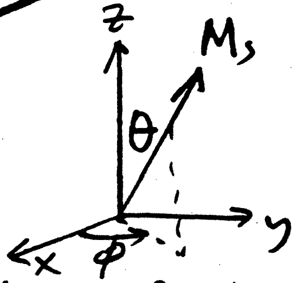
Co Cr Ta/C

THIN FILMS

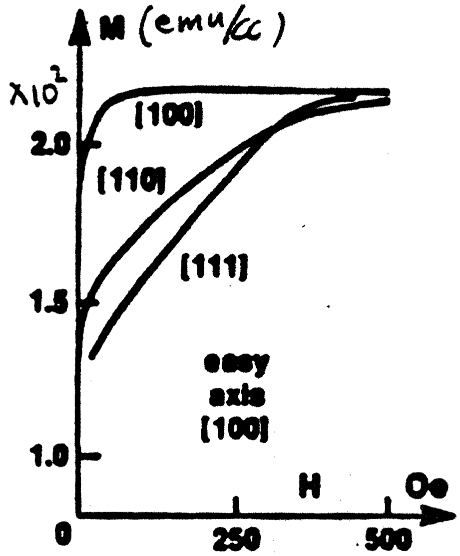
(Bate)

MAGNETO-CRYSTALLINE ANISOTROPY



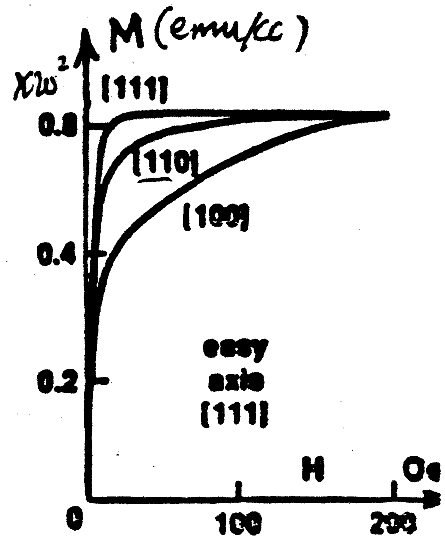


Iron



$K_1 = 4.8 \times 10^5$ erg/cc
$K_2 = 5 \times 10^4$

Nickel



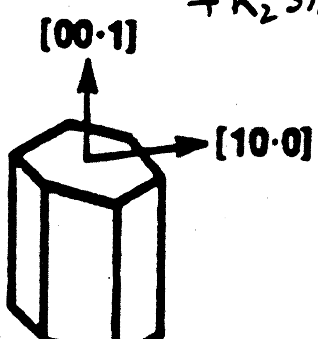
$K_1 = 4.5 \times 10^4$
$K_2 = 2.34 \times 10^4$

MAGNETO-CRYSTALLINE ENERGY DENSITY

UNIAXIAL: $E_K = K_1 \sin^2\theta + K_2 \sin^4\theta$

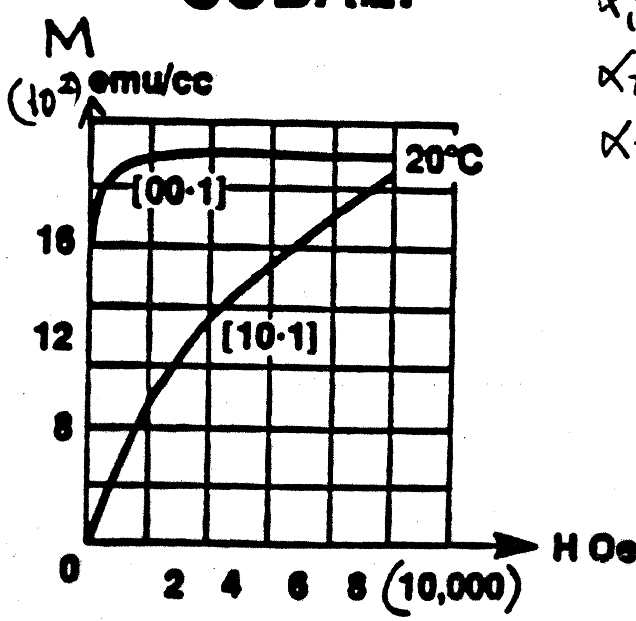
CUBIC: $E_K = K_0 + K_1[\alpha_1^2\alpha_2^2 + \alpha_1^2\alpha_3^2 + \alpha_2^2\alpha_3^2] + K_2$

$\alpha_1 = \sin\theta \cos$
$\alpha_2 = \sin\theta$
$\alpha_3 = \cos\theta$



$K_1 = +3.98 \times 10^6$ erg/cc
$K_2 = +1.98 \times 10^6$ erg/cc

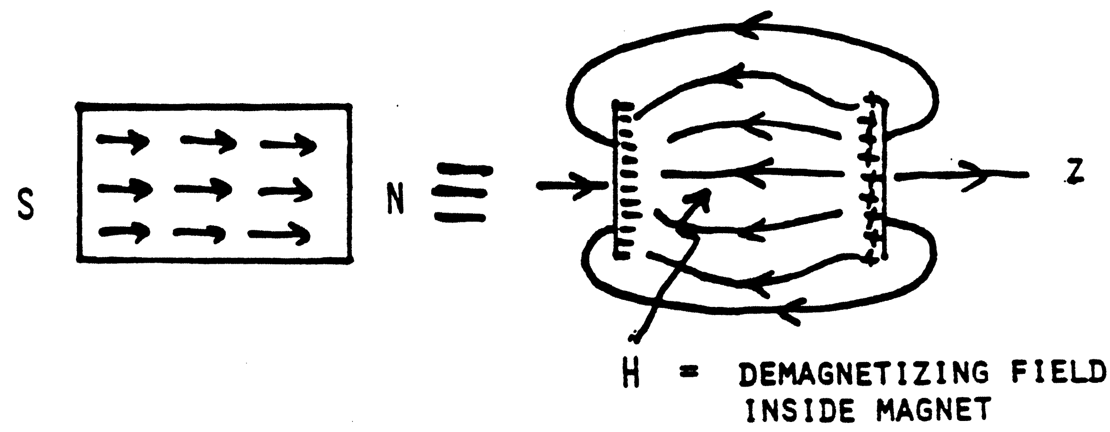
COBALT

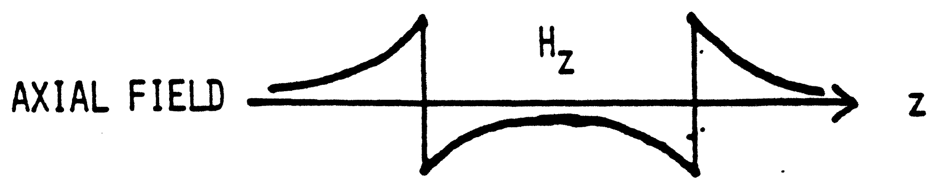


(Bate)

DEMAGNETIZING FIELDS

UNIFORMLY MAGNETIZED BAR MAGNET OR RECORDED BIT





AVERAGE DEMAGNETIZING FIELD = $\vec{H}_{DEMAG} = - N_D \vec{M}$

AVERAGE DEMAGNETIZATION FACTOR = N_D

SUM OF DEMAGNETIZATION FACTORS = $N_X + N_Y + N_Z = 4\pi$

$$\vec{B}_{INT} = \vec{H}_{INT} + 4\pi \vec{M}_{INT}$$

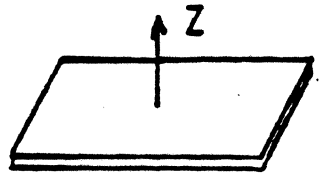
$$\vec{H}_{INT} = \vec{H}_{APP} + \vec{H}_{DEMAG}$$

CGS: B[gauss], H[oersteds], M$\left[\frac{emu}{cm^3}\right]$

SHAPE ANISOTROPY

DEMAGNETIZATION FACTORS OF DIFFERENT SHAPES

SHEET

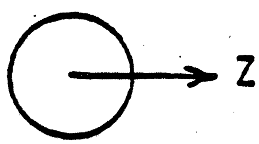


$N_x = N_y = 0 \;,\; N_z = 4\pi$

CYLINDER

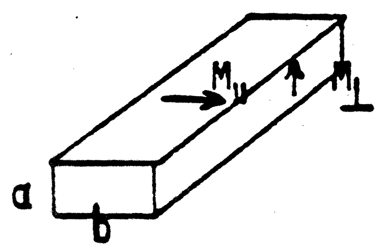
$N_x = N_y = 2\pi, \; N_z = 0$

SPHERE



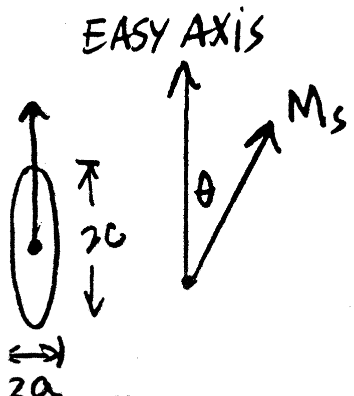
$N_x = N_y = N_z = \frac{4\pi}{3}$

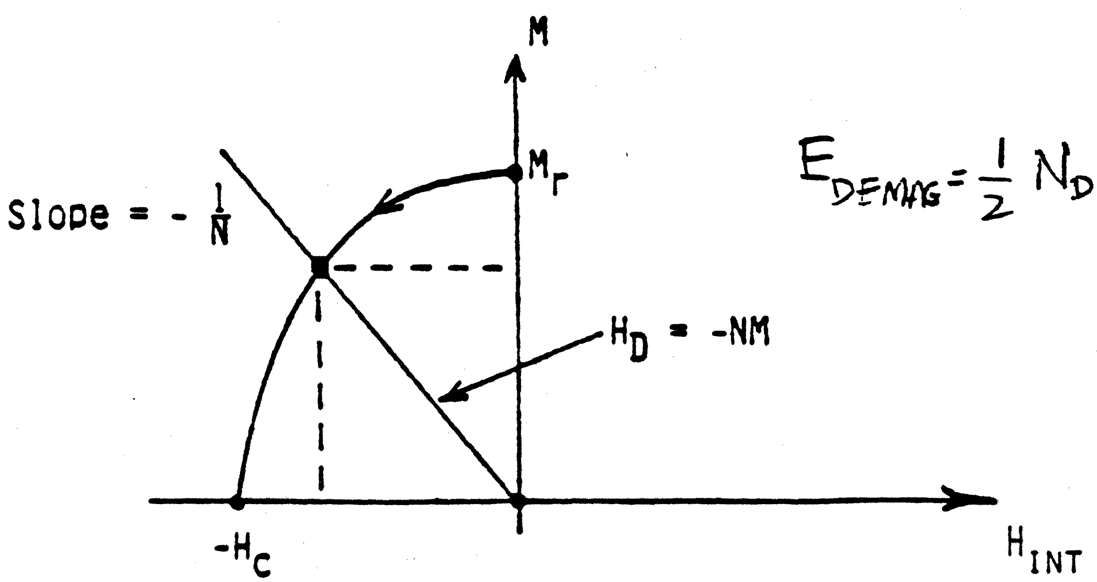
RECTANGULAR BAR



$N_{\parallel} = \frac{a}{a+b} 4\pi, \quad N_{\perp} = \frac{b}{a+b} 4\pi$

(approximately)





$E_{DEMAG} = \frac{1}{2} N_D M_s^2$

MAGNETOSTATIC DEMAGNETIZATION ENERGY DENSITY

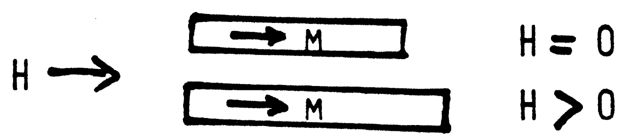
$E_{Demag} = K_s \sin^2\theta \qquad K_s = \frac{1}{2}(N_a - N_c) M_s^2$

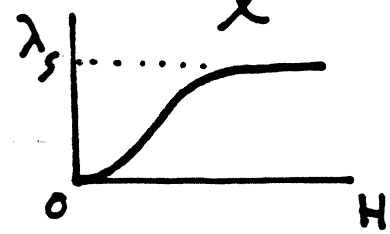
MAGNETOSTRICTION

DIMENSIONS OF MATERIAL CHANGE WHEN MAGNETIZED

MAGNETOSTRICTION COEFFICIENT = $\lambda = \frac{\Delta \ell}{\ell}$

$\lambda > 0$

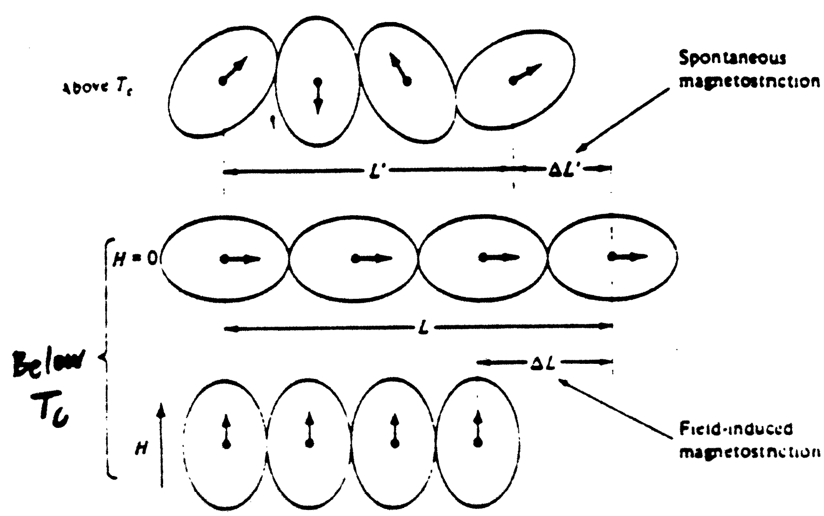




(parts per 10^6)

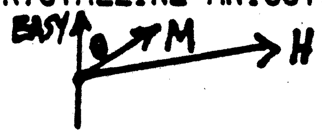
	λ_{100}	λ_{111}	λ_{poly}
Fe	+ 21	− 21	− 7
Ni	− 46	− 24	− 34
$FeO \cdot Fe_2O_3$	− 20	+ 78	+ 40
$Co_{0.8}Fe_{0.2}O \cdot Fe_2O_3$	− 590	+ 120	
$CoO \cdot Fe_2O_3$			− 110

PHYSICAL ORIGIN IS SPIN-ORBIT COUPLING



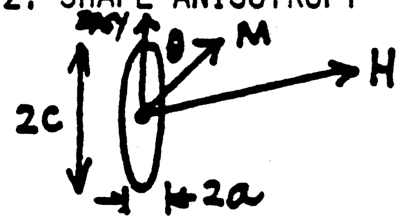
MAGNETIC ANISOTROPY ENERGY DENSITY

1. CRYSTALLINE ANISOTROPY



$$E_K = K_U \sin^2 \theta$$

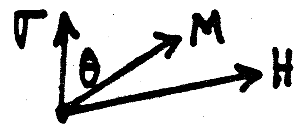
2. SHAPE ANISOTROPY



$$E_S = K_S \sin^2 \theta$$

$$K_S = \frac{1}{2}(N_A - N_C)\, M_S^2$$

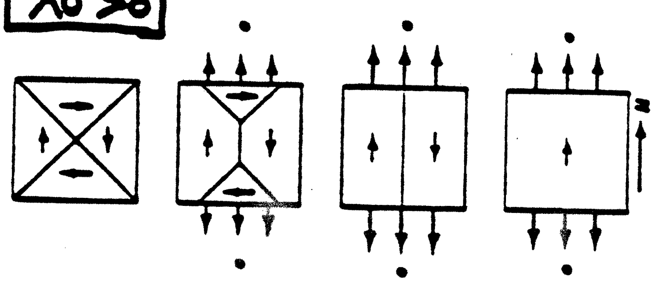
3. STRESS ANISOTROPY



$$E = K_\sigma \sin^2 \theta$$

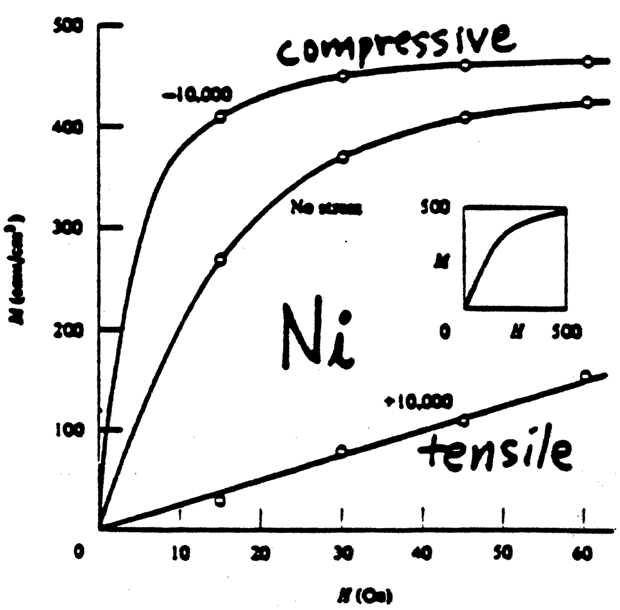
$$K_\sigma = \frac{3}{2} \lambda\sigma$$

$\lambda\sigma > 0$



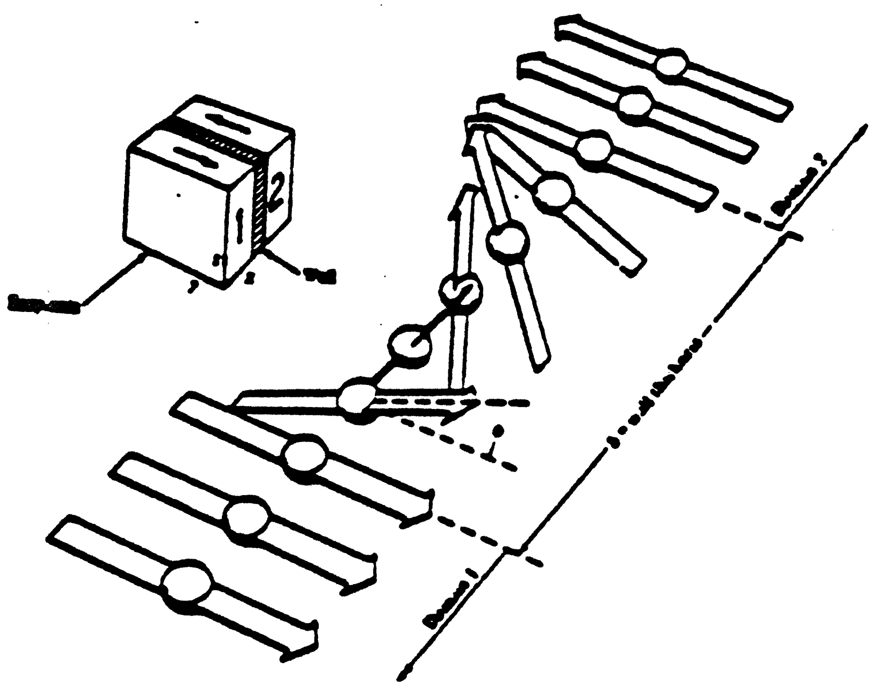
TENSILE $\sigma > 0$

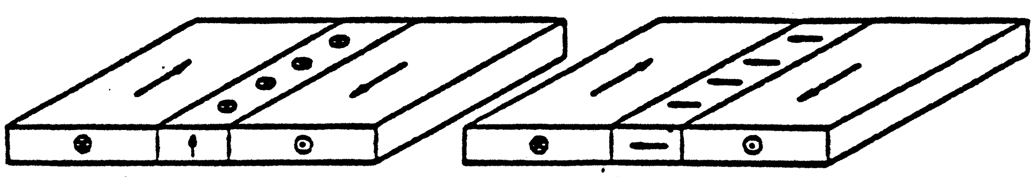
COMPRESSION $\sigma < 0$



MAGNETIC DOMAIN WALLS

THE BOUNDARY BETWEEN OPPOSITELY MAGNETIZED DOMAINS IN BULK MATERIALS IS CALLED A <u>180° BLOCH WALL</u>

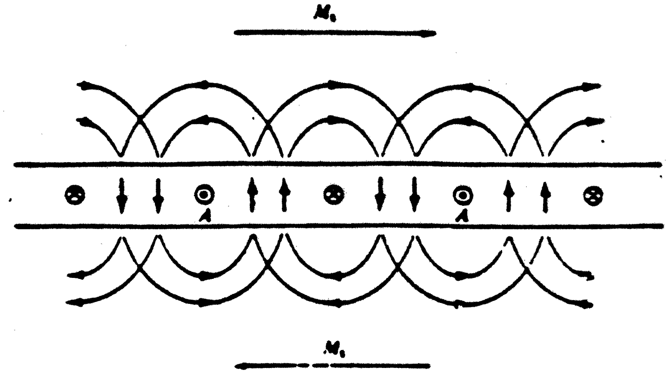




BLOCH WALL

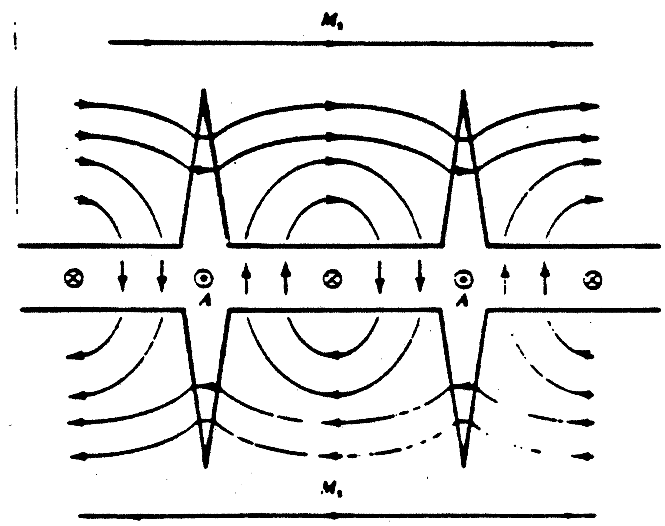
NEEL WALL

CROSS-TIE WALL FORMATION



(a)

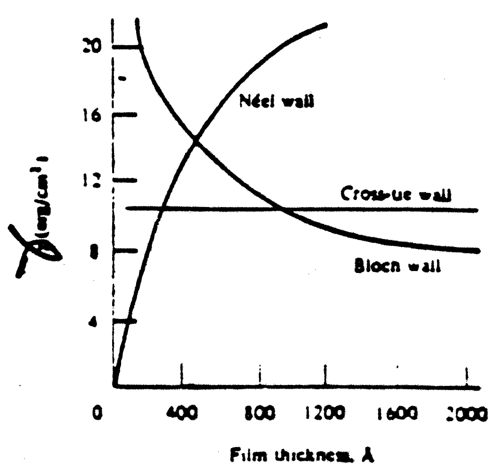
Alternating Néel Wall



(b)

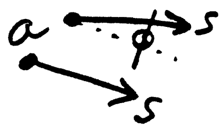
Cross-Tie Walls

THICKNESS DEPENDENCE OF WALL ENERGY DENSITIES



MINIMUM DOMAIN WALL THICKNESS

ASSUME A SIMPLE CUBIC ARRAY OF SPIN DIPOLE MOMENTS WITH A LATTICE PARAMETER a AND ASSUME THE WALL TO BE N ATOMS THICK SO THE WALL THICKNESS IS GIVEN BY $\delta = Na$



THE NEAREST NEIGHBOR EXCHANGE ENERGY OF A PAIR OF DIPOLE MOMENTS IS GIVEN BY $W_{Ex.} = -2 J_{ex} S^2 \cos\phi$

AND THE ANGLE BETWEEN ADJACENT MOMENTS IS $\phi = \pi/N$

THEN SINCE THE $\cos(\emptyset) \cong 1 - \frac{1}{2}\emptyset^2$

THE EXCESS EXCHANGE ENERGY OF N PAIRS IS $W_{EX \atop N\text{-pairs}} \cong \frac{J_{ex} S^2 \pi^2 a}{\delta}$

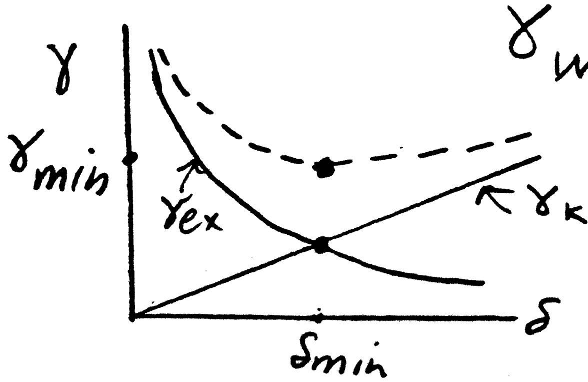
FINALLY, THE EXHANGE ENERGY PER UNIT WALL AREA IS GIVEN BY

$$\gamma_{EX} = \frac{J_{ex} S^2 \pi^2}{a} \frac{1}{\delta}$$

THE MAGNETO-CRYSTALLINE ANISOTROPY ENERGY PER UNIT WALL AREA IS GIVEN BY $\gamma_K = K\delta$

THE TOTAL WALL ENERGY PER UNIT WALL AREA IS GIVEN BY

$$\gamma_{WALL} = \frac{A_{ex}}{\delta} + K\delta \quad , \quad A_{ex} = \frac{J_{ex} S}{a}$$



THE MINIMUM WALL THICKNESS IS

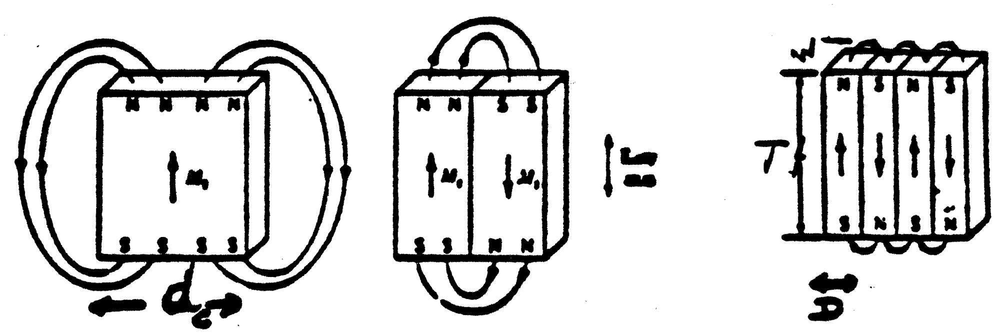
$$\delta_{min} = \sqrt{\frac{A_{ex}}{K}}$$

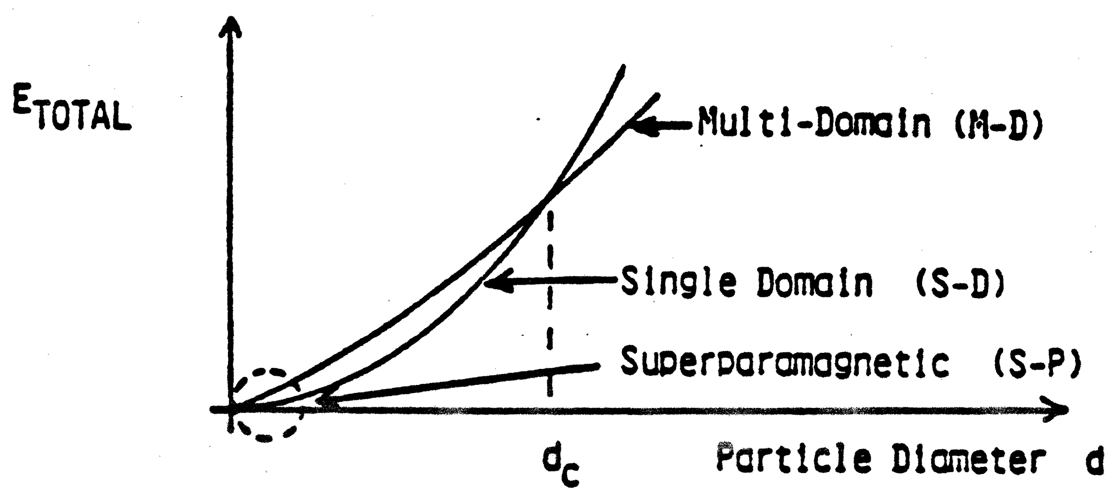
THE MINIMUM WALL ENERGY/WALL AREA IS

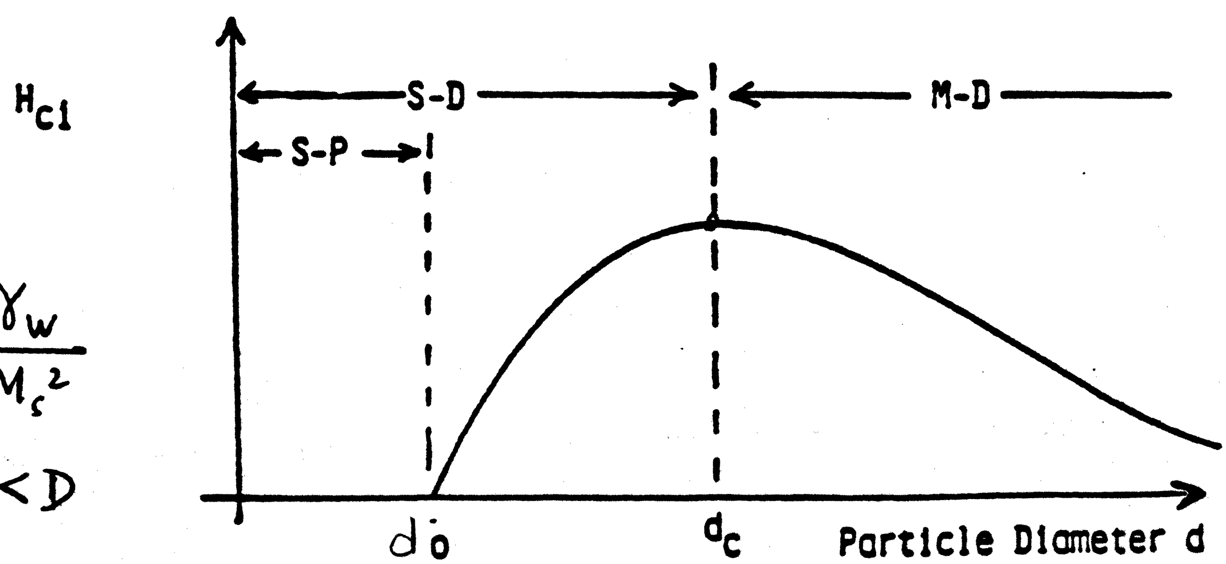
$$\gamma_{min} = 2\sqrt{A_{ex} K}$$

	Fe	Ni
$\delta_{min} \cong$	300Å	720Å

SINGLE AND MULTIDOMAIN PARTICLES





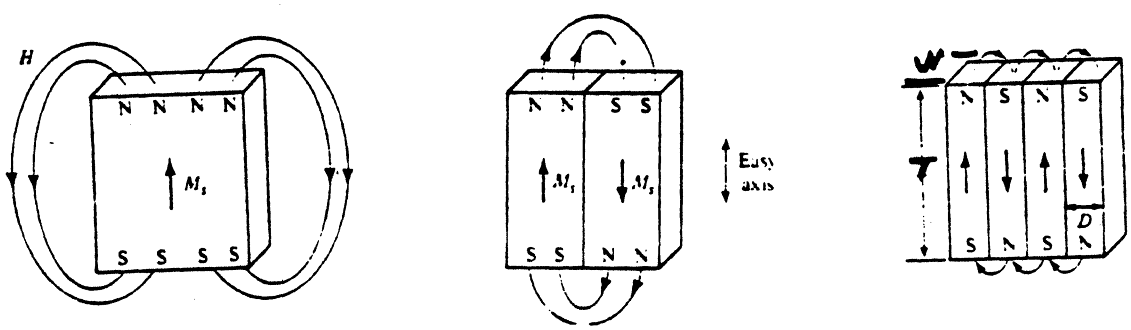


$$d_c = \frac{k \gamma_w}{\pi^2 M_s^2}$$

for $\delta_w << D$

MINIMUM MAGNETIC DOMAIN SIZE

ASSUME A UNIAXIAL SINGLE CRYSTAL WITH A PARALLEL-PLATE DOMAIN STRUCTURE WHICH IS EXPECTED TO EVOLVE IN MINIMIZING THE MAGNETOSTATIC DEMAGNETIZATION STRAY FIELD ENERGY.



THE TOTAL ENERGY PER UNIT AREA OF THE TOP OF THE CRYSTAL IS GIVEN BY

$$E_{TOTAL} = E_{DEMAG} + E_{WALL}$$

$$E_{TOTAL} = K M_S^2 D + \gamma_W \frac{T}{D}$$

WHERE $K = 1.7$ FOR $W =$ AND $K = 1$ FOR $W = D$ AND $\gamma_W = 2\sqrt{A_{ex}}$

THE MINIMUM DOMAIN SIZE IS GIVEN BY

$$D_{min} = \sqrt{\frac{\gamma_W T}{k M_s^2}}$$

THE MINIMUM ENERGY PER UNIT SURFACE AREA IS GIVEN BY

$$E_{min} = 2\sqrt{k M_s^2 \gamma_W T}$$

Cobalt

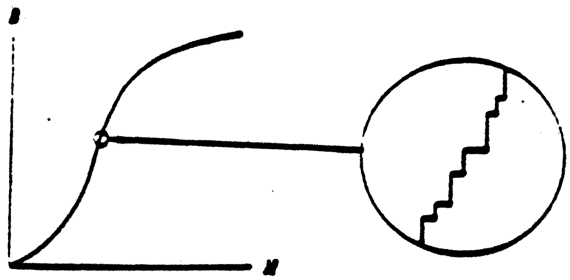
$M_s = 1422$ emu/cm^3 $k = 1.7$

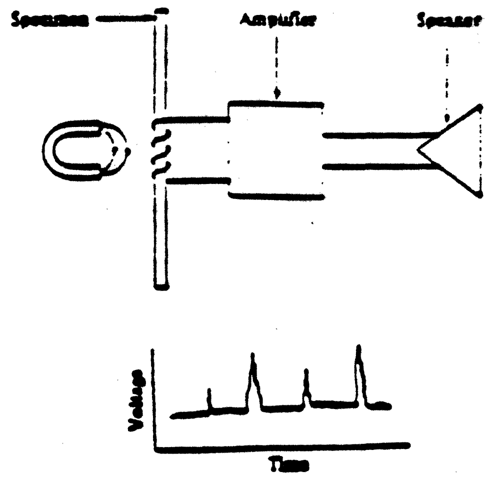
$\gamma_W = 7.6$ ergs/cm^2 $T = 1\ \mu m$

$D_{min} \cong 1500$ Å

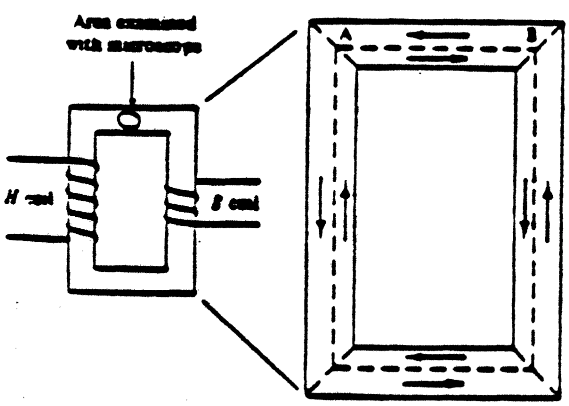
MAGNETIZATION BY WALL MOTION

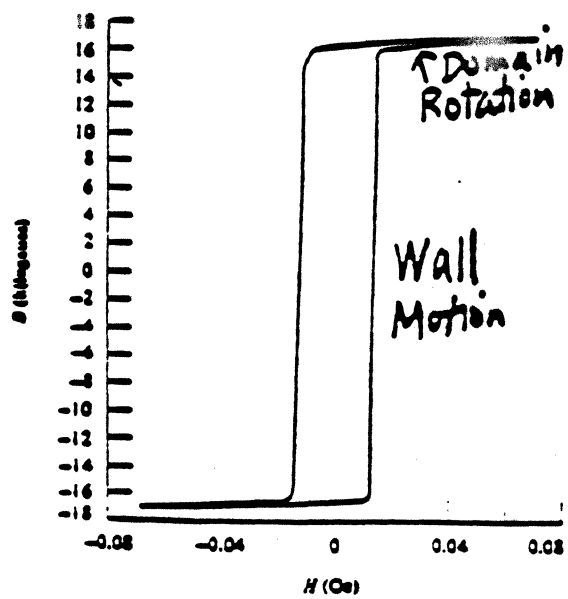
THE "BARKHAUSEN EFFECT" DEMONSTRATED IN 1919 THE EXISTENCE OF DOMAINS <u>INDIRECTLY</u> BY SHOWING DISCONTINUOUS WALL MOTION.





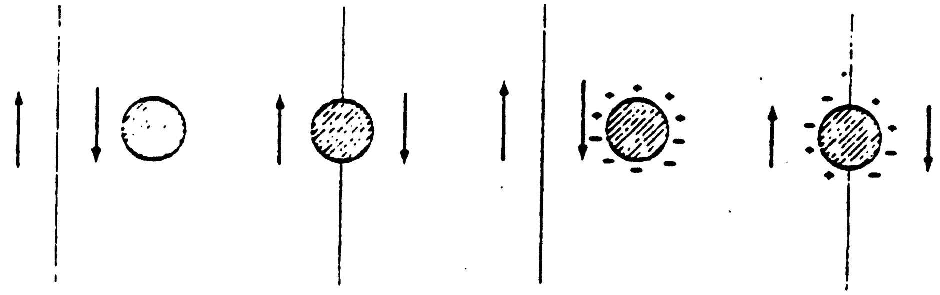
A <u>DIRECT</u> OBSERVATION OF MAGNETIC DOMAINS USING BITTER COLLOID WAS DISCLOSED BY WILLIAMS & SHOCKLEY & BOZORTH IN 1949. A BELL LABS MOVIE IS AVAILABLE FOR SHOWING THIS.



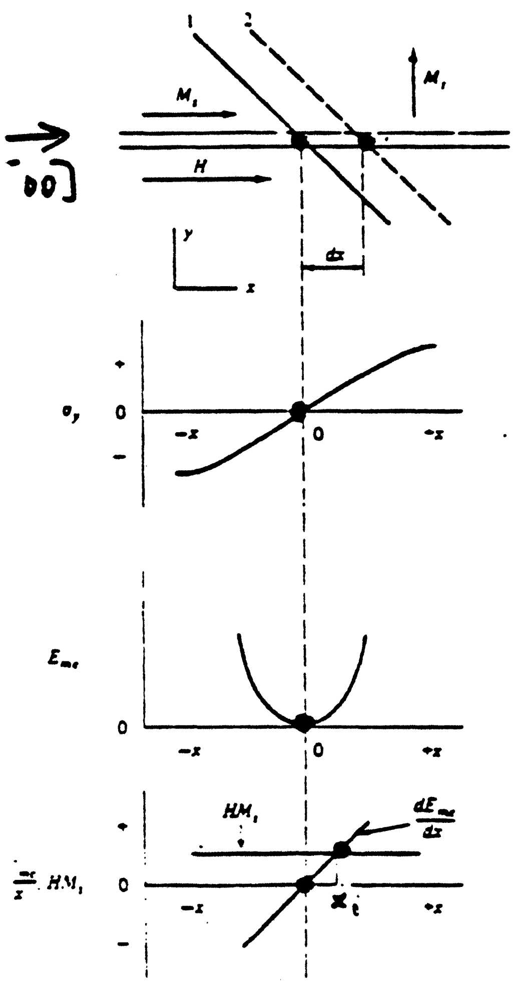


Magnetization results from 180° wall motion

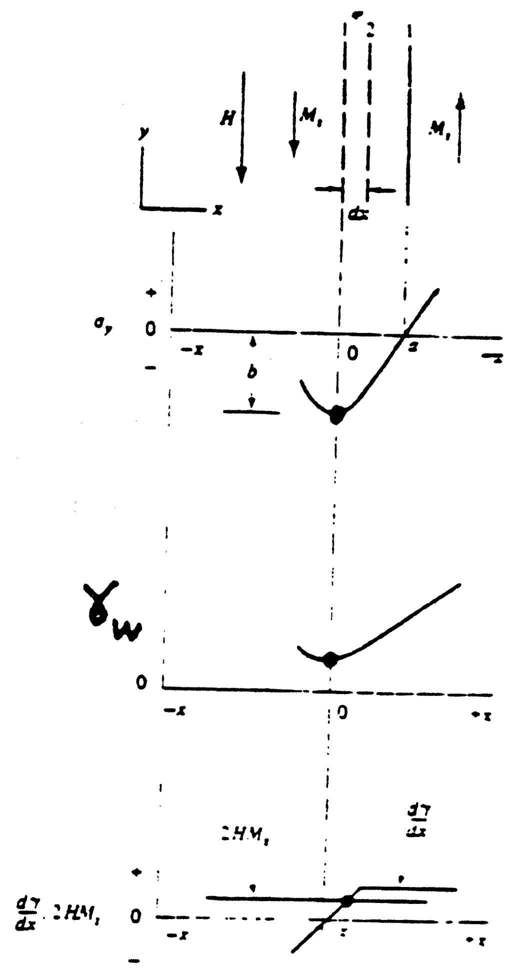
EFFECTS OF INCLUSIONS AND MICROSTRESSES ON WALL MOTION



90° WALL



180° WALL



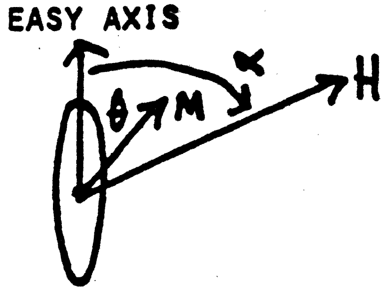
δ_w = wall thickness

l = wavelength of microstress

$$\mu_{R\,\text{initial}} = 1 + \frac{2 M_s^2}{3 \lambda_{100} \frac{d\sigma_y}{dx}\, l}$$

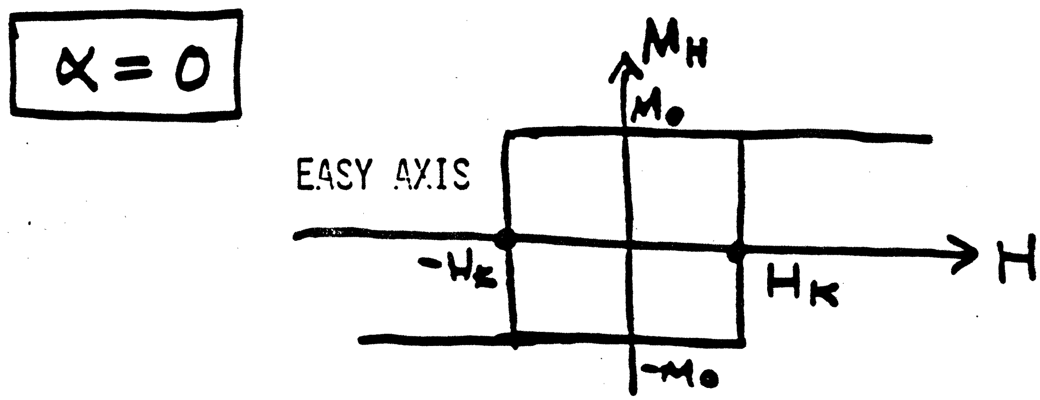
$$\mu_{R\,\text{initial}} = 1 + \frac{2 M_s^2}{3 \lambda_{100} \frac{d^2\sigma_y}{dx^2}\, \delta_w\, l}$$

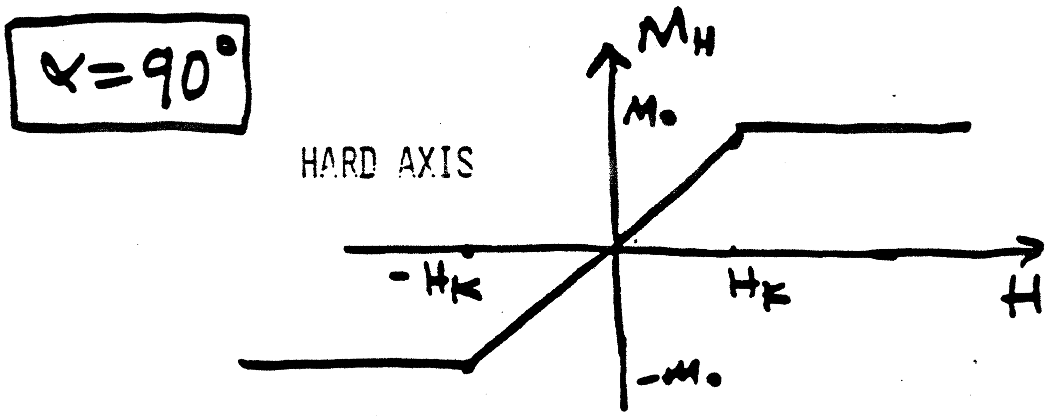
MAGNETIZING BY DOMAIN ROTATION



ANISOTROPY ENERGY DENSITY = $K_U \sin^2 \theta$

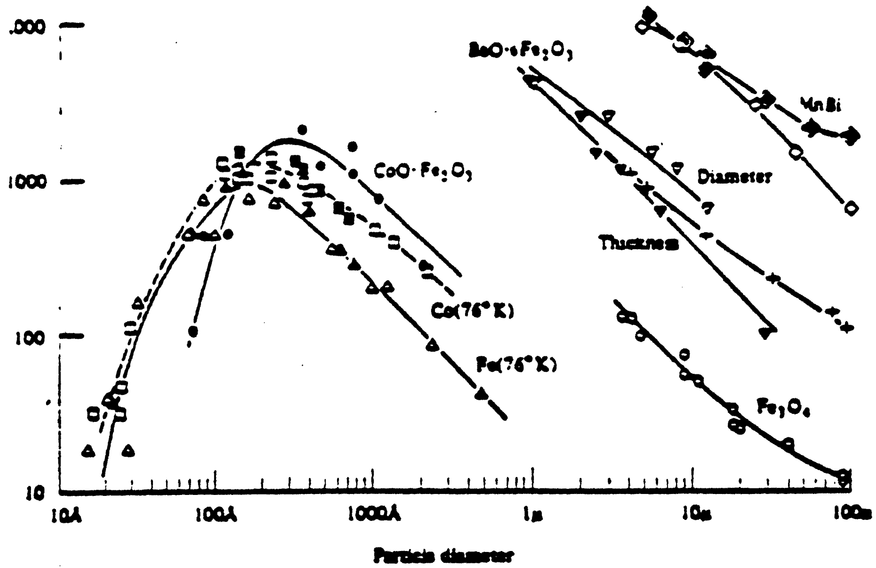
ANISOTROPY FIELD = $2 \frac{K_U}{M} = H_K$

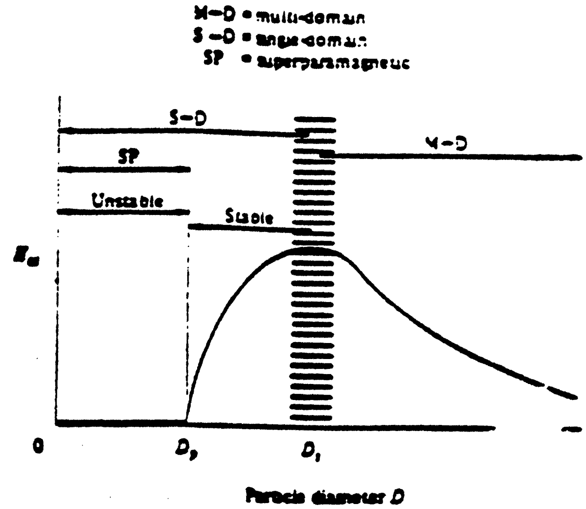




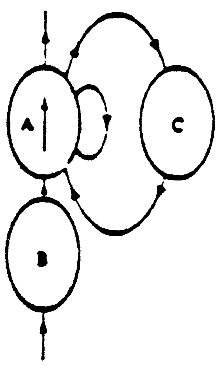
FINE MAGNETIC PARTICLES

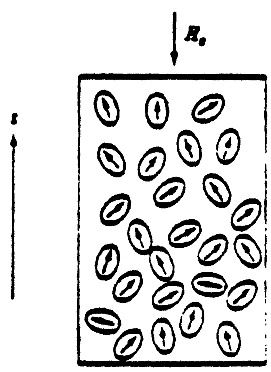
A. COERCIVITY

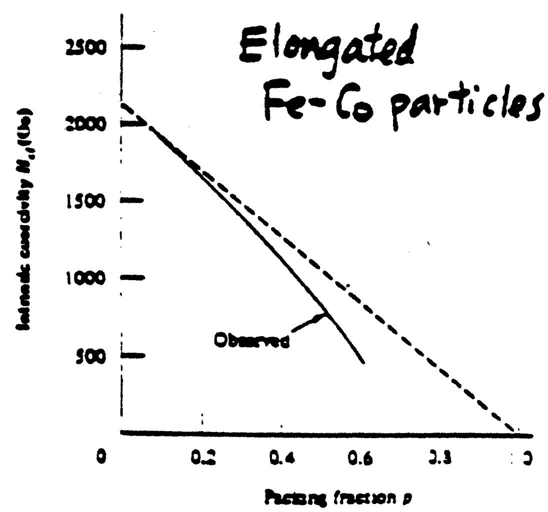




B. PARTICLE INTERACTION





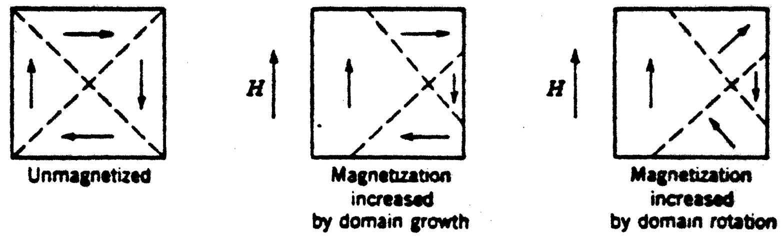


ROTATION REVERSAL

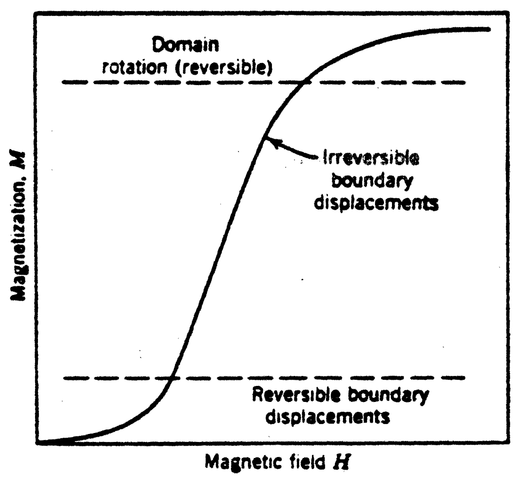
1. COHERENT
2. INCOHERENT (FANNING, CURLING)

MAGNETIZING PROCESSES

Domain Wall Motion and Domain Rotation

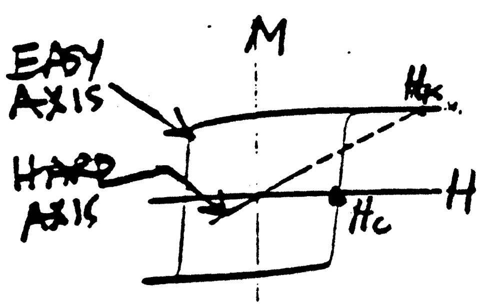


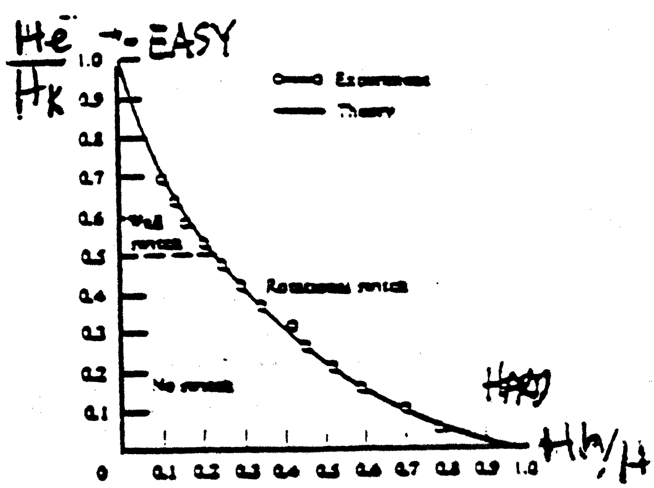
Fundamental magnetization process



Typical magnetization curve

Thin Film Hysteresis Loop and Switching





$$H_K = \frac{2K}{M_s}$$

FACTORS AFFECTING MAGNETIC PROPERTIES

1. COMPOSITION
2. TEMPERATURE
3. STRESS
4. SIZE, SHAPE, ORIENTATION OF GRAINS
5. CONCENTRATION AND DISTRIBUTION OF CRYSTAL IMPERFECTIONS
6. IMPURITIES

MAGNETIC PROPERTIES

A. INTRINSIC (STRUCTURE INSENSITIVE)

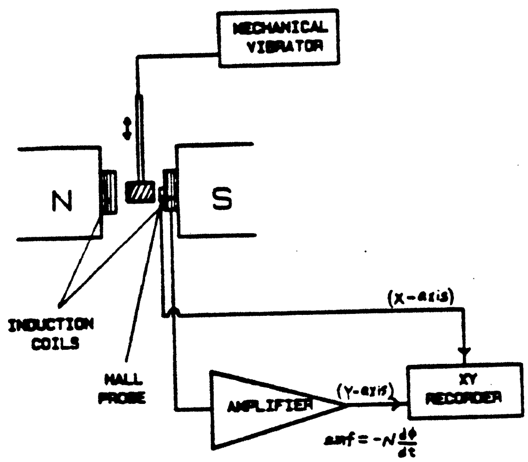
1. SATURATION MAGNETIZATION
2. CURIE TEMPERATURE

B. EXTRINSIC (STRUCTURE SENSITIVE)

1. FLUX DENSITY (INDUCTION)
2. APPROACH TO SATURATION INDUCTION
3. PERMEABILITY
4. COERCIVE FORCE AND COERCIVITY
5. REMANENCE AND RETENTIVITY

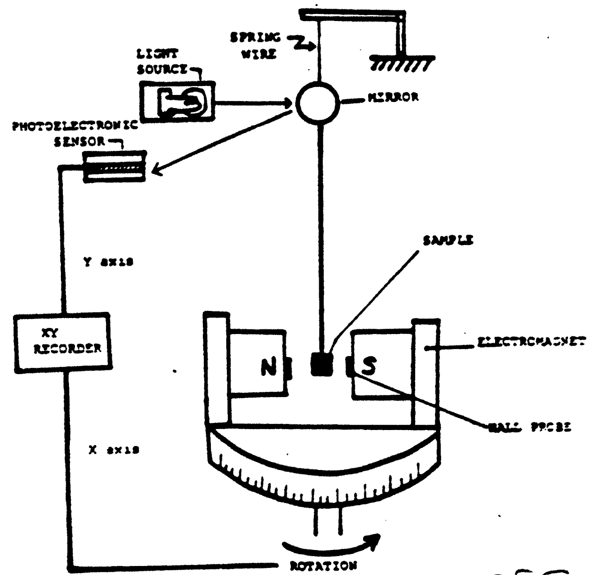
MAGNETIZATION MEASUREMENT TECHNIQUES

VIBRATING SAMPLE MAGNETOMETER



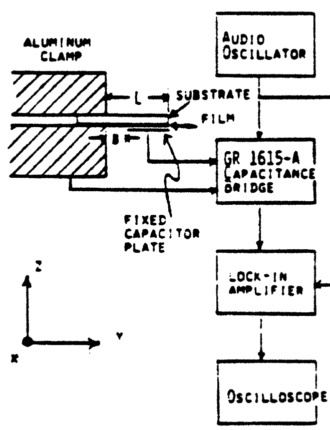
MEASURES MOMENT

TORQUE MAGNETOMETER

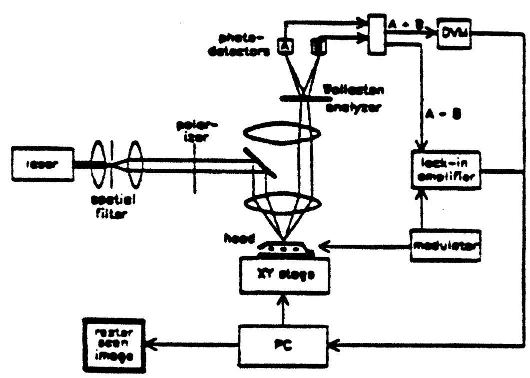


MEASURES "K"

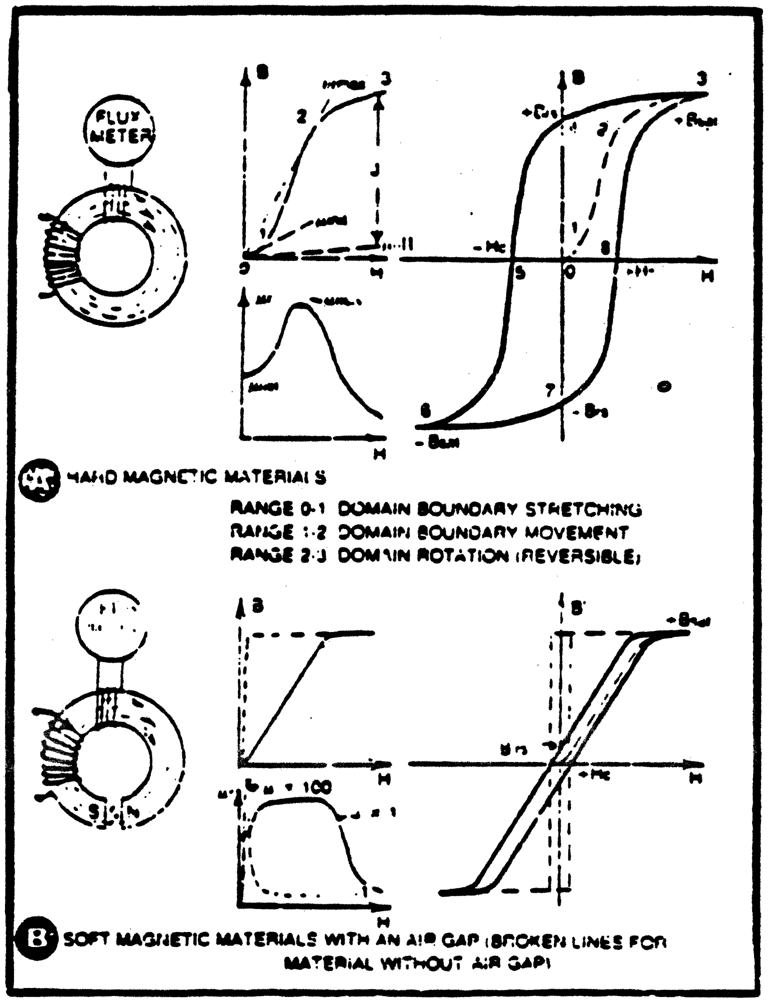
MAGNETOSTRICTION MEASUREMENT



Schematic of scanning Kerr microscope



HYSTERESIS LOOPS OF HARD AND SOFT MATERIALS



Magnetization curves and hysteresis loops.

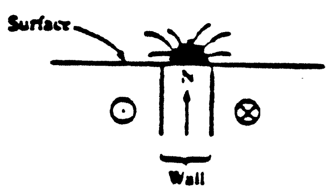
MAGNETIC DOMAIN AND WALL OBSERVATION TECHNIQUES

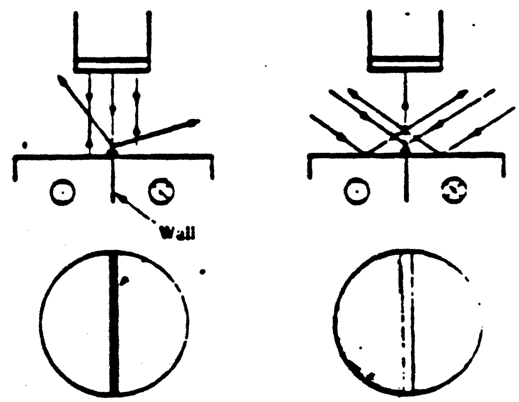
	Method	Cause	Effect observed	Speed	Maximum magnification	Limitations
	Bitter colloid	Stray fields	Walls (domains using extra applied fields)	Quasi-static	≈ 1,000 optically ≈ 10,000 electron microscope	Possibility of interaction with sample. Static method
TEM	Electron microscope (transmission)	Magnetization	Domains and walls	Fast	≈ 100–≈ 20,000 with diminishing sensitivity to magnetization with increasing magnification	Necessity of removing film from substrate
EMM	Electron microscope (reflection)	Stray fields	Walls	Fast	—	Complex to interpret
	Kerr effect	Magnetization	Domains and walls (in principle)	Fast	≈ 250	Low contrast
	Faraday effect	Magnetization	Domains and walls (in principle)	Fast	≈ 400	Useful only for extremely thin films

SEM

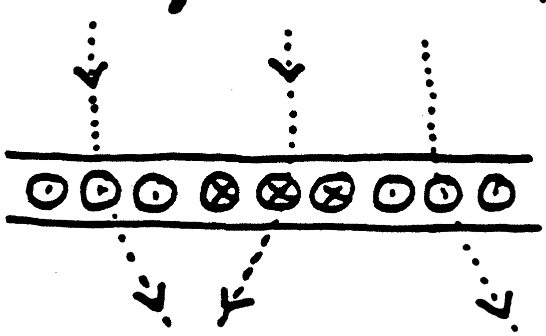
SEMPA

Bitter Colloid



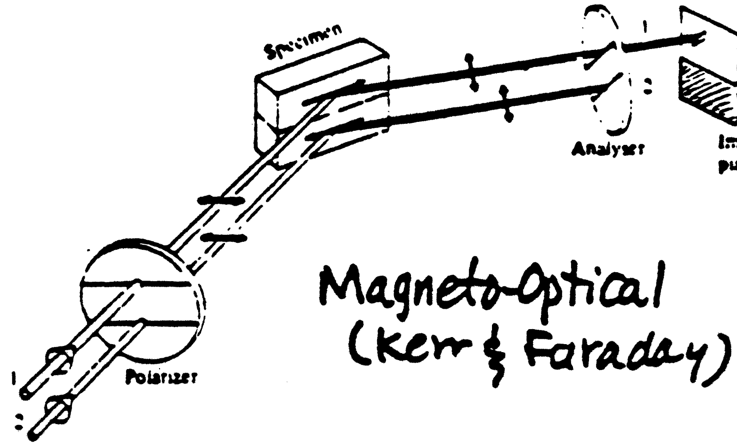


Lorentz Electron Microscopy



(TEM, SEM, EMM)
SEMPA

Kerr



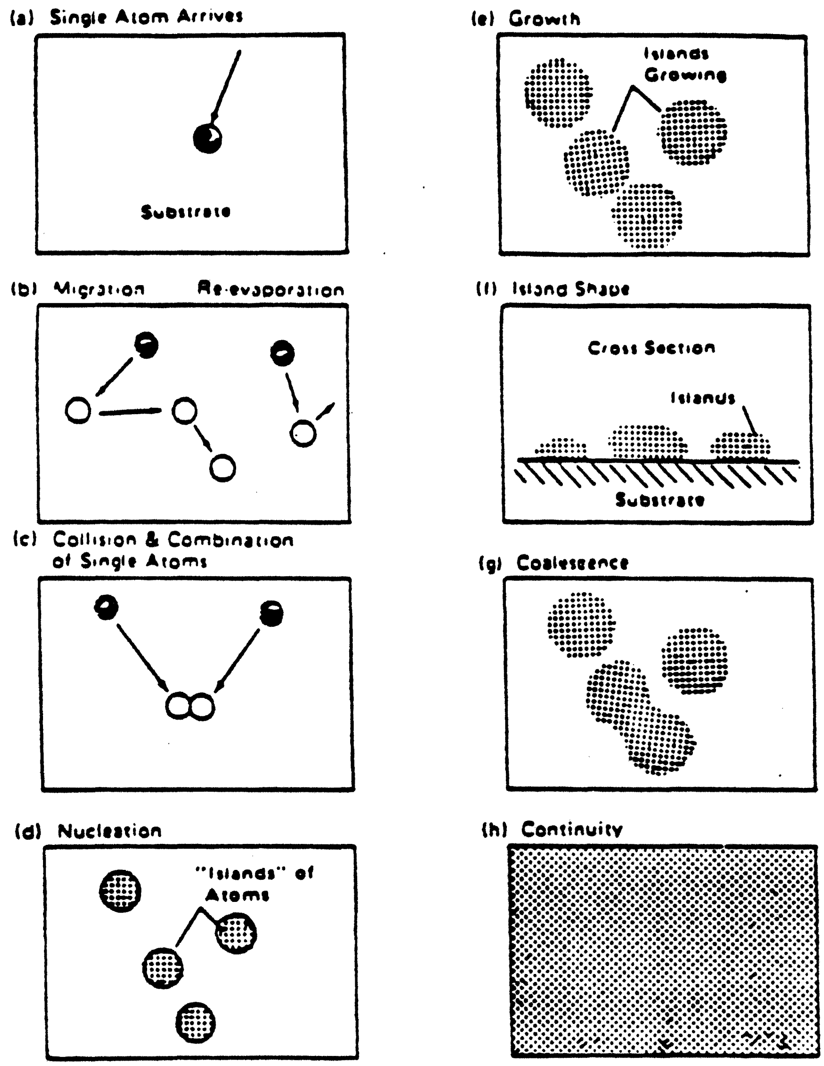
Magneto-Optical (Kerr & Faraday)

THIN FILM DEPOSITION TECHNIQUES

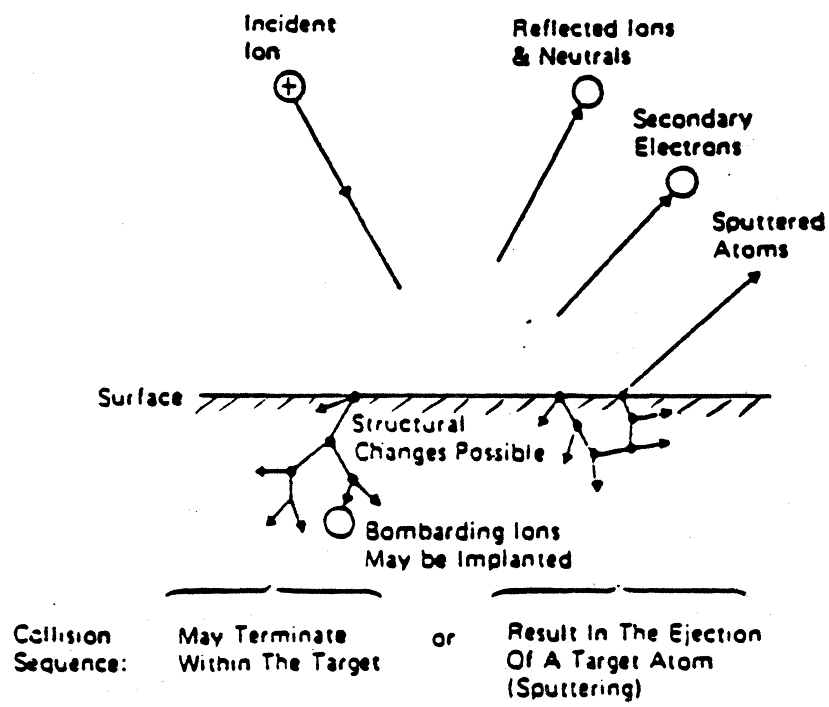
	EVAPORATION	ION PLATING	SPUTTERING
Mechanism of Production of Depositing Species	Thermal Energy	Thermal Energy	Momentum transfer
Deposition Rate	Can be very high (up to 750,000 Å/min.)	Can be very high (up to 250,000 Å/min.)	Low except for pure metals (e.g. Cu - 10,000 Å/min.)
Depositing Specie	Atoms and Ions	Atoms and Ions	Atoms and Ions
Throwing Power for:			
a. Complex Shaped Object	Poor line-of-sight coverage except by gas scattering.	Good, but nonuniform thickness distributions.	Good, but nonuniform thickness distribution.
b. Into Small Blind Holes	Poor	Poor	Poor
Metal Deposition	Yes	Yes	Yes
Alloy Deposition	Yes	Yes	Yes
Refractory Compound Deposition	Yes	Yes	Yes
Energy of Depositing Species	Low ≈ 0.1 to 0.5 eV	Can be high (1-100 eV)	Can be high (1-100 eV)
Bombardment of Substrate/Deposit by Inert Gas Ions	Not normally	Yes	Yes or no depending on geometry.
Growth Interface Perturbation	Not normally	Yes	Yes
Substrate Heating (by external means)	Yes normally	Yes or No	Not generally

	CHEMICAL VAPOR DEPOSITION	ELECTRODEPOSITION	THERMAL SPRAYING
Mechanism of Production of Depositing Species	Chemical Reaction	Deposition from Solution	From Flames or Plasma
Deposition Rate	Moderate (200 - 2500 Å/min.)	Low to High	Very high
Depositing Specie	Atoms	Ions	Droplets
Throwing Power for:			
a. Complex Shaped Object	Good	Good	No
b. Into Small Blind Holes	Limited	Limited	Very Limited
Metal Deposition	Yes	Yes - Limited	Yes
Alloy Deposition	Yes	Quite Limited	Yes
Refractory Compound Deposition	Yes	Limited	Yes
Energy of Depositing Species	Can be high with Plasma-aided CVD	Can be high	Can be high
Bombardment of Substrate/Deposit by Inert Gas Ions	Possible	No	Yes
Growth Interface Perturbation	Yes (by rubbing)	No	No
Substrate Heating (by external means)	Yes	No	Not normally

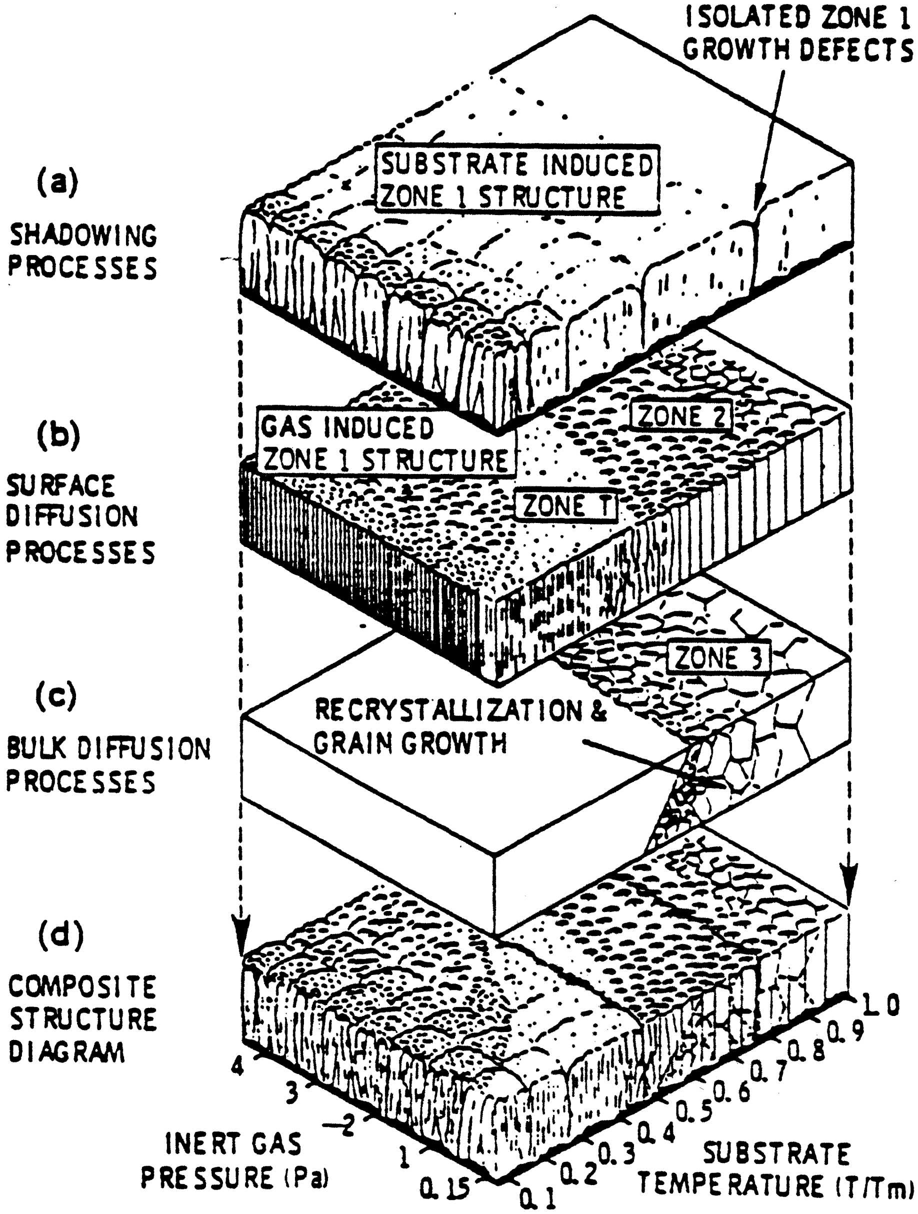
FORMATION OF A THIN FILM



SPUTTERING PROCESSES



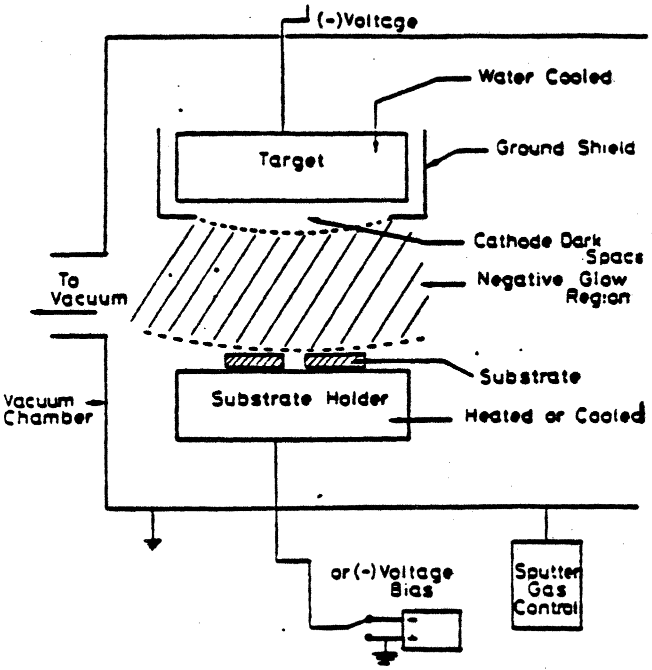
PHYSICAL PROCESSES OF MICROSTRUCTURE ZONES



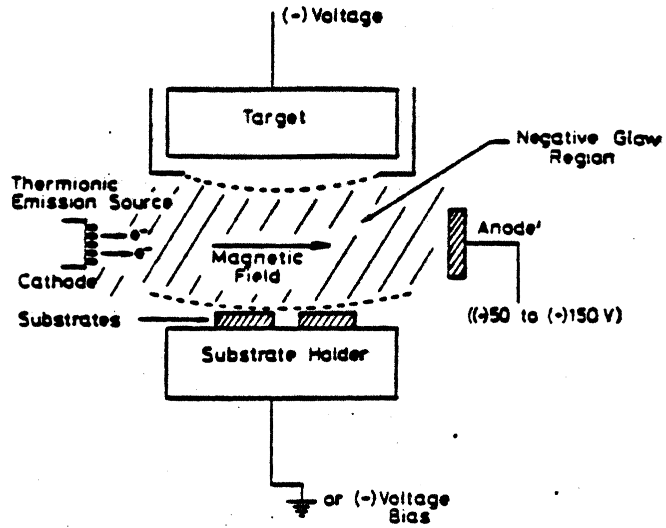
J. THORNTON

THIN FILM SPUTTERING TECHNIQUES

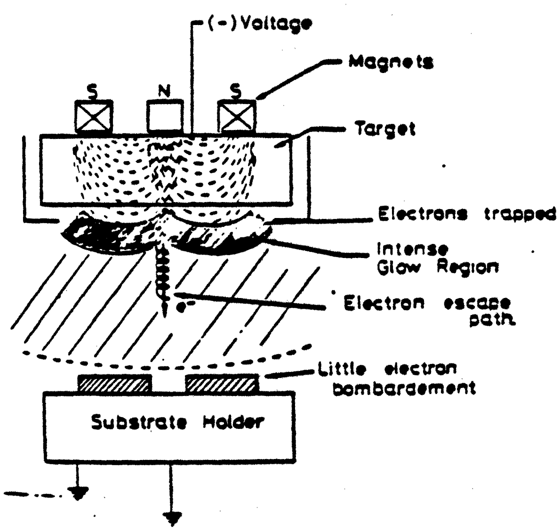
RF DIODE SPUTTERING WITH BIAS



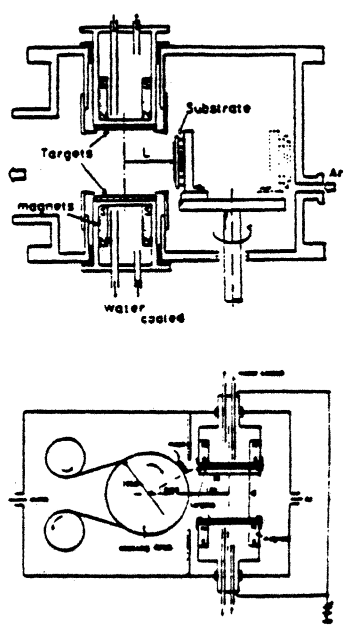
TRIODE SPUTTERING WITH BIAS



DC OR RF MAGNETRON SPUTTERING



FACING TARGET SPUTTERING



THIN FILM MATERIALS CHARACTERIZATION TECHNIQUES

PRIMARY EXCITATION \ DETECTED EMISSION		OPTICAL	X-RAYS	ELECTRONS		IONS (+ AND -)
PHOTONS	OPTICAL	"AA": ATOMIC ABSORPTION "IR": INFRARED } SPEC- VISIBLE } TROS- "UV": ULTRAVIOLET } COPY		"ESCA": ELECTRON SPECTR. F. CHEMICAL ANALYSIS	"UPS": VAC. UV PHOTOELECTRON SPECTROSCOPY - OUTER SHELL	
PHOTONS	X-RAYS		X-RAY FLUORESCENCE SPECTROMETRY X-RAY DIFFRACTION		"XPS": X-RAY PHOTOELECTRON SPECTROSCOPY - INNER SHELL	
ELECTRONS			"EPM": ELECTRON-PROBE MICRO-ANALYSIS	"AES": AUGER ELECTRON SPECTROSCOPY "SAM": SCANNING AUGER MICROANALYSIS "SEM": SCANNING ELECTRON MICROSCOPY "TEM": TRANSMISSION ELECTRON MICROSCOPY		
IONS (+ AND -)		["SCANIIR": Surf. Comp. by Anal. of Neutral and Ion Impact Radiation]	[Ion-Induced X-Rays]			"SIMS": SECONDARY ION MASS SPECTROMETRY "IPM": ION-PROBE MICRO-ANALYSIS "ISS": ION SCATTERING SPECTROMETRY ["RBS": Rutherford Backscattering Spectrometry]
RADIATION		"ES": EMISSION SPECTROSCOPY				"SSMS": SPARK SOURCE MASS SPECTROGRAPHY

Characteristic	AES	XPS	ISS	SIMS	RBS	NRA	IXX
Elemental Analysis							
Sens.Varia.	Good	Good	Good	Poor	Fair	Fair	Good
Resolution	Good	Good	Fair	Good	Fair	Good	Good
Detection Limits	0.1%	0.5%	0.1%	10^{-4}% or higher	10^{-3} or higher	10^{-2} or higher	10^{-2} or higher
Quantification	← with difficulty → req.standards			very difficult req.standards	← absolute → no standards		
Chemical State	Yes	Yes	No	Yes		No	
Depth Analysis	← Destructive → sputter				← Non-destructive →		very difficult
Depth Resolution	← Atomic layer to % of sputter depth				10 nm	10 nm	None
Lateral Resolution	200nm	2mm	100μm	100-1μm	← 1mm →		
Sample Alteration	High for Alkali Halogen Organic Insulators	← Low →			← Very Low →		

MATERIALS FOR THIN FILM HEADS

METALS FOR HEADS

SOFT MAGNETIC MATERIALS FOR MAGNETIC HEADS

	Composition	Permeabilities μ init	μ max	Coercivity H_c Oersted	Saturat. induct. B_s Gauss	Resist. ρ $\mu\Omega$. cm
Permalloy	79 Ni 17 Fe 4 Mo	20.000	100.000	0.05	8.700	55
Mu-Metal	77 Ni 16 Fe 5 Cu 2 Cr	30.000	100.000	0.02	7.500	55
Hy-Mu 800B	80 Ni 16 Fe 4 Mo	70.000	250.000	0.002	8.000	[illegible]
Sendust	85 Fe 9 Si 6 Al	10.000		0.06	10.000	90

(F. Jorgensen)

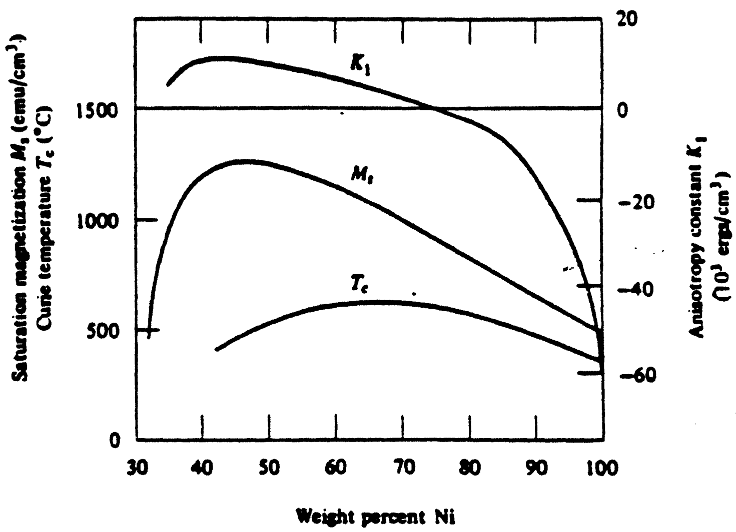
ame	Approximate composition (weight percent) Ni	Fe	Other	Initial permeability	Maximum permeability	Coercivity H_c (Oe)	B_s (gauss)	T_c (°C)	Resistivity (microhm-cm)
Low-Cost Alloys									
n	–	100	–	150	5,000	1.0	21,500	770	10
icon iron	–	96	4 Si	500	7,000	0.5	19,700	690	[illegible]
ain-oriented silicon iron	–	97	3 Si	1,500	40,000	0.1	20,000	740	47
High-Permeability Alloys									
Permalloy	78	22	–	8,000	100,000	0.05	10,800	580	16
pernik	50	50	–	4,000	70,000	0.05	16,000	500	45
79 Permalloy	79	17	4 Mo	20,000	100,000	0.05	8,700	460	55
umetal	77	16	5 Cu, 2 Cr	20,000	100,000	0.05	6,500		62
permalloy	79	16	5 Mo	100,000	1,000,000	0.002	7,900	400	60
High-Saturation Alloys									
rmendur	–	50	50 Co	800	5,000	2.0	24,500	980	7
-Permendur	–	49	49 Co, 2 V	800	4,000	2.0	24,500	980	27
perco	–	64	35 Co, 0.5 Cr	650	10,000	1.0	24,200	970	28
permendur	–	49	49 Co, 2 V		60,000	0.2	24,000	980	27

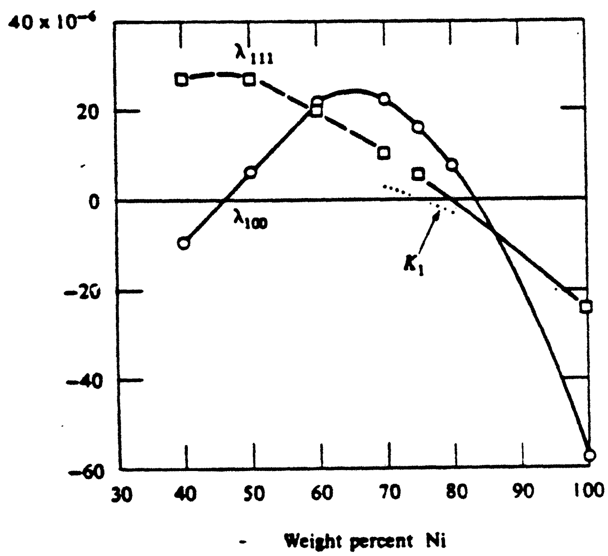
(Cullity.)

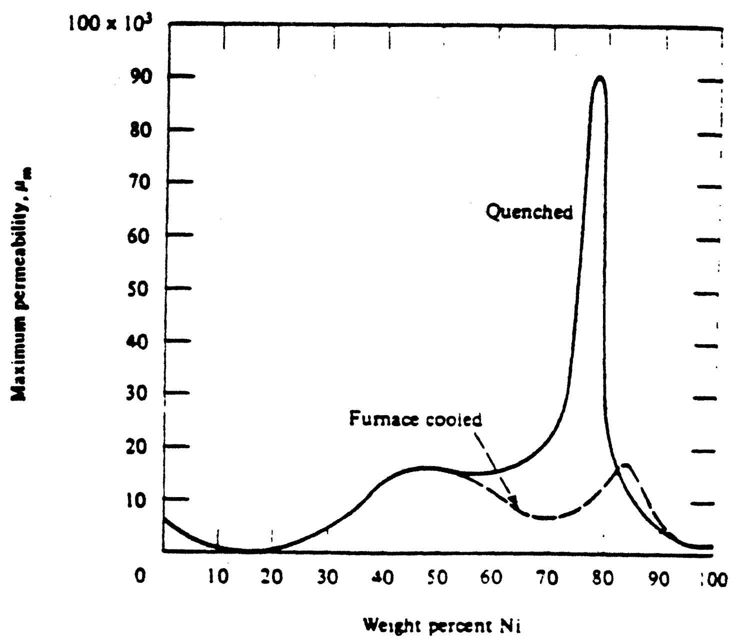
$$\mu_{wall} \propto \frac{M_s^2}{K_{eff}} \qquad \mu_{ROT} \propto \frac{M_s^2 d}{\sqrt{K_{eff}}}$$

d = grain diameter

MAGNETIC PROPERTIES OF NI FE ALLOYS







(Cullity)

PROPERTIES OF AMORPHOUS MAGNETIC THIN FILMS FOR MAGNETIC RECORDING HEADS

Alloy film (at. %)	$4\pi M_s$ (kG)	H_c (Oe)	H_k (Oe)	λ_s (10^{-6})	ρ ($\mu\Omega$ cm)
(1) $Fe_{73}B_{27}$	14	≤0.1	7	50	
(2) $Fe_{80}B_{20}$	~15	~0.04*	7*		
(3) $Fe_{70}Si_{30}$	12	≤0.1	5	30	
(4) $Fe_{72}Si_{28}$	12	0.2	4	30	140
(5) $Fe_{75}C_{25}$	13	<1.0*	<100*	10–13	
(6) $Fe_{58}N_{42}$	9-12	< 100			
(7) $Co_{83}Ti_{17}$	9–10	≤0.45	14*	1.5	~130
(8) $Co_{83}Ta_{17}$	9–10	5–30			
(9) $Co_{93}Zr_{7}$	14–15	0.2*	2–5*	1–3	
(10) $Co_{92.6}Zr_{7.4}$	13	1.0			120–170
(11) $Co_{93}Hf_{7}$	14–15	0.3*	2–5*		
(12) $Fe_{73}B_{21}Si_{6}$	12	~0.2	6	26	
(13) $Fe_{80}B_{15}C_{5}$	14–16	≤1*	~10*		
(14) $Fe_{73}Si_{18}C_{9}$	16–17	~0.2*	~7*		
(15) $Co_{74}Fe_{6}B_{20}$	10–11	<1	~0	<1	
(16) $Co_{79}Fe_{6}B_{15}$	11–13	0.05	~3*	~0.2	90
(17) $Co_{79}Fe_{5}B_{14}$Mo	14–15	0.05	18	~0	
(18) $Co_{83}Ti_{12}B_{5}$	8–9	0.03	10	~0	
(19) $(CoFeB)_{96}Cr_{4}$	10	~2	≤1000		115
(20) $(Co_{93}Fe_{7})_{92}Nb_{8}$	14	≤0.5			
(21) Co Zr Nb	14	.05	2	0.1	

* Annealed (field).

J. K. Howard

J. Vac. Sci. Tech

A4, 1-13 (1986)

FERRITES FOR HEADS

Properties	Symbol	Units	O-6	O-8	T-1	O-3	Q	Q-1	Q-2	Q-3	C-2	TC-7	TC-6	TC-3	TC-4
			STANDARD FERRAMIC MATERIALS									LINEAR TEMPERATURE COEFFICIENT FERRAMIC MATERIALS			
Initial permeability	μ_o	—	@100 kc 4700**	@100 kc 3000	@100 kc 2000	@100 kc 1500	@ 1 mc 850	@ 1 mc 125	@ 1 mc 40	@ 1 mc 16	@ 1 mc 430	@100 kc 1400	@100 kc 1500	@100 kc 1000	@ 1 mc 95
Maximum permeability	μ_{max}	—	6000	4800	3600	4000	4300	400	115	42	4000	1850	2400	2000	420
Saturation flux density @ H = 25 oersteds	B_s	Gauss	4700	4700	4400	4500	3400	3300	2400	2600	3700	3500	4000	3600	3300
Residual magnetism	B_r	Gauss	1400	1000	1000	1600	1470	1800	750	1470	2500 @ D.C. H_m = 1 oersted	550	1600	700	2300
Coercive force	H_c	Oersted	0.10	0.12	0.18	0.15	0.18	2.1	4.7	21	.36 @ D.C.	0.25	0.42	0.25	3.2
Temperature coefficient between +25°C to +80°C	T.C.	%/°C	—	—	—	0.32	0.65	.1 max.	.1 max.	.1 max.	—	0.8 to 2.2 *	***	0.8 to 3.5 *	3.5 to 6.5 *
Curie point	T_c	+°C	210	215	180	190	150	350	450	500	210	140	180	165	425
Volume resistivity	ρ	Ω-Cm	LOW	LOW	LOW	LOW	MED.	HIGH	HIGH	HIGH	LOW	LOW	LOW	LOW	HIGH
Loss factor x 10^{-6} 100 kc/s / 1MC/s / 10MC/s / 50MC/s / 150MC/s		1/μQ	6	7	25	33	300	20 / 60	85 / 170	420	—	5	6.7 / 60	3.3	47
Frequency range	Max.		400 kc	400 kc	400 kc	400 kc	1 mc	10 mc	50 mc	225 mc	—	500 kc	500 kc	1.5 mc	20 mc
Configurations (special configurations on request)			Toroids Recording Heads	Toroids, E, I, U, Cores, Cup, Rods, Powder	SAME	SAME	SAME	SAME	SAME	SAME	Toroids, E, I, U Cores, Cups	Toroids, Cup Cores	SAME	SAME	SAME

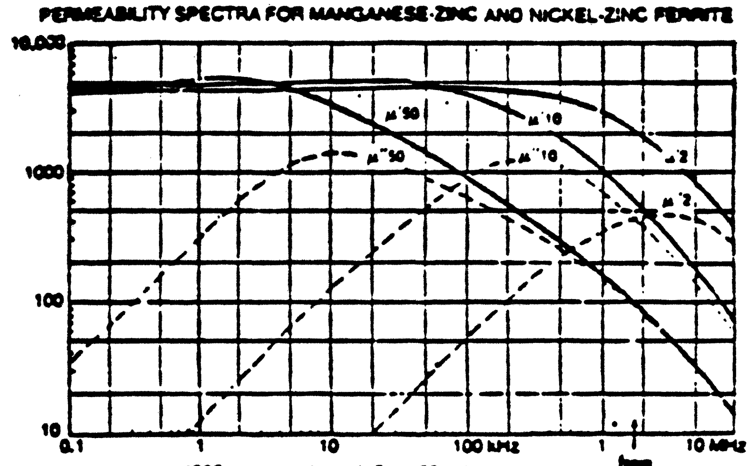
* Temperature Factor (T F) x 10^6 Is Equal To $\Delta\mu/\mu^2C$

** The Tolerance Of O-6 Initial Permeability — ±1600

*** Not to exceed ± 7.5% from 0° C to + 60° C

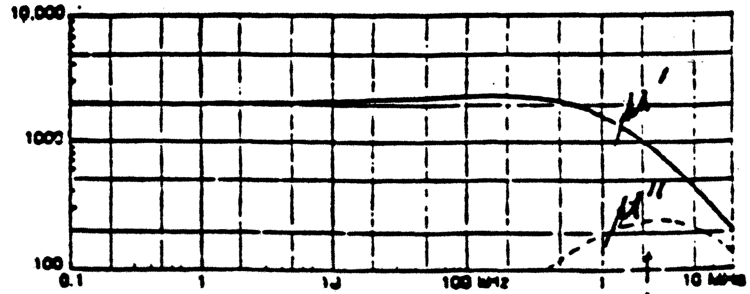
		μ_{i}	μ_{max}	H_c (Oe)	B_s (G)	ρ (μΩ-cm)
	Mn-Zn	2-5,000	5-10,000	0.05	4-6,000	$>10^4$
	Ni-Zn	2,000	2,000	0.15	3,000	$>10^{10}$
	Mn-Zn	3-10,000	7-20,000	0.02 -0.15	4-6,000	$>10^6$

PERMEABILITY SPECTRA FOR MANGANESE-ZINC AND NICKEL-ZINC FERRITE



MnZn: μr = 4000
ρ = 10^4 μΩ.cm
Bs = 5000 G
Hc = 0.1 Oe

μ'50 – μ"50 : 50 mils
μ'10 – μ"10 : 10 mils core
μ'2 – μ"2 : 2 mils core

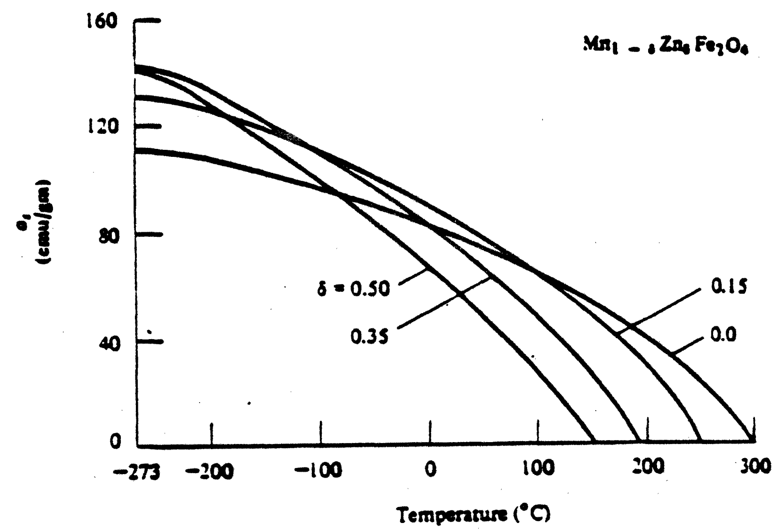


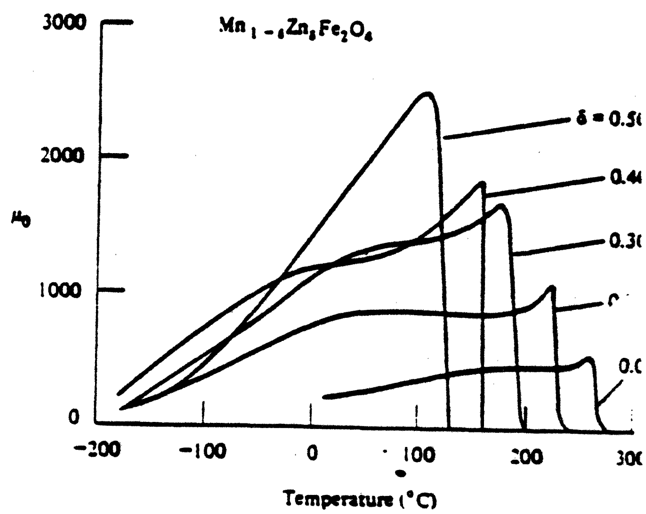
NiZn: μr = 2000
ρ = 10^{10} μΩ cm
Bs = 3000 G
Hc = 0.15 Oe

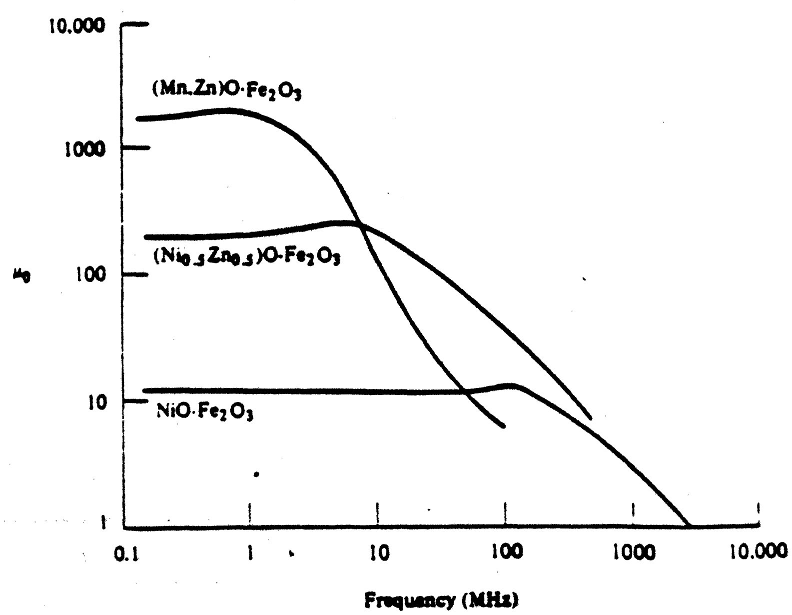
NO EDDY CURRENT LOSSES.

MAGNETIC PROPERTIES OF FERRITES

Composition (mole %)		Sat. ind. (gauss)	Curie temp. (°C)	Initial perm. (gm Oe⁻¹)	Density (gm cm⁻³)	Coercive force (Oe)	Resistivity (ohm cm)
$MnFe_2O_4$	$ZnFe_2O_4$						
48	52	3300	100	1400	4·9	0·2	20
58	42	4500	150	900	4·9	0·3	50
62	38	4700	150	1100	4·9	0·4	80
79	21	5100	210	700	4·8	0·5	80
$NiFe_2O_4$	$ZnFe_2O_4$						
36	64	3600	125	650	4·9	0·4	10^5
50	50	4200	250	230	4·5	0·7	10^5
64	36	4100	350	90	4·2	2·1	10^5
80	20	3600	400	45	4·1	4·2	10^5
100	—	2300	500	17	4·0	11·0	10^5

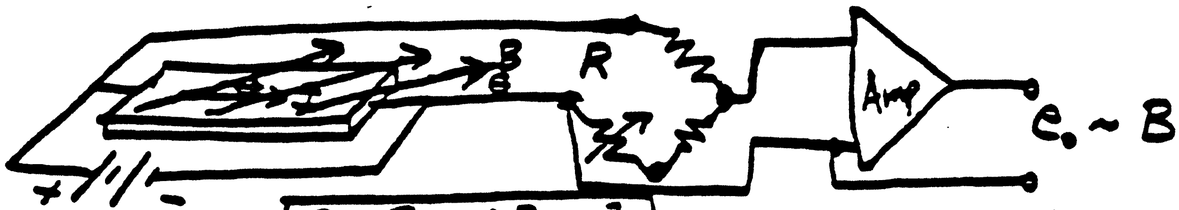






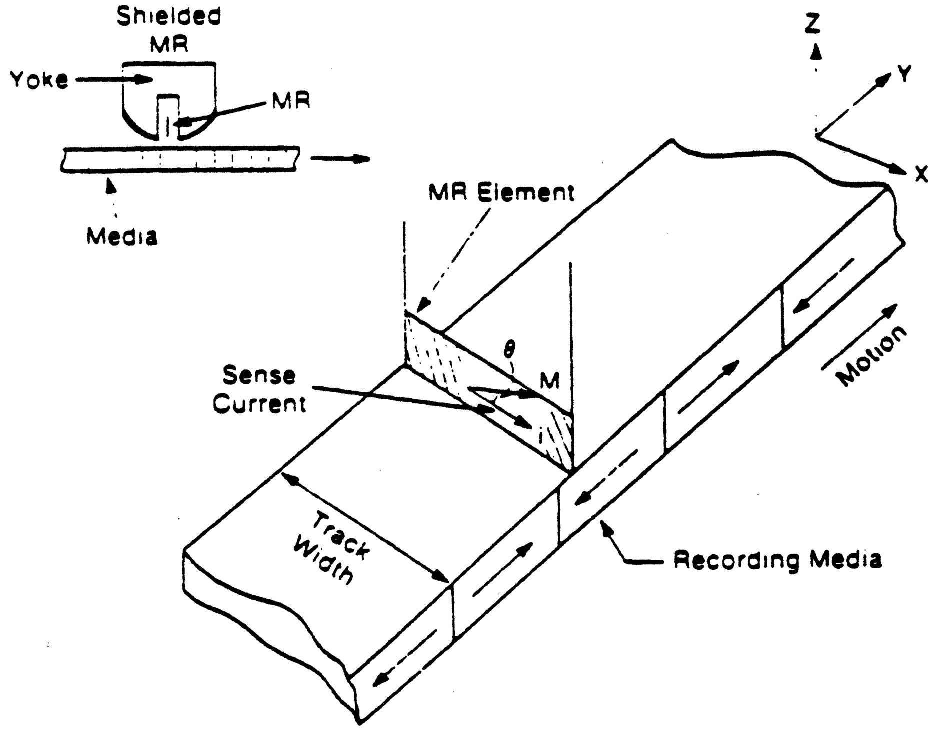
(Cullity)

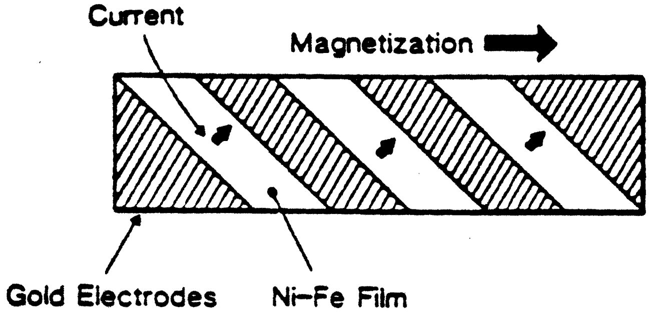
MAGNETORESISTIVE EFFECT FOR THIN FILM READ HEADS

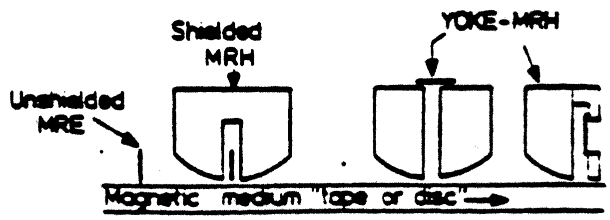


$$R = R_o + \Delta R \cos^2\theta$$

$\frac{\Delta R}{R_o} = 0.02$ for Permalloy ($Ni_{0.8}Fe_{0.2}$)



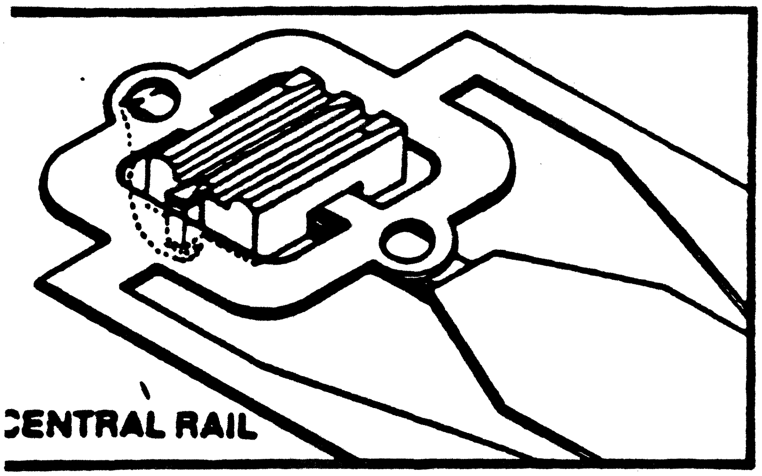




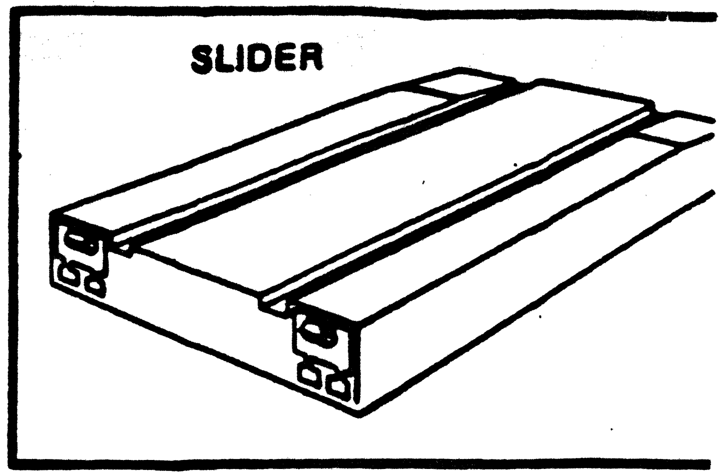
"Barber-pole" magnetoresistive element.

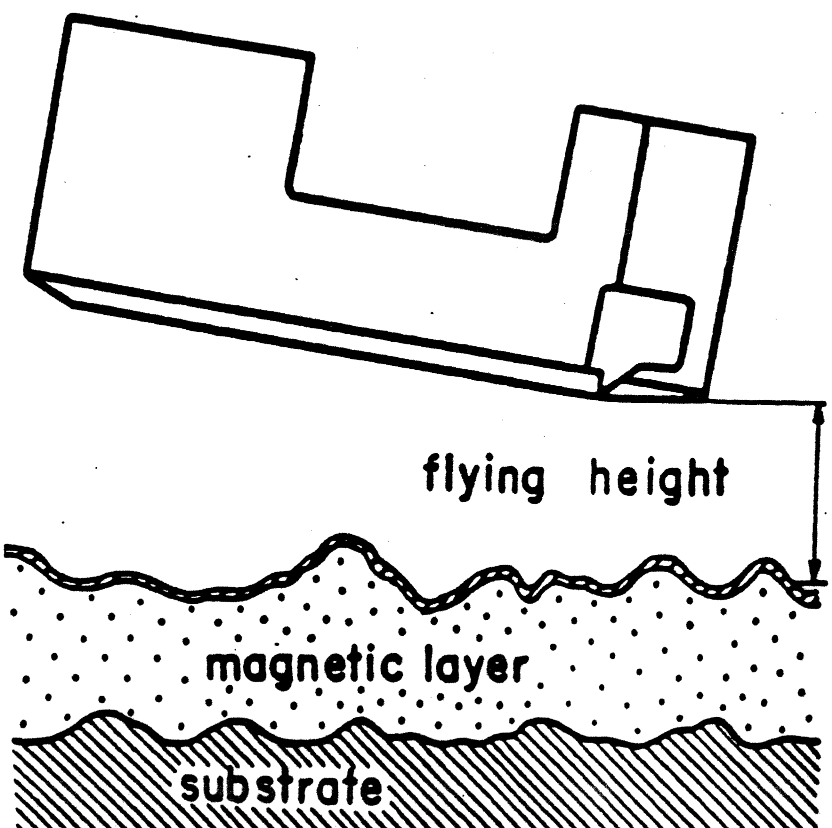
THIN FILM HEAD
VS
FERRITE

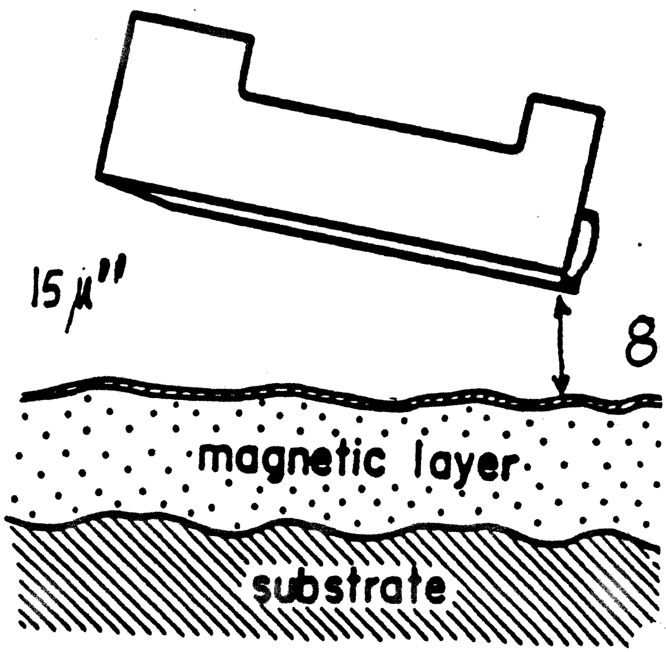
CONVENTIONAL WINCHESTER FERRITE HEAD



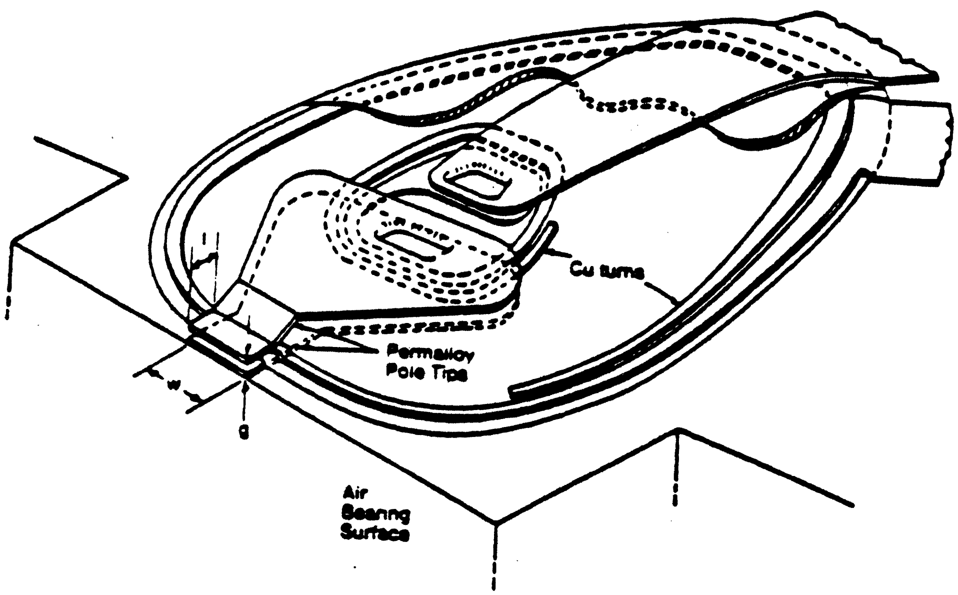
THIN FILM HEAD

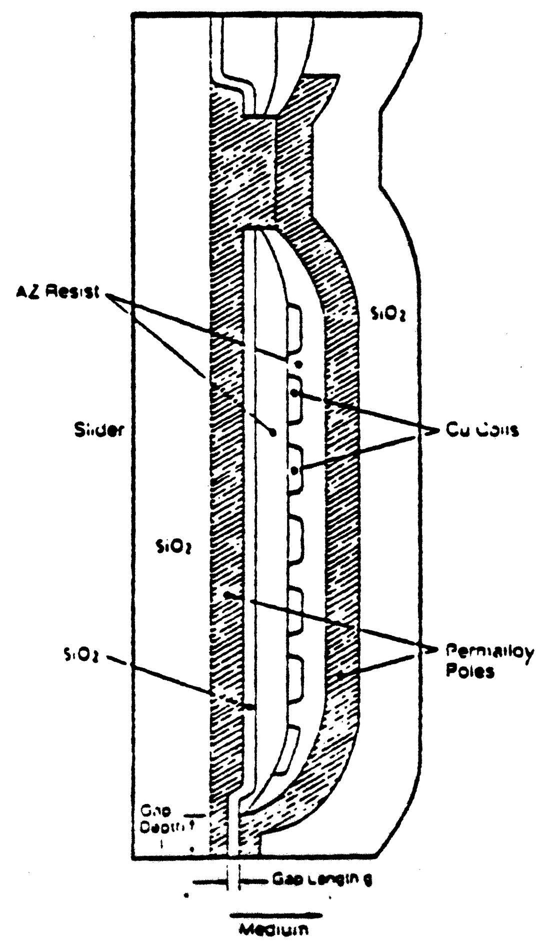






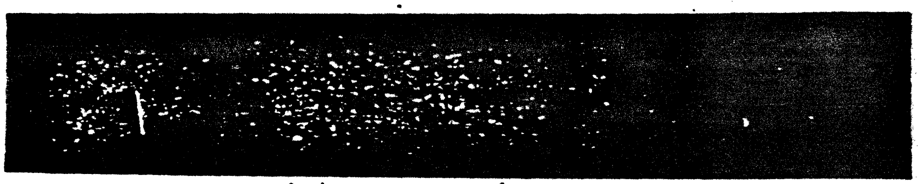
THIN FILM HEAD FOR DISK RECORDING



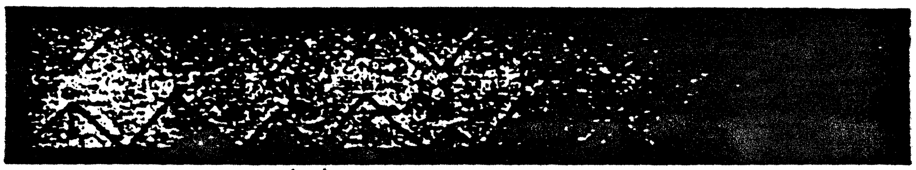


DOMAIN STRUCTURE OF MAIN POLE

OF A THIN FILM HEAD

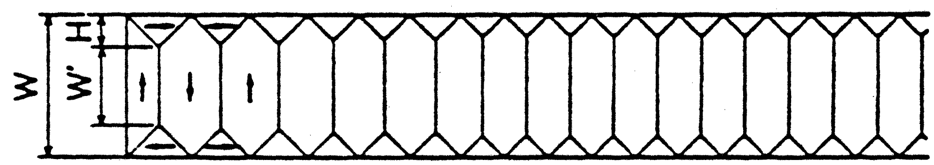


(b) H_k = 6.0 Oe

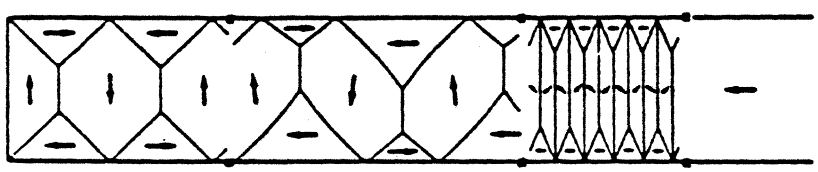


(c) H_k = 2.4 Oe

Domain structures of main pole films having track width of 50 μm, thickness of 0.3 μm and length of 3.5 mm for various anisotropy fields.



(a)

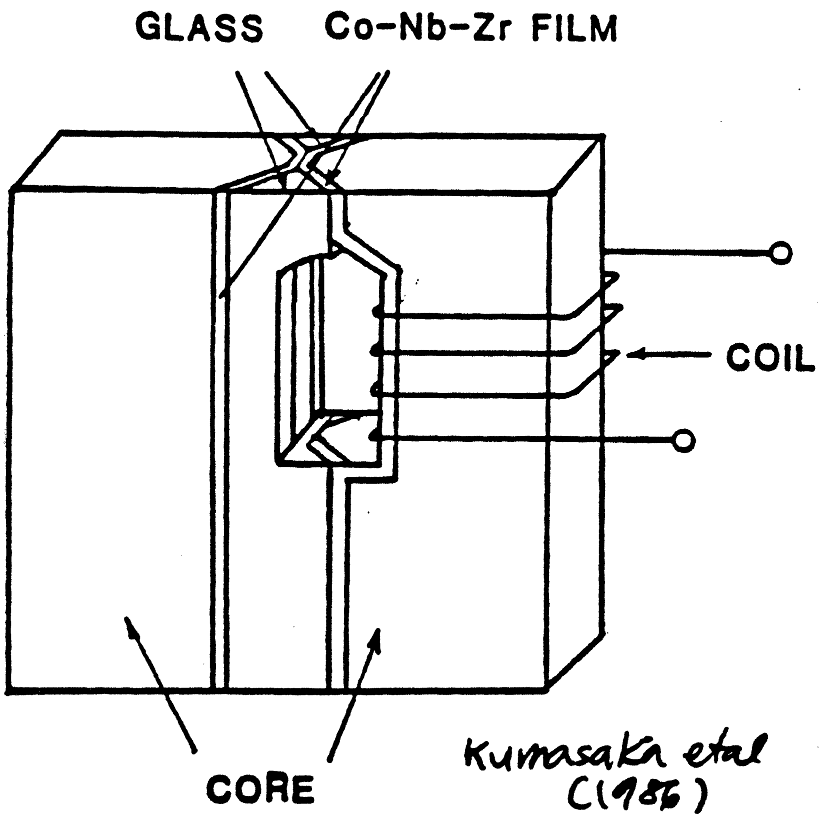


(b)

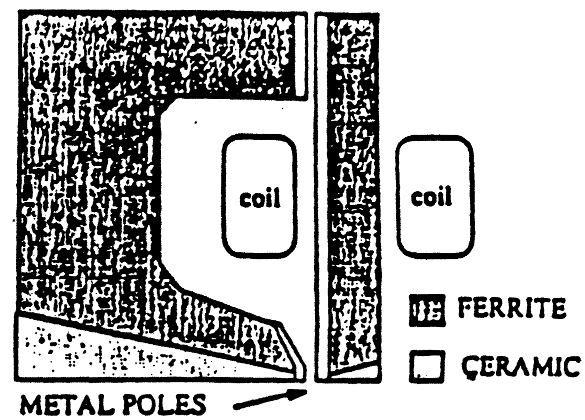
Schematic models of domain structure for films of (a) wide track or high H_k, (b) narrow track and low H_k.

COMPARISON OF RING AND SINGLE POLE HEADS

METAL-IN-GAP RINGS HEADS



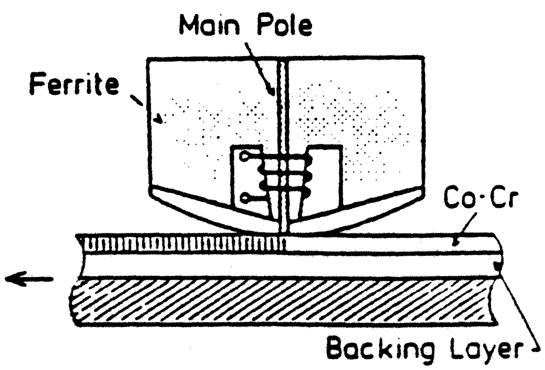
Kumasaka et al (1986)



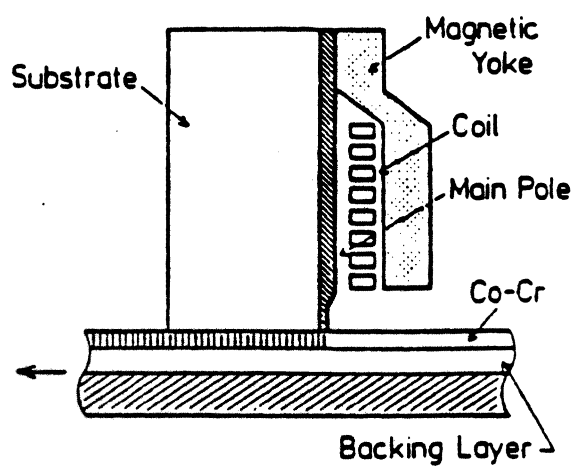
Dugas et al (1987)

SINGLE POLE HEADS

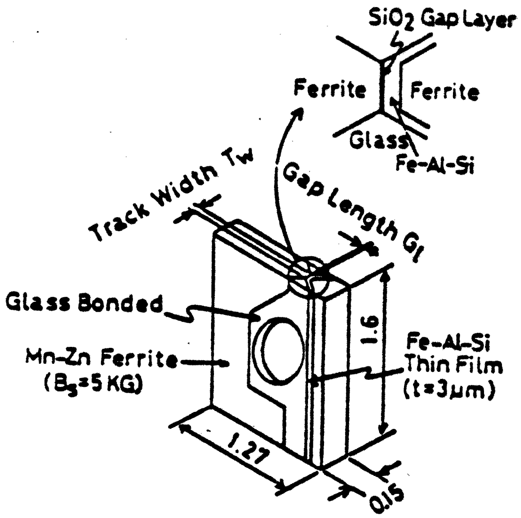
MAIN-POLE DRIVEN



THIN FILM HEAD



SENDUST METAL-IN-GAP MINI-COMPOSITE FERRITE RING HEAD



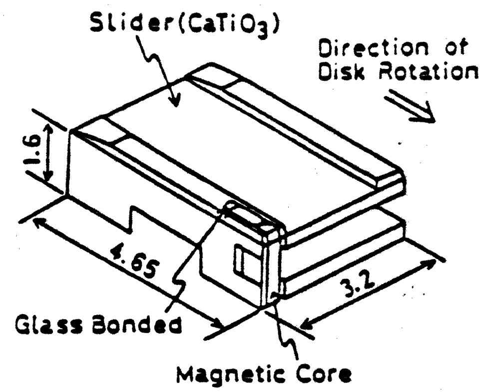
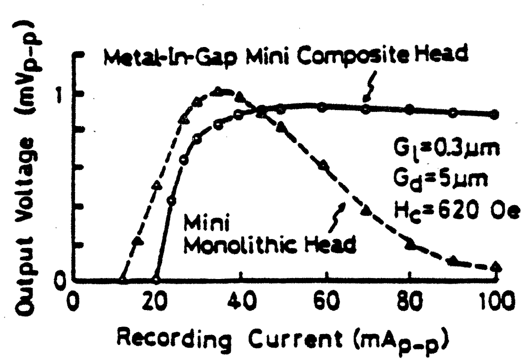
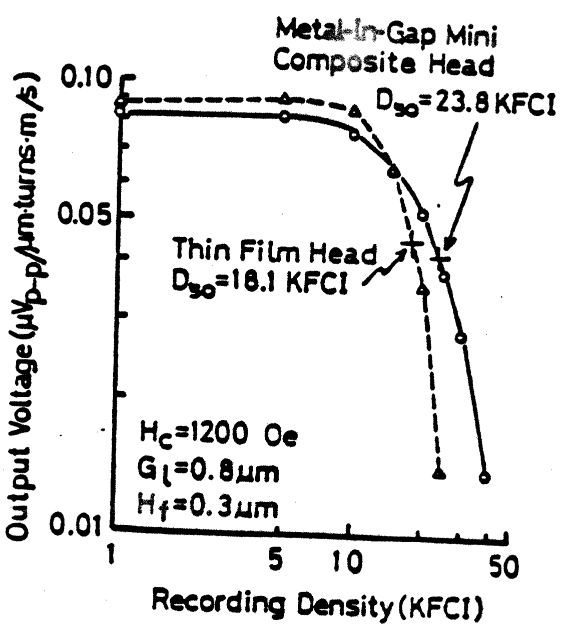
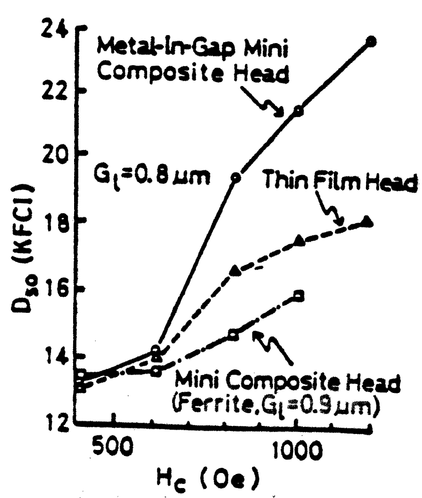


Table I Properties of magnetic materials

	B_S(KG)	μ at 5MHz
Fe-Al-Si	11~12	1000~2000
Mn-Zn Ferrite	5	900~1000

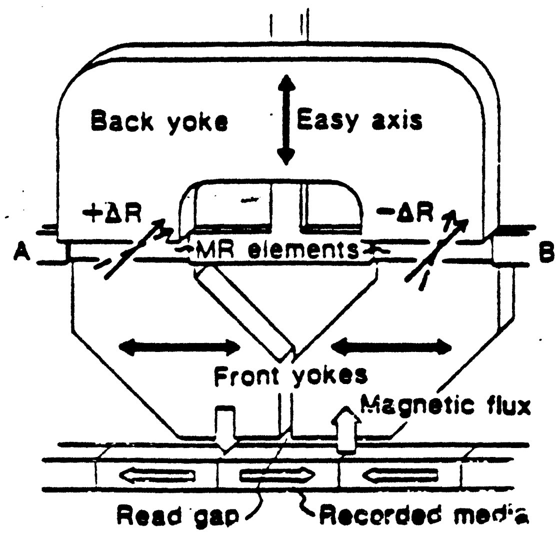


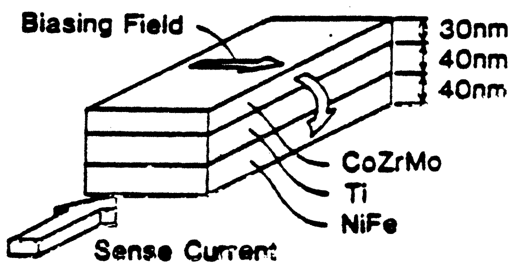


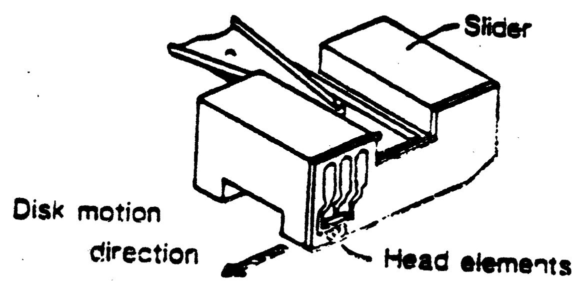


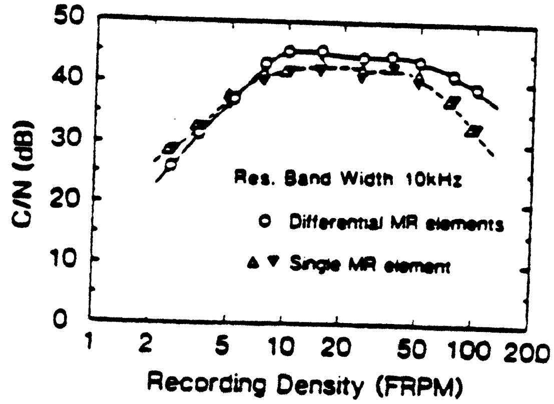
Noguchi etal (Hitachi Metals) (1987)

A YOKE MAGNETORESISTIVE HEAD FOR HIGH TRACK DENSITIES









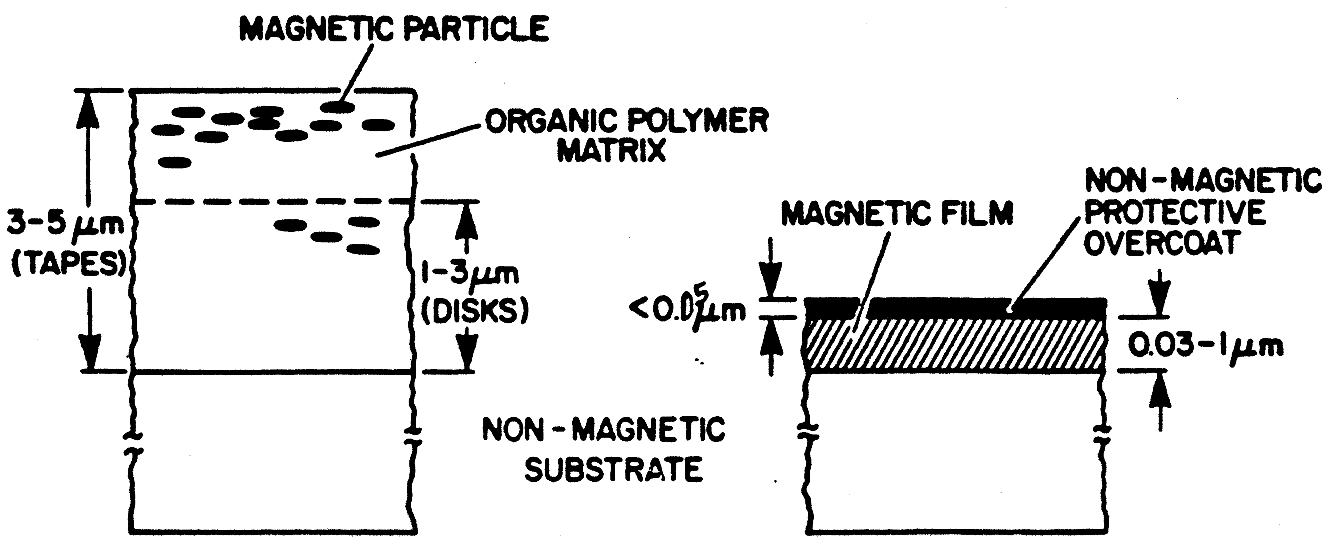
Maruyama et al (NEC) (1987)

Head Comparison

Inductive	MR
Thin film processing	Thin film processing
Velocity dependent	Velocity independent
Same read/write devices	Separate read/write devices
Lower signal levels	High output level
Higher input impedence	Low input impedence
Compromised writer/reader	Optimized writer/reader
Currently at near maximum	Higher track densities
Need to fly low to disk	Can fly higher
Equal read/write widths	Write wide/ read narrow

FILM VERSUS PARTICLES FOR RECORDING MEDIA

FILMS	PARTICLES
ROUGHNESS MORE CRITICAL	CANNOT BE MADE VERY THIN
OVERCOAT REQUIRED	MECHANICAL RESILIENCE IS GOOD
HARMONIC DISTORTION AT LOW FREQUENCY	BETTER WIDE BAND RECORDING
OPTICAL READOUT POSSIBLE	
HIGHER RESOLUTION	
THIN LAYERS EASILY MADE	
BETTER SATURATION RECORDING	



Effect of Squareness of Hysteresis Loop

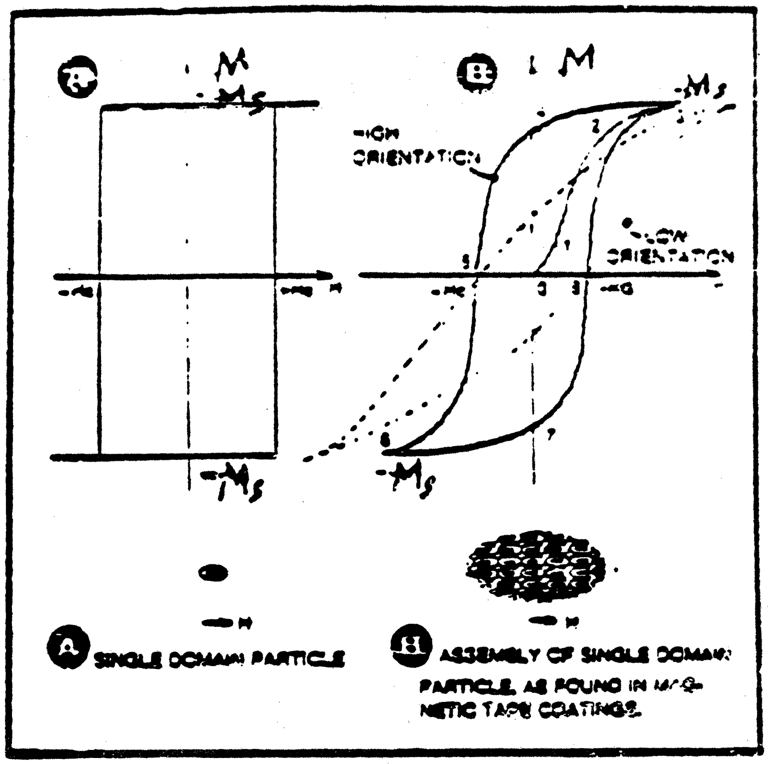


Fig. 3-7. Different hysteresis loops for tape materials. (A), single domain particle (B), assembly of single domain particle, as found in magnetic tape coatings.

Effect of Coercivity and Squareness

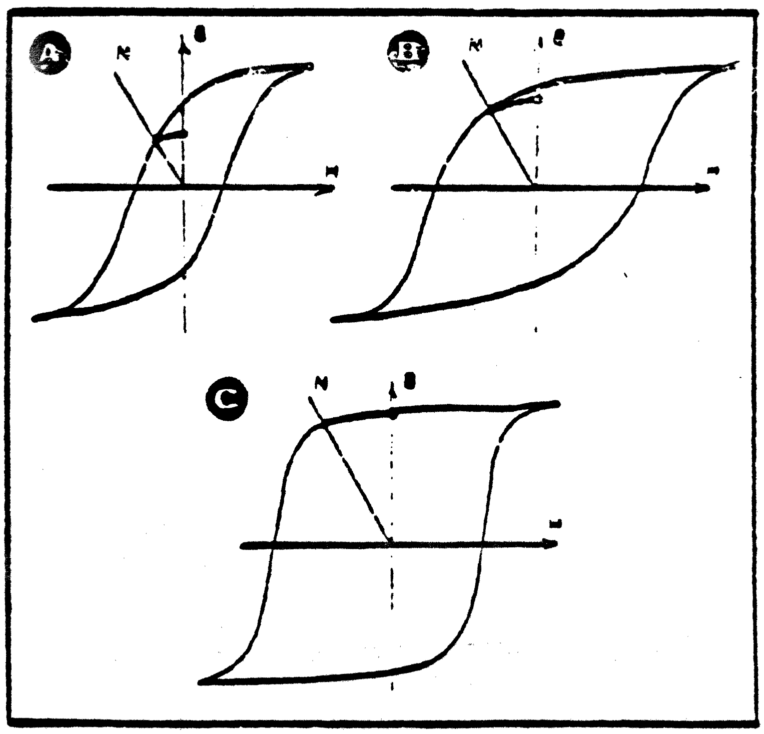
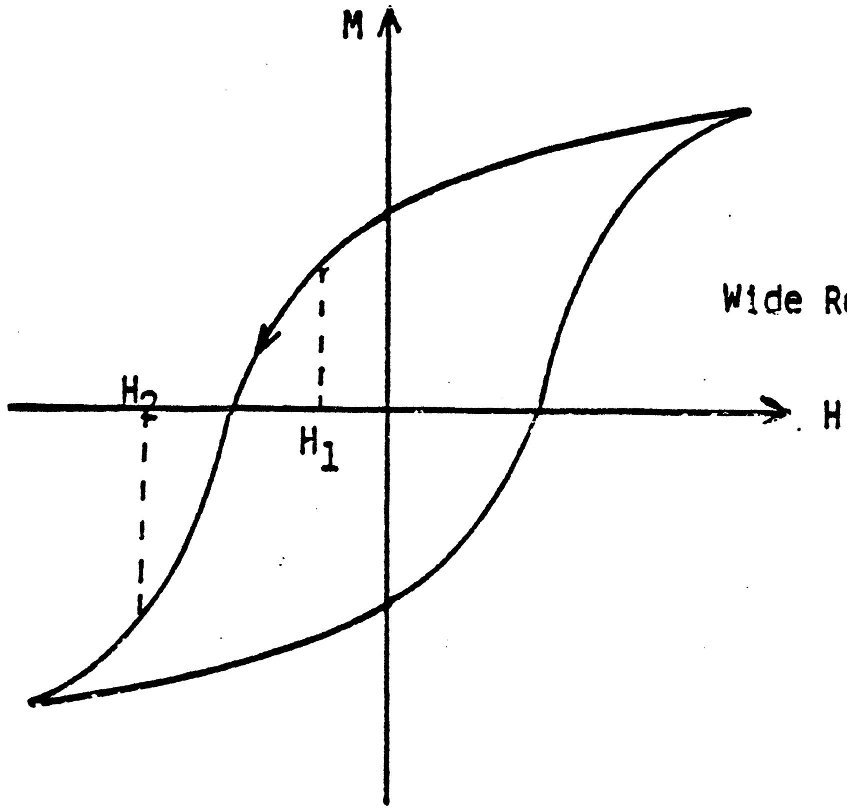


Fig. 6-1. Maximum remanence in magnetic tapes- (A), low coercivity (B), high coercivity. (C), high coercivity, good orientation.

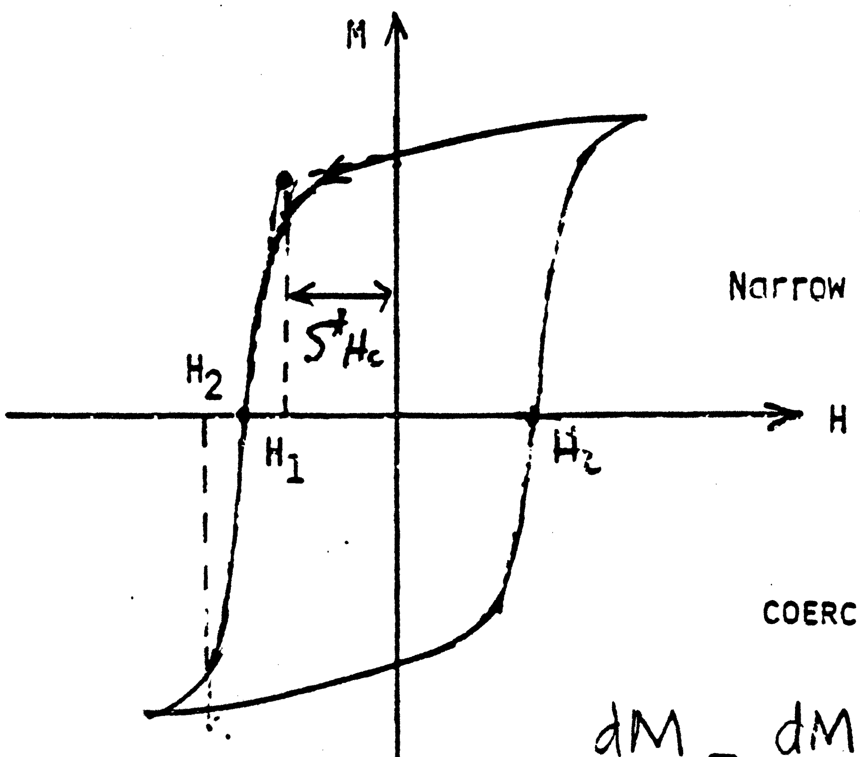
SWITCHING FIELD DISTRIBUTION



Low Squareness

Wide Range of Switching Fields

$\Delta H = H_2 - H_1$



High Squareness

Narrow Range of Switching Fields

$$\text{COERCIVITY SQUARENESS} = S^* = 1 - \frac{\Delta H}{2 H_c}$$

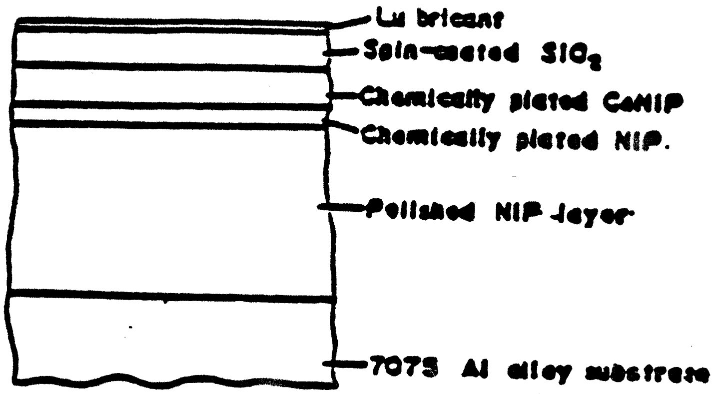
$$\frac{dM}{dx} = \frac{dM}{dH} \cdot \frac{dH}{dx}$$

↑ slope on side of loop

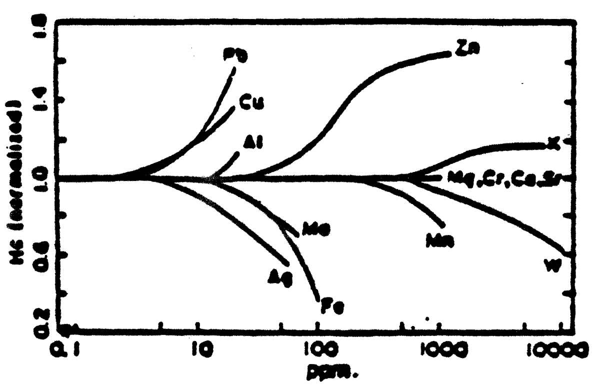
↑ Head field gradient

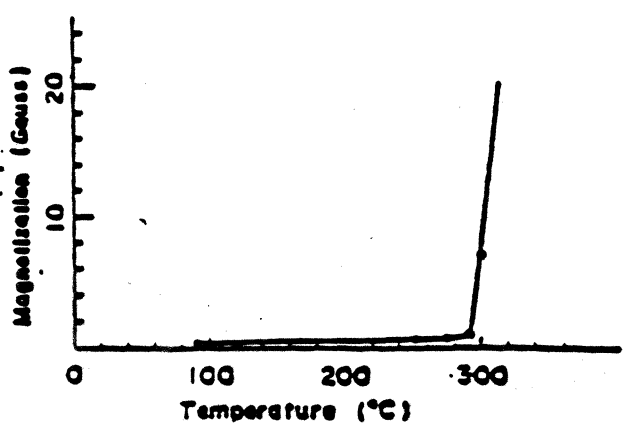
THIN FILM LONGITUDINAL MEDIA

CHEMICALLY PLATED MAGNETIC DISKS



Plated disk cross-section structure.





Y. Suganuma et al, IEEE MAG-18, 1215 (1982)

MAGNETIC RECORDING MEDIA EVAPORATED AT OBLIQUE INCIDENCE

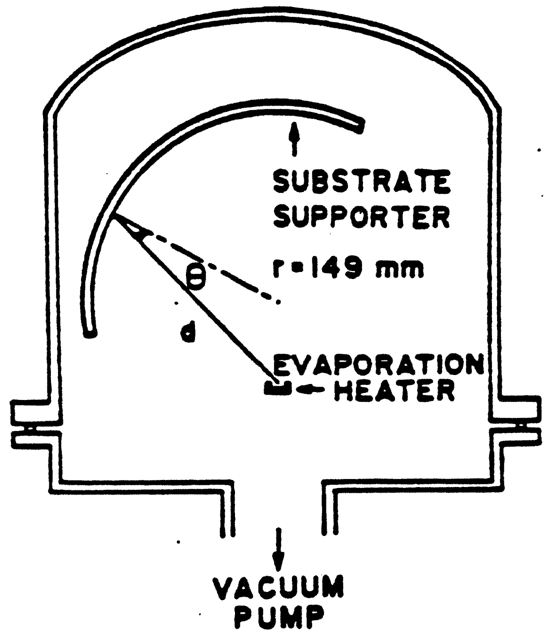


Fig. 1. Illustration of used vacuum system for the oblique incidence. Ferromagnetic alloys were evaporated on a polyimide film which was fixed on a cylindrical shaped substrate supporter.

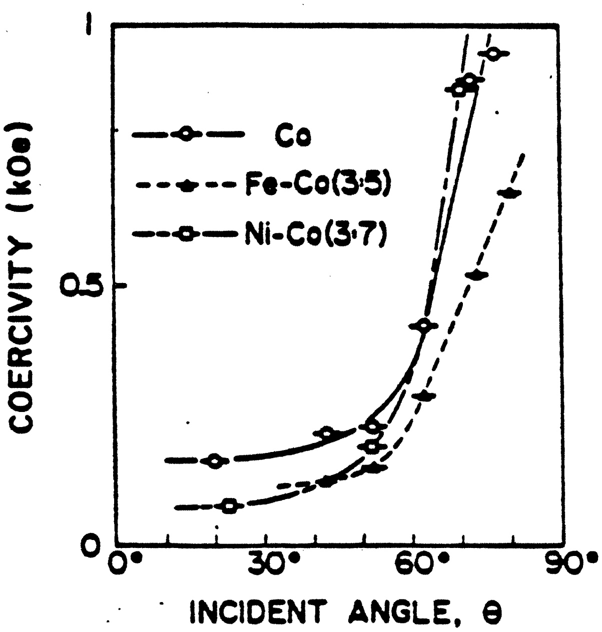


Fig. 2. The coercive force of Co, Fe-Co and Ni-Co thin films were plotted against the angle of incidence.

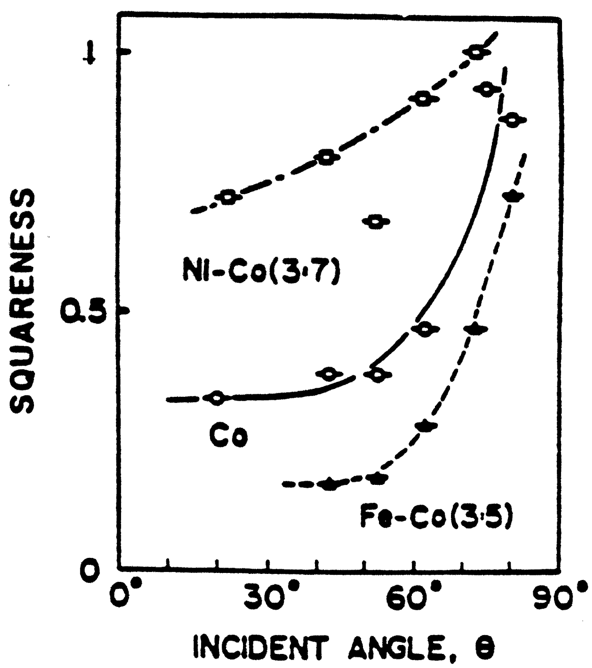


Fig. 3. The squareness in easy direction of Co, Fe-Co and Ni-Co thin films were plotted against the angle of incidence.

E. Kita et al, IEEE Trans. MAG-17,3193(1981)

SPUTTERED CO-Pt FILMS FOR HIGH DENSITY RECORDING

Table 2 Medium properties.

Items	$Co_{0.70}Ni_{0.10}Pt_{0.20}$	Plated Co-Ni-P
Coercivity (Oe)	893	640
Remanence (Gauss)	10,470	7,200
Squareness Br/Bs	0.90	0.76
Coercive Squareness S*	0.97	0.82
Medium thickness (Å)	300	300
Overcoat thickness (Å)	200	200

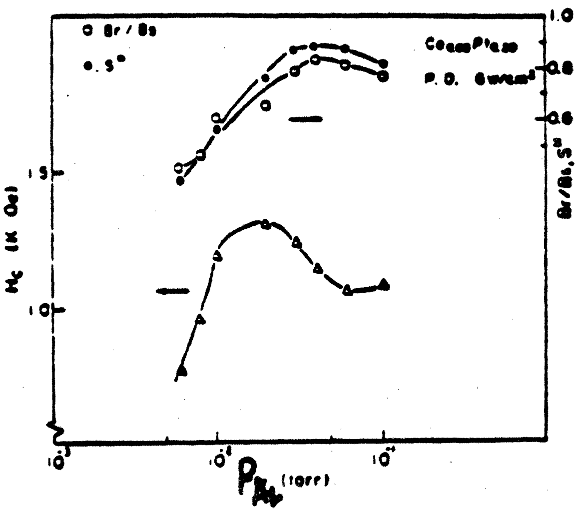


Fig.4 Coercivity and squareness dependences on argon pressure in the Co0.80 Pt0.20 film.

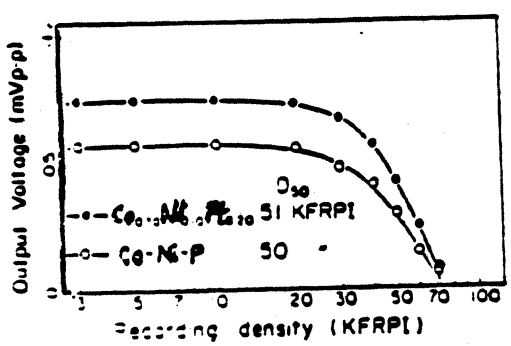


Fig.7 Output voltage versus recording density.

M. Yanagisawa et al, IEEE Trans. MAG-19, 1638 (1983)

CONTINUOUS THIN FILM MEDIA

3.2 GByte Disk System

(PATTY)

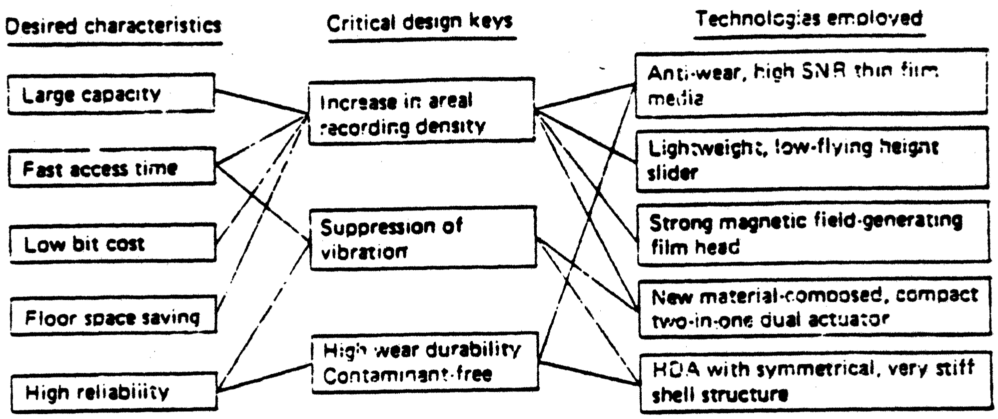
	γ-Fe_2O_3 Thin Film	Co-Ni-P Thin Film
1. Read-write Characteristics		
* Output Signal Voltage	≧0.60 mV_{p-p}	≧0.55 mV_{p-p}
* Resolution	≧75%	≧55%
* Recording Density	≧550 FRPM	≧620 FRPM
* Over-write Characteristics	≦−26 dB	≦−26 dB
* SNR	>32 dB	>28 dB
2. Signal Quality		
* Number of Defects per Surface	≦100	≦100
3. Disk Size		
* Inner Diameter	100+0.1 mm −0.0 mm	100+0.1 mm −0.0 mm
* Outer Diameter	210±0.1 mm	210±0.1 mm
* Thickness	1.905±0.025 mm	1.905±0.025 mm
4. Thin Film Media Properties		
* Film Thickness	0.17±0.01 μm	0.08 +0.005 μm −0.003 μm
* Coercivity	700±40 Oe	600±30 Oe
* Residual Flux Density	2500±200 Gauss	7200±300 Gauss
* Coercive Squareness	≧0.77	≧0.77
5. Mechanical Properties		
5.1 Surface Roughness		
* Arithmetic Average	≦0.01 μm	≦0.01 μm
* Axial Runout	≦40 μm	≦40 μm
* Acceleration of Axial Runout (a)	$\|a\|$ ≦40 m/sec²	$\|a\|$ ≦40 m/sec²
* Minimum Head Flying He Height	≦0.18 μm	≦0.15 μm
5.2 Lubricating Properties		
* Maximum Coefficient of Friction	≦0.3	≦0.3
* CSS Characteristics	≧20,000 cycles	≧20,000 cycles
6. Protective Film Thickness	0.000 μm	0.08 ±0.01 μm
7. Reliability	* No deterioration is caused at 40℃ for 7 months under 80% relative phumidity * Output signal quality does not deteriorate	

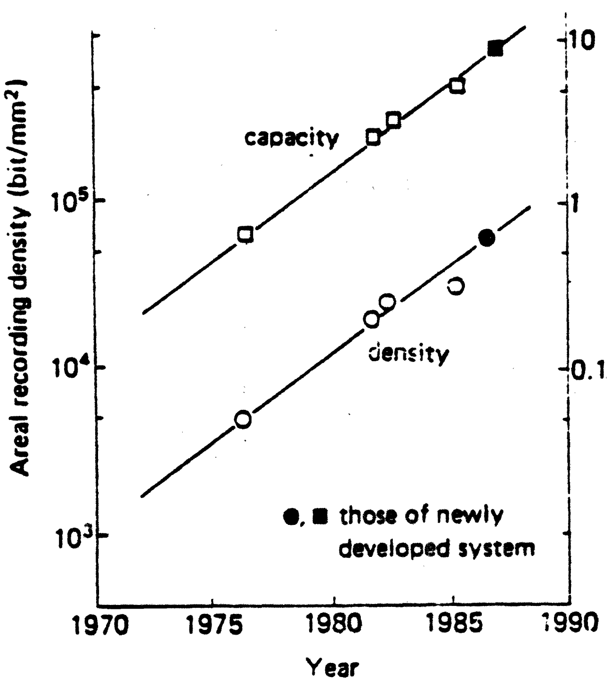
S. Hattori et al, NEC (1983)

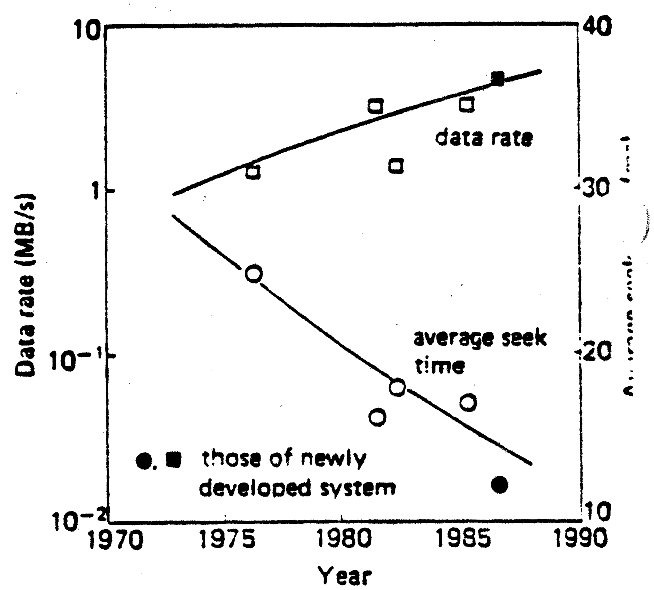
ADVANCED CONTINUOUS THIN FILM MEDIA

8.8 GByte Disk System

(GEMMY)







Thin Film Media

	γ-Fe_2O_3	CoNiP
B_R (G)	2200	8000
H_c (Oe)	700	800
δ (Å)	1600	500

Thin Film Head

Gap (µm)	0.5
Pole (µm)	3
Slider	Al_2O_3-TiC
Height (µm)	< 0.2

GEMMY

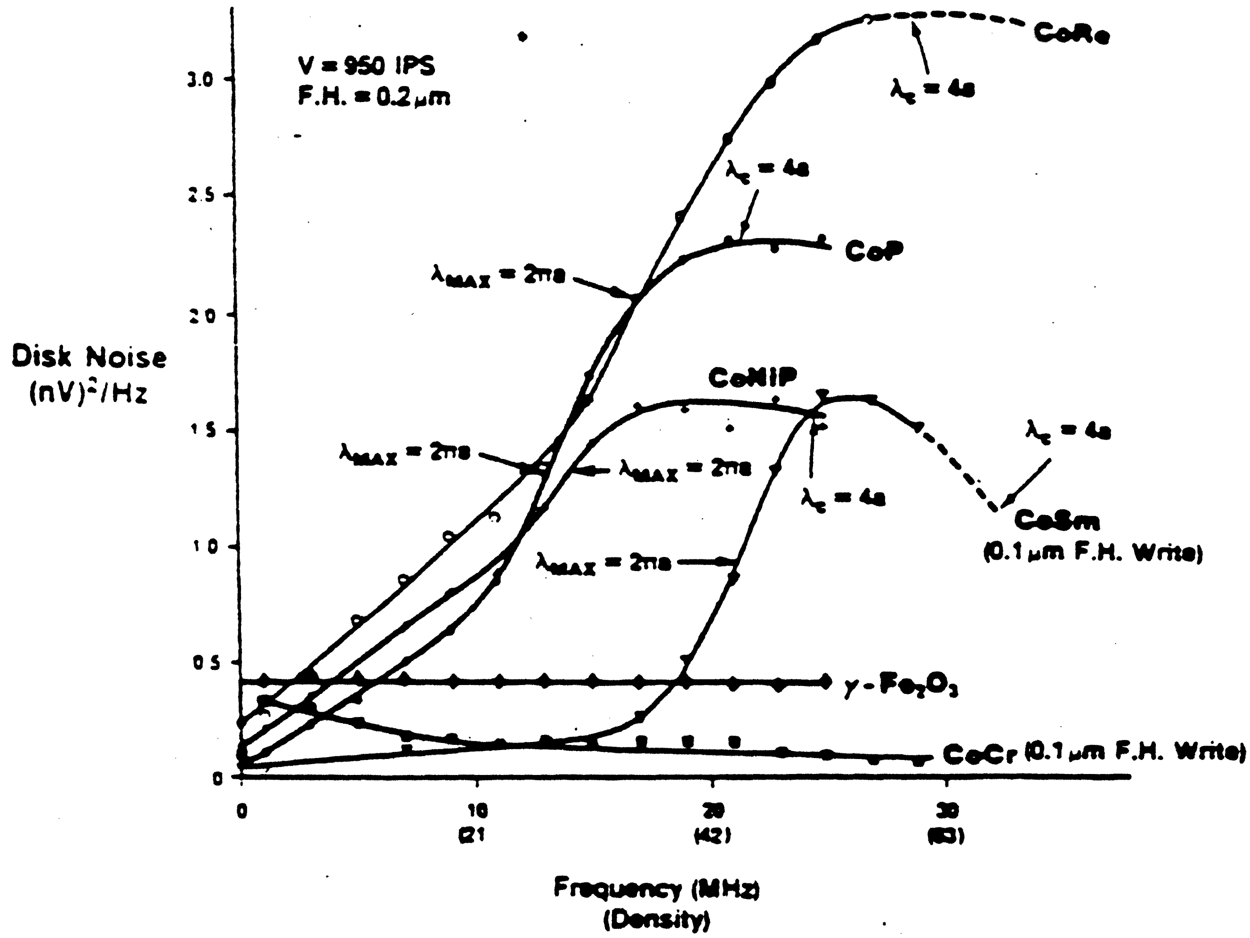
Specifications / Storage units	Newly developed	PATTY	IBM 3380
Storage capacity (GByte) per Unit	8.8	3.2	5
per HDA	2.2	0.4	1.26, 2.52
per Actuator	1.1	0.4	1.26
Data rate (MByte/s)	4.4	1.344	3
Average seek time (ms)	12	18	17
Latency time (ms)	3.3	10	8.3
Recording density			
Areal density (bit/mm²)	62k	24k	
Linear density (bit/mm)	1240	550	
Track density (track/mm)	50	43	
F. C. S	1987	1982	1985

SNR = 28db

O/W = 32db

Mitsuya et al

(NTT, 1987)



S/N AND PERFORMANCE SURVEY
(950 IPS/0.2μm F.H. READ)

Media	γ-Fe_2O_3	Co-P	Co-Ni-P	CoSm	CoRe	CoCr	
D_{70} (KFCI)	12.5	19	18	20	21	22	25
S_{70} (μV_{o-p})	185	170	154	133	126	59	108
N_{DC} ($nV/\sqrt{Hz}$)	0.67	0.21	0.40	0.20	0.48	.34	.31
N_{AC} ($nV/\sqrt{Hz}$)	0 (120ma)	1.17 (80ma)	1.16 (80ma)	0.52 (150ma)	>1.81 (80ma)	~ 0 (150ma)	.22 (150ma)
$(S/N)_{TOTAL\ MEDIA}$ (dB)	36	30	29	35	25	32	36
$(S/N)_{O.W.\ ON\ TRACK}$ (dB)	28	39	35	27.5	34	20	23

↑ 0.1μm F.H. Write (CoSm)

↑ 0.1μm F.H. Write (CoCr, 25 KFCI)

Belk etal (1985)

REVERSED DC ERASED MAGNETIC RECORDING MEDIA NOISE

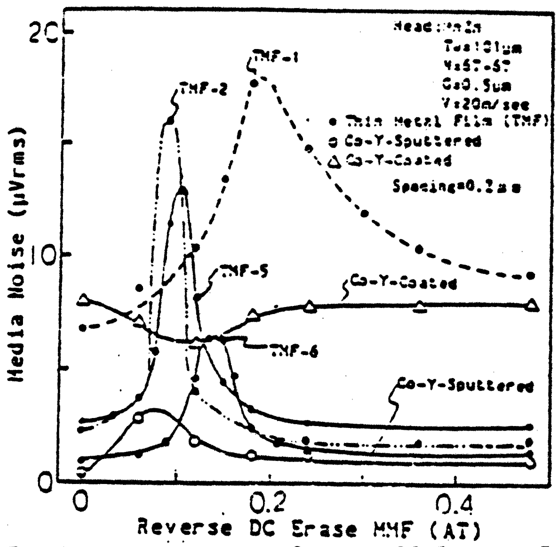


Fig.1 Media Noise vs. Reverse DC Erase MMF

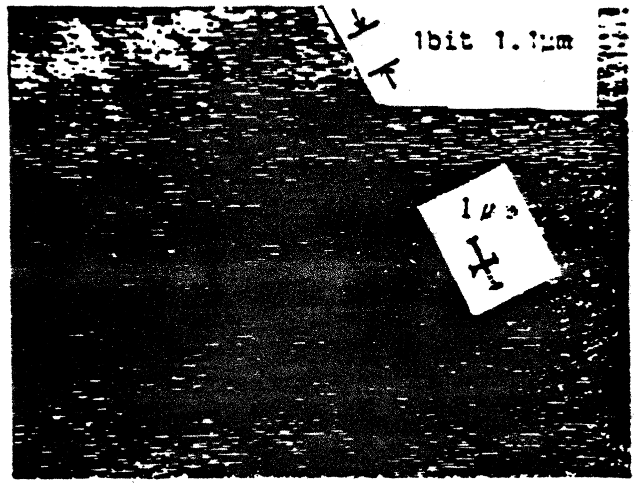


Fig.2 Signal Recorded Magnetic Domain Structure

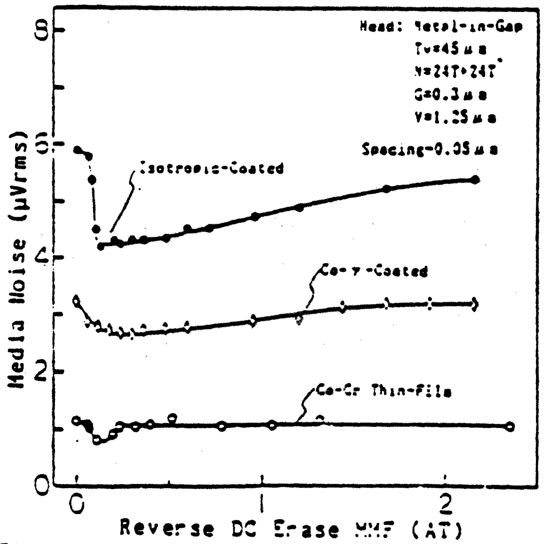


Fig.4 Media Noise vs. Reverse DC Erase MMF

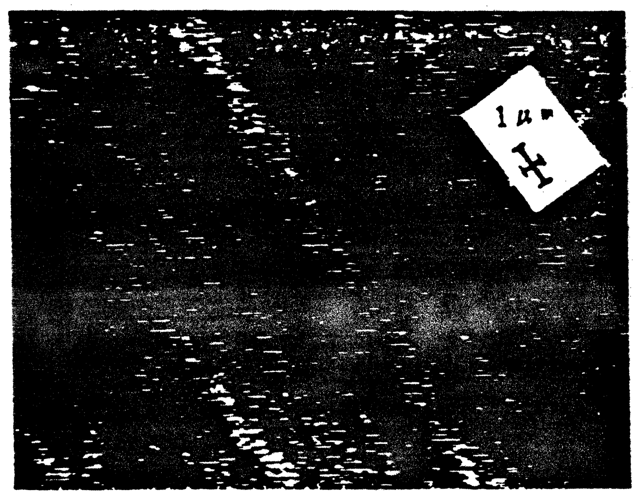
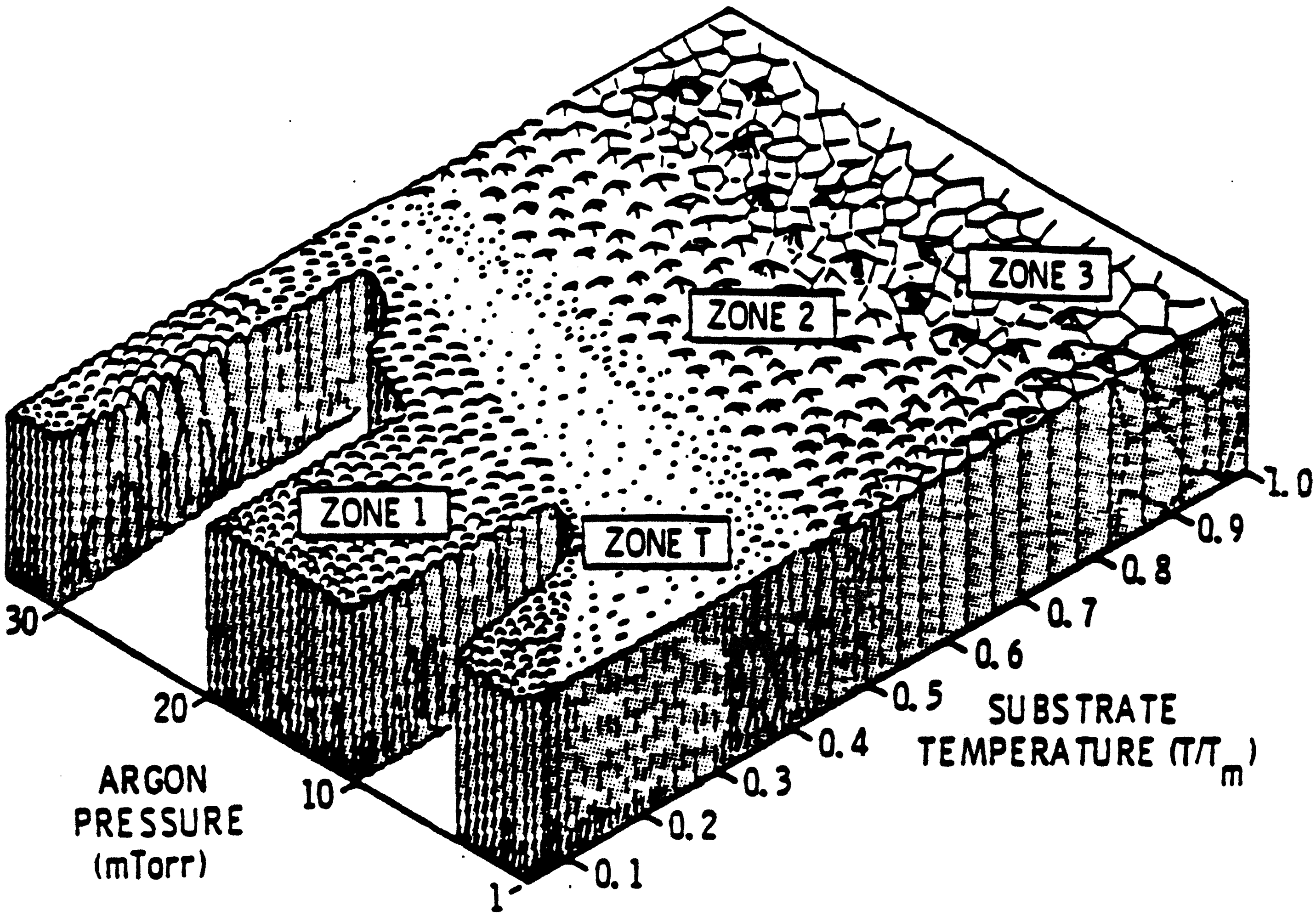


Fig.3 Reversaly DC Erased Magnetic Domain Structure

Aoi et al (1987)

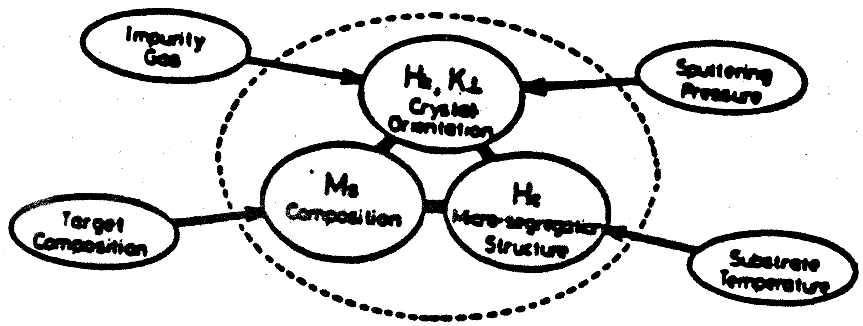
MICROSTRUCTURE OF SPUTTERED THIN FILMS

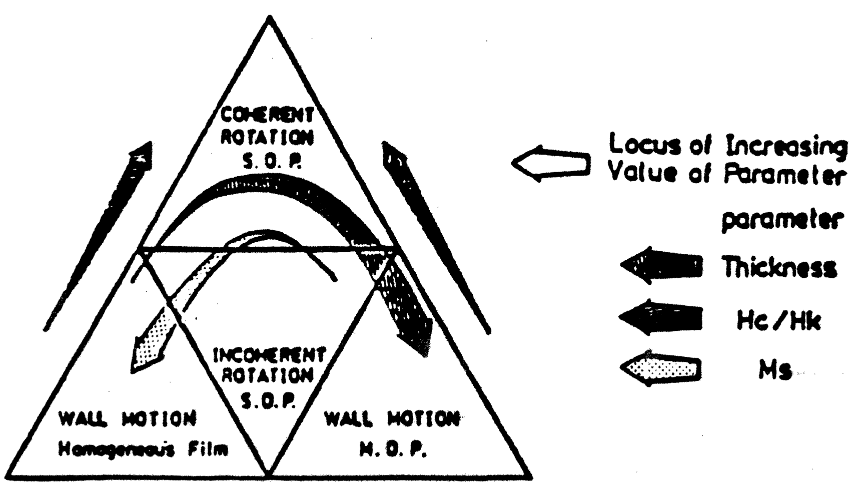


Thornton

FACTORS AFFECTING THE MAGNETIC AND REVERSAL PROPERTIES OF THIN FILMS

1. COMPOSITION
2. TEMPERATURE
3. STRESS
4. SIZE, SHAPE, ORIENTATION OF GRAINS
5. CONCENTRATION AND DISTRIBUTION OF CRYSTAL IMPERFECTIONS
6. IMPURITIES

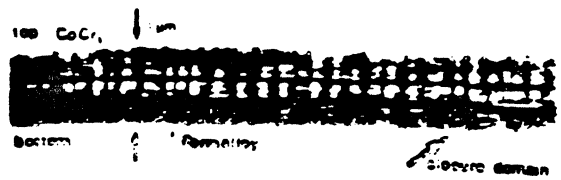


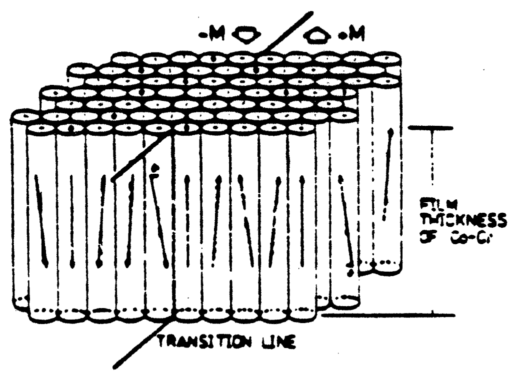


Ouchi (1987)

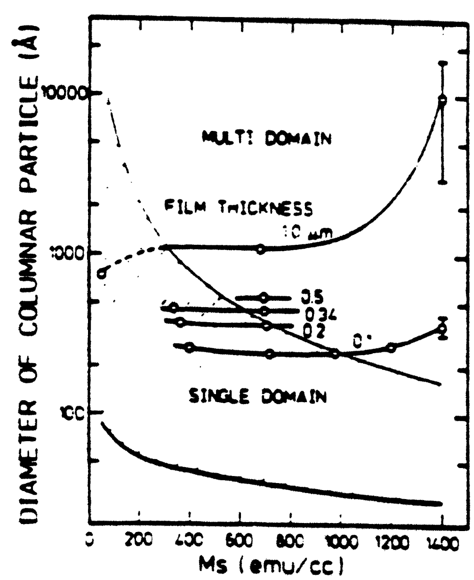
MICROMAGNETICS OF SPUTTERED COCR FILMS

LORENTZ MICROGRAPH OF CROSS SECTION OF COCR/PERMALLOY FILMS

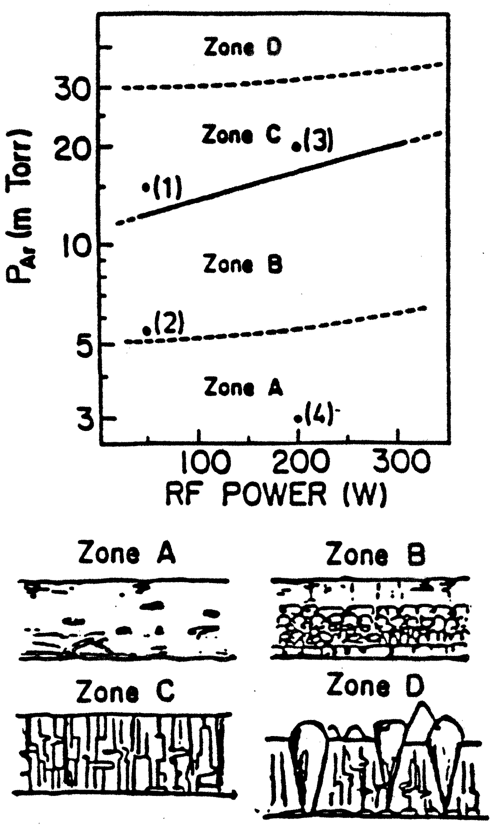


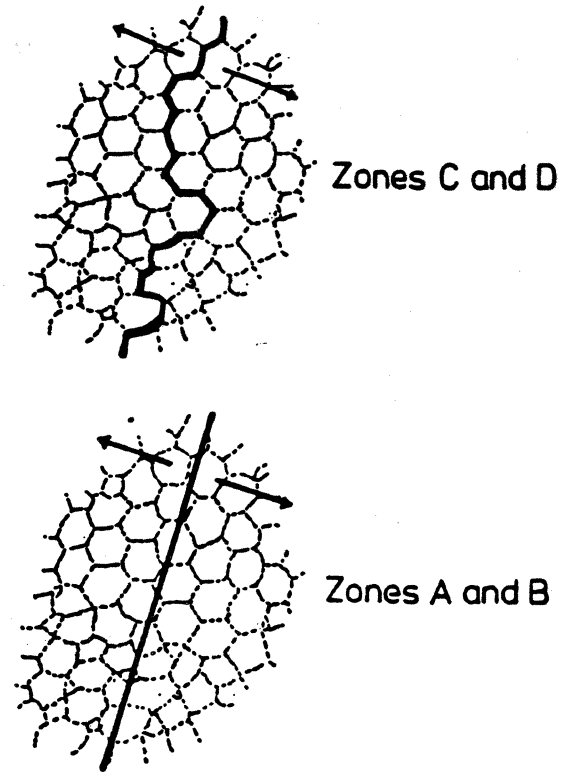


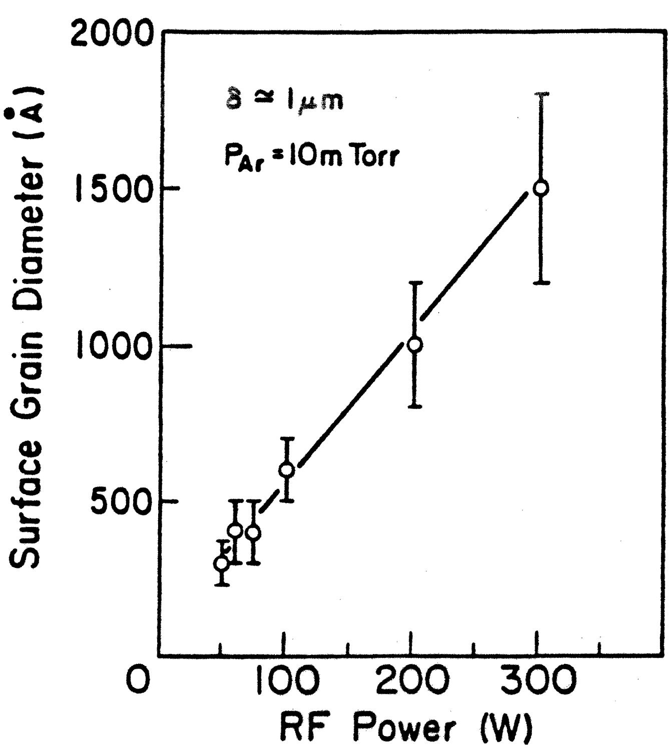
STRUCTURE OF MAGNETIZATION TRANSITION

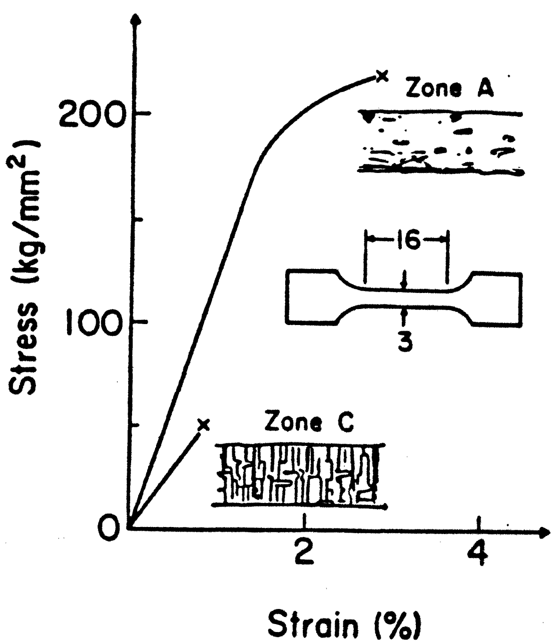


MICROSTRUCTURES AND MECHANICAL PROPERTIES OF RF SPUTTERED CoCr FILMS



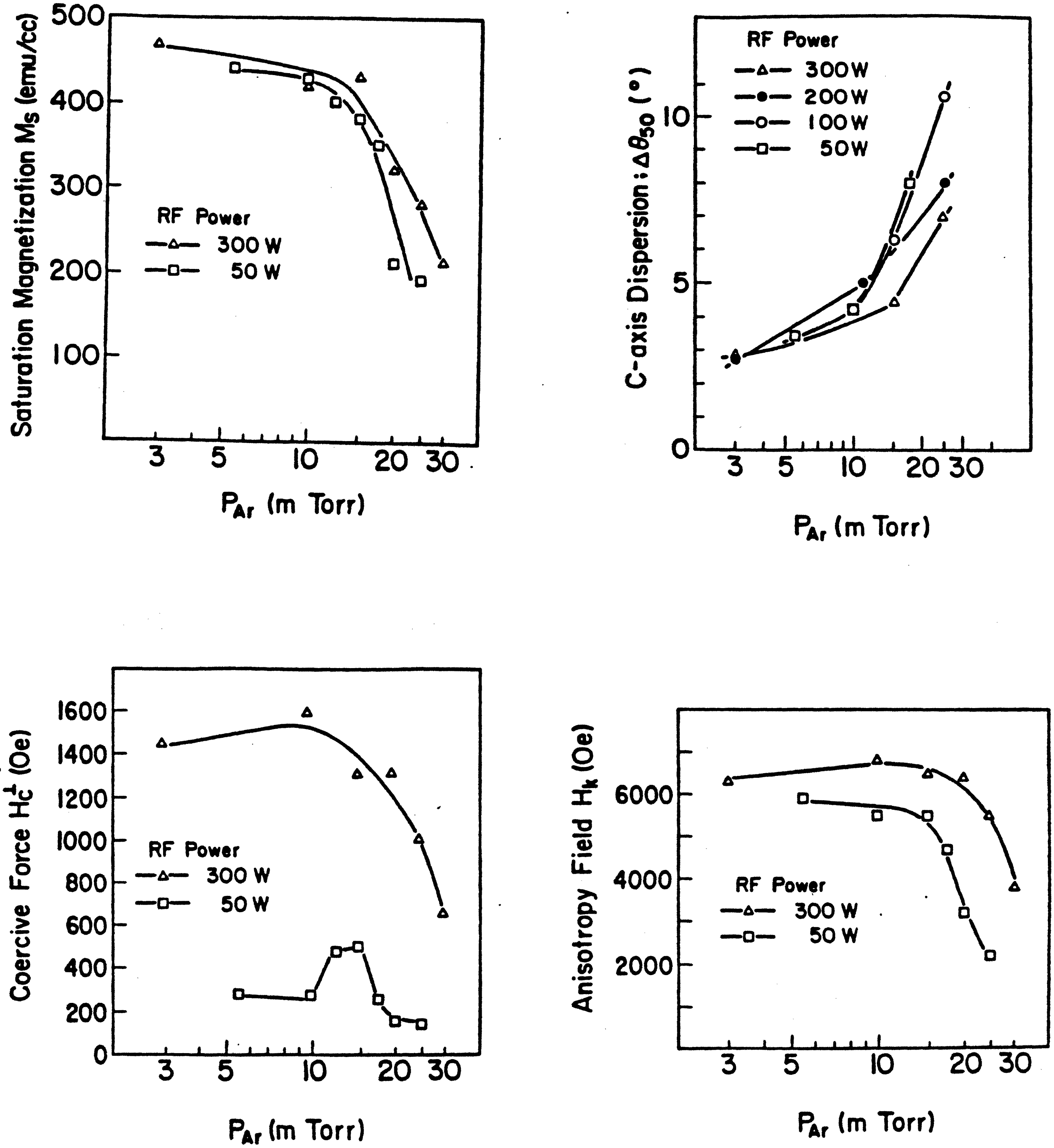






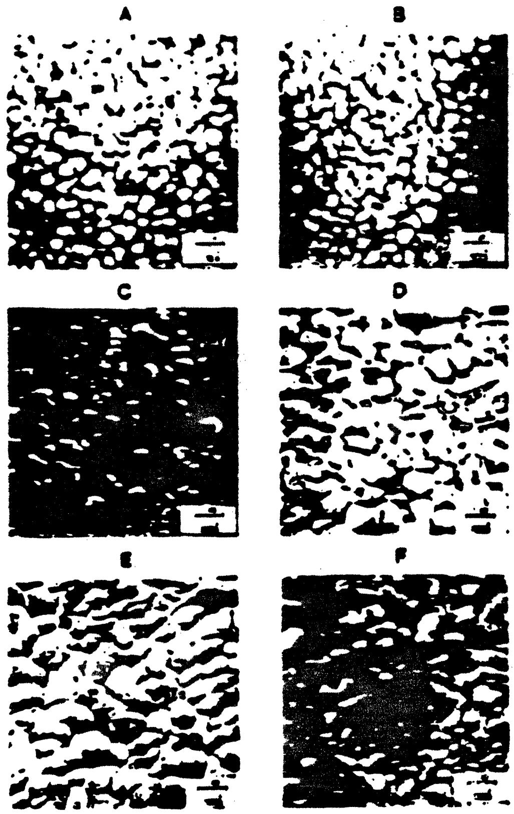
Sagoi et al (1984)

ARGON PRESSURE DEPENDENCE OF MAGNETIC PROPERTIES OF RF SPUTTERED CoCr



Sagoi et al (1984)

MICROSTRUCTURE AND COERCIVITY OF COCR FILMS DEPOSITED ON VARIOUS SUBSTRATES BY DC MAGNETRON SPUTTERING



Sem micrographs of 10,000A thick Co-Cr thin films sputtered on six different substrates: (A) Al. (B) NiP. (C) Si(111). (D) Si(100). (E) Cover glass. (F) Si wafer with SiO_2.

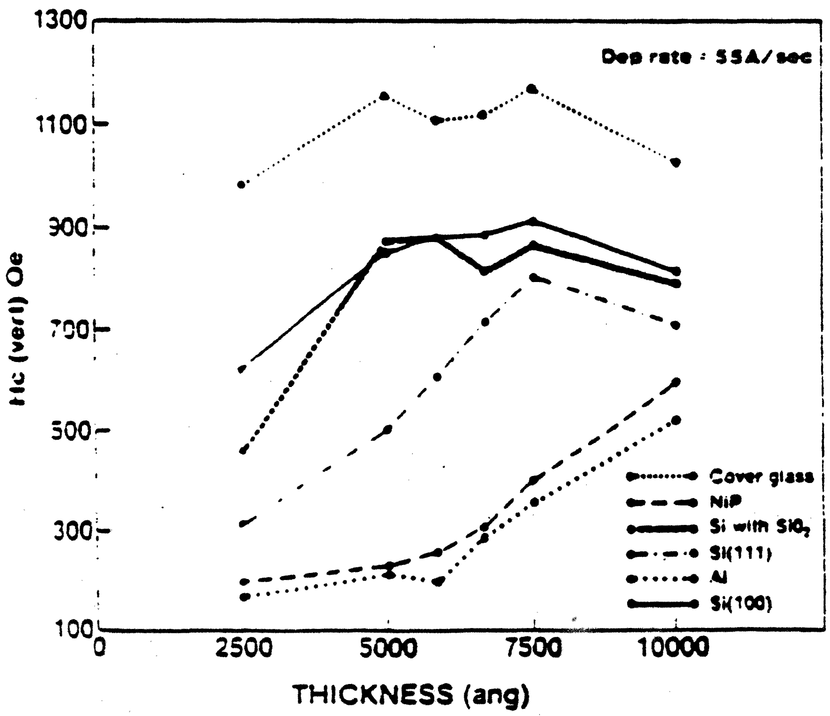
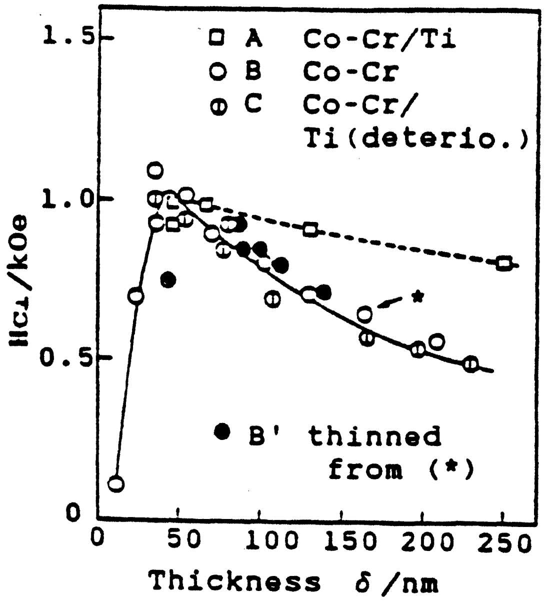


Fig. 3: Relationship between Hc (vert) and thickness for the six substrates sputtered at 55A/sec.

Ravipati (1990)

VACUUM DEPOSITED CoCr PERPENDICULAR MEDIA (TAPE)



PET substrate

Table Head dimensions.

ad	A	B	C
p Length(μm)	0.16	0.28	0.2
ack Width(μm)	50	22	5
aber of Coil Turns(turn)	20	22	20
p Depth(μm)	8	25	14

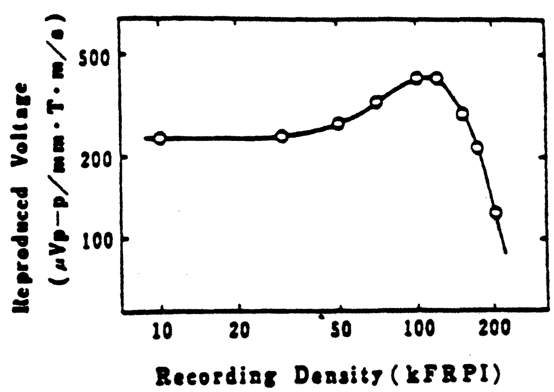
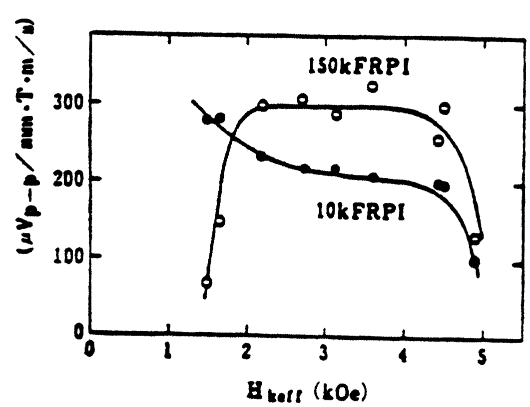


Fig. 2 Recording density characteristics.



1 Dependence of reproduced voltage on Hkeff.

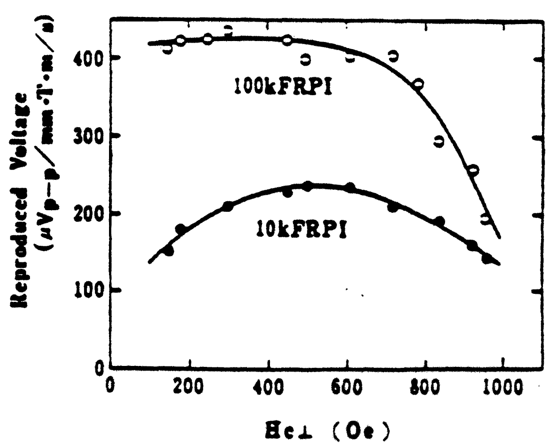
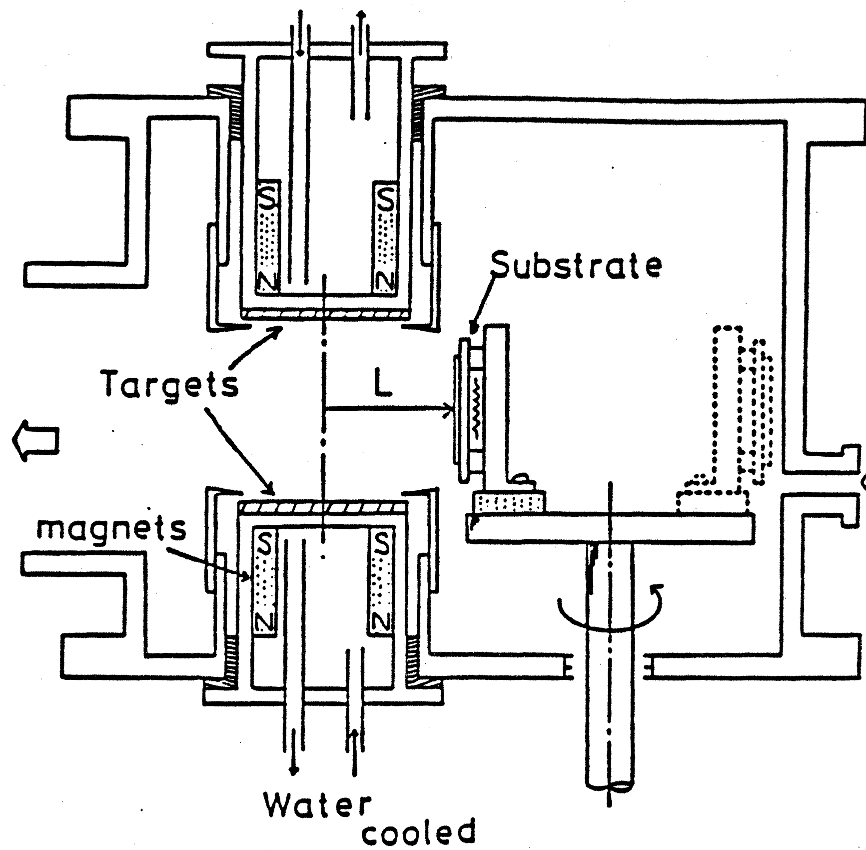


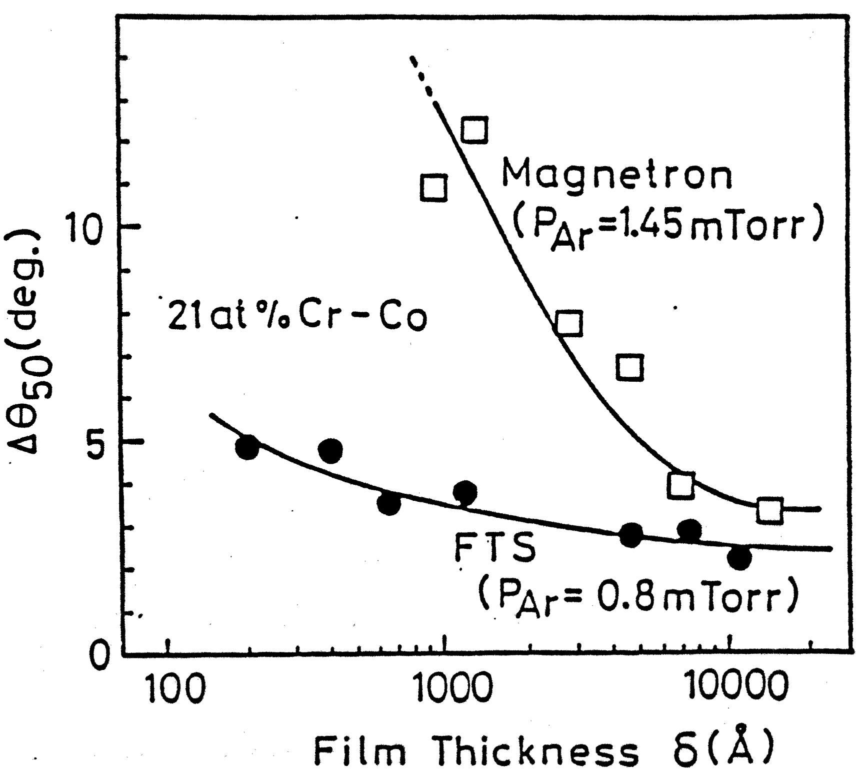
Fig. 4 Dependence of reproduced voltage on Hc⊥.

Sugita etal (Matsushita) (1987)

FACING TARGET SPUTTERING OF CoCr FILMS

(FTS)

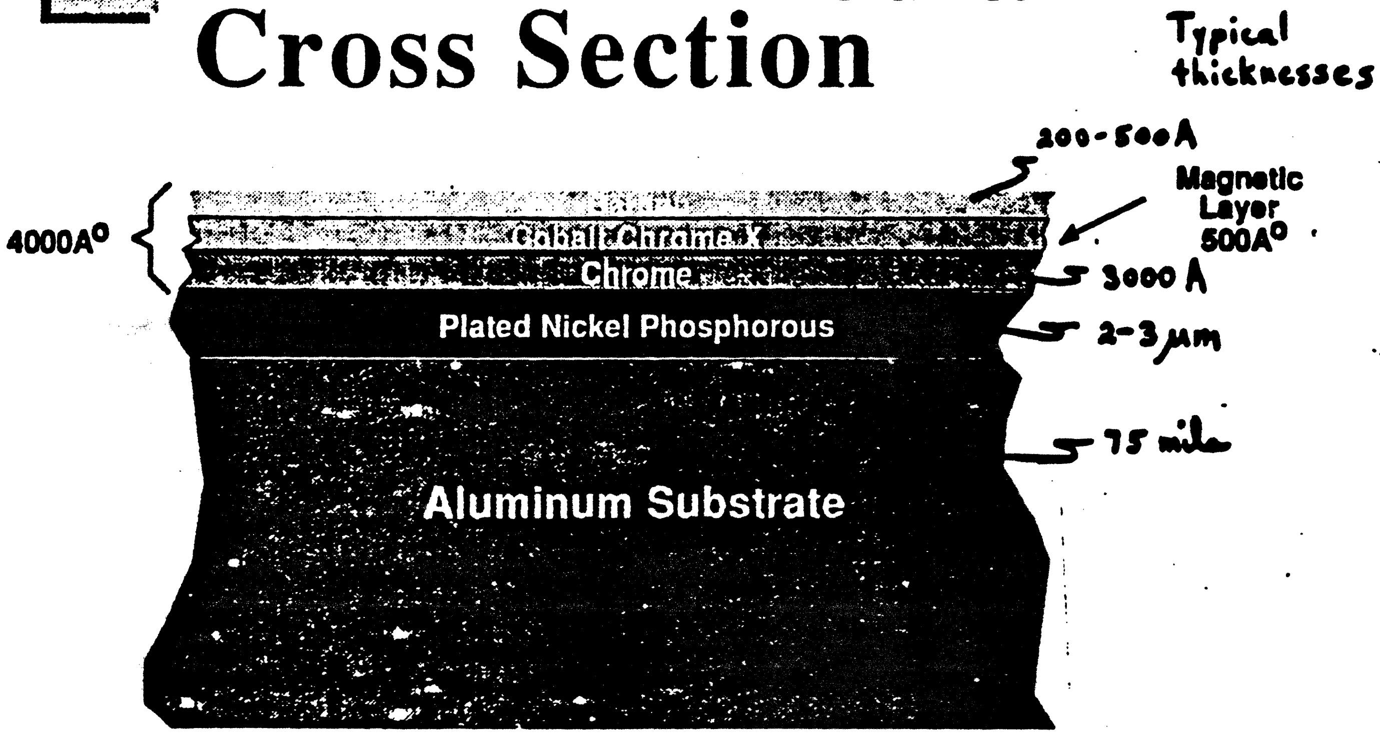




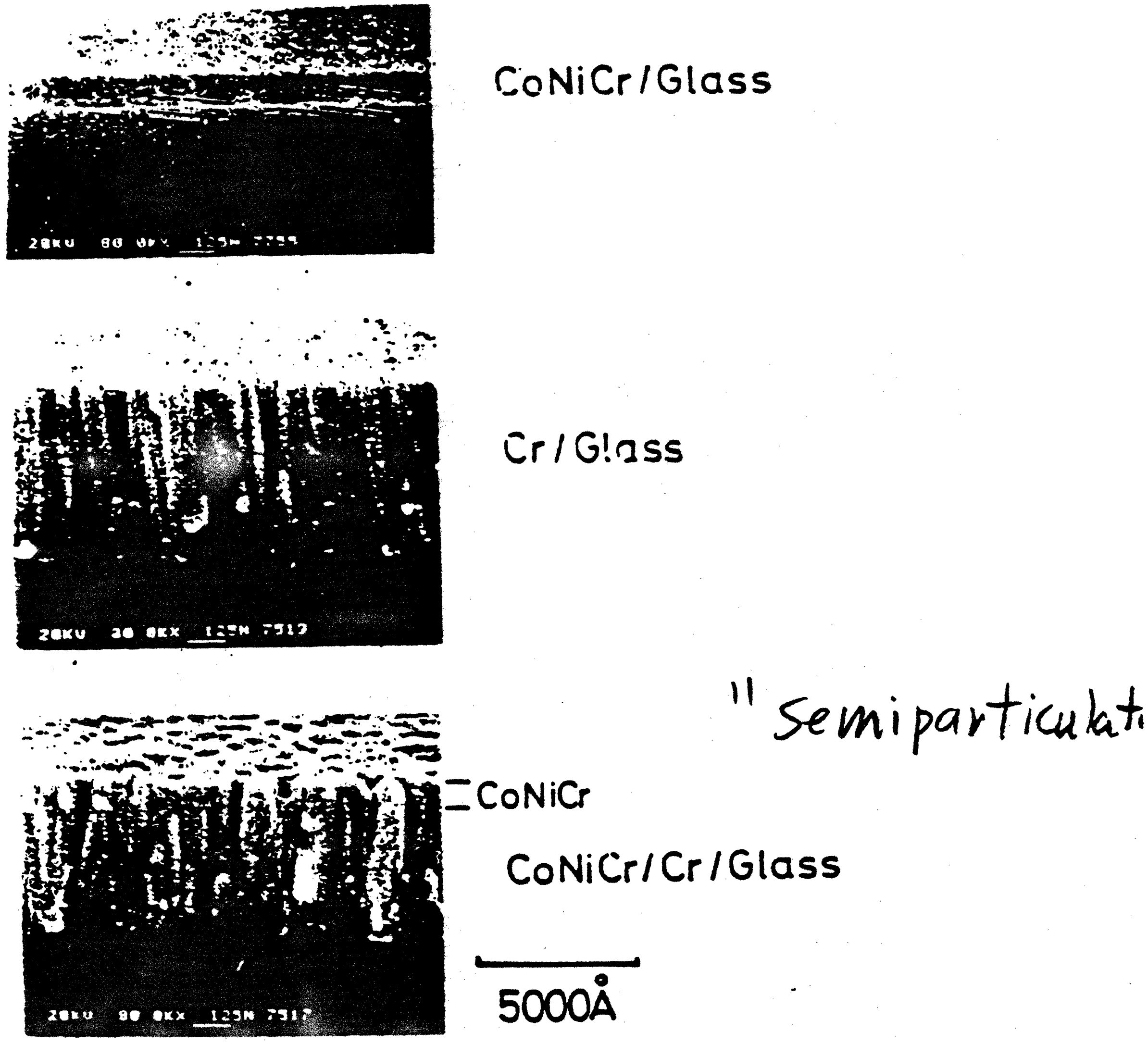
Niimura
(198-

SEMIPARTICULATE THIN FILM RIGID DISK MEDIA

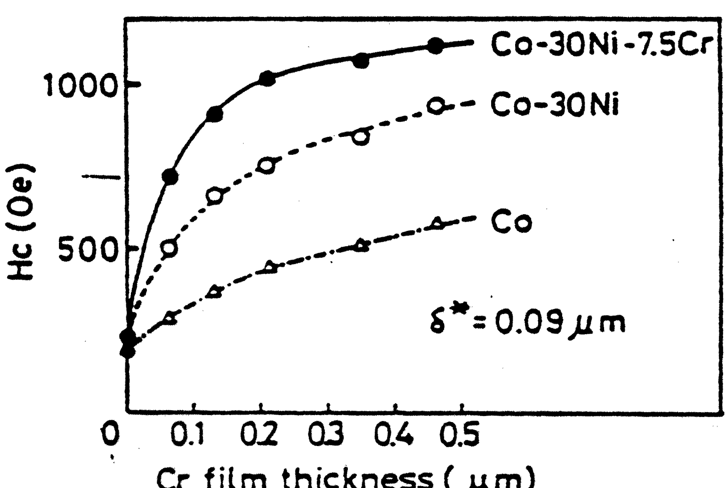
Thin-Film Media Cross Section



MICROSTRUCTURE AND COERCIVITY OF CONICR SPUTTERED FILMS



SEM cross section micrographs of CoNiCr and Cr single layer and CoNiCr/Cr double layer films.



Relationship between Cr underlayer thickness and Hc of Co, Co-30Ni and Co-30Ni-7.5Cr film.

Ishikawa etal (1986)

Sputtered CoCrM and CoNiM Ternary Alloys on Cr

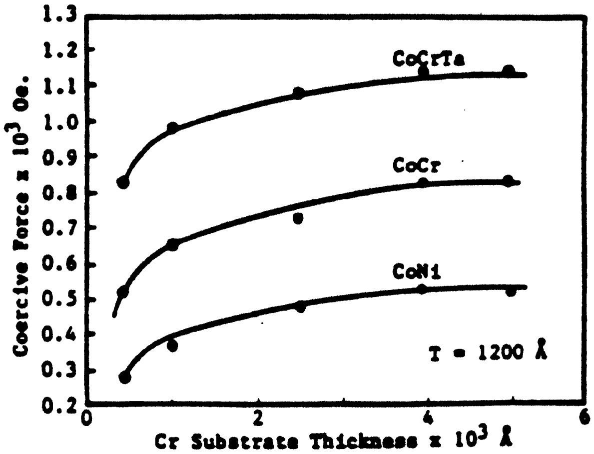


Figure 1: Relationship Between Film Coercivity and Chromium Substrate Thickness

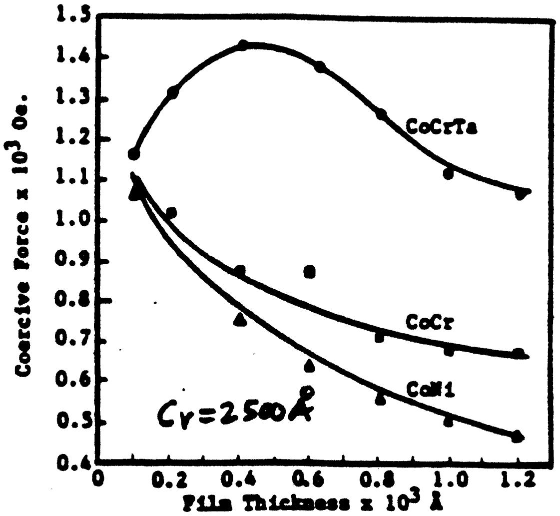


Figure 2: Coercive Force as a Function of Thickness

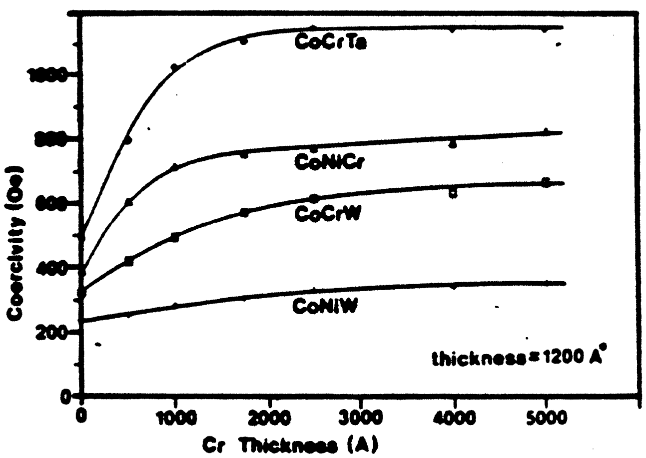


Figure 3: Coercivity Vs. Cr Underlayer Thickness for a Magnetic Thickness of 1200A.

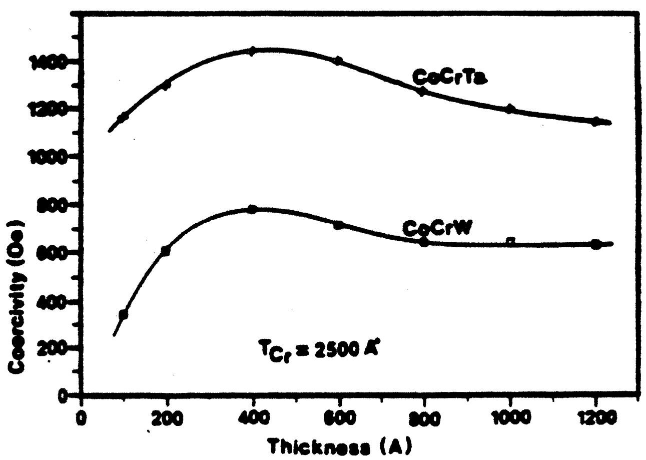


Figure 1: Coercivity of CoCrTa and CoCrW on a Cr Underlayer of 2500A.

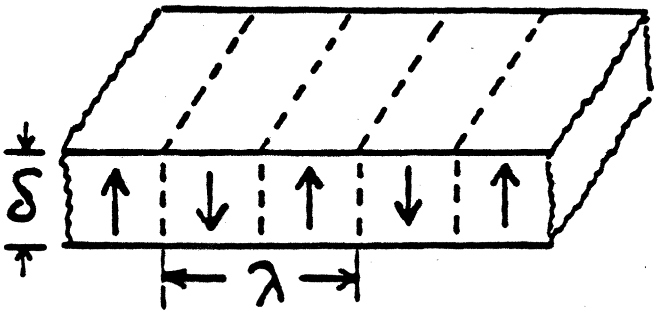
DISC	A_t (u^{*})	A_g (u^{*})	Mr T (uin T)	Hc (Oe)	E_{70} (uV)	D_{70} (Kfci)	D_{50} (Kfci)	Res (%)	OW (dB)
CoCr	9.3	5.0	1.93	774	787	23.3	26.0	84	37.6
CoCr	9.2	5.0	1.78	730	662	23.9	31.0	85	35.0
CoCr	10.5	6.2	2.23	725	773	21.3	27.0	78	33.6
CoCrTa	6.15	2.3	1.41	1253	586	28.1	33.0	85	34.0
CoCrTa	7.3	3.1	1.91	1253	830	25.7	30.0	89	30.8
CoCrTa	8.6	4.2	2.30	1120	929	24.1	28.0	84	32.0

Fisher et al (198

Allen et al (198

COMPARISON OF PERPENDICULAR & LONGITUDINAL MODES

(a) Perpendicular Mode

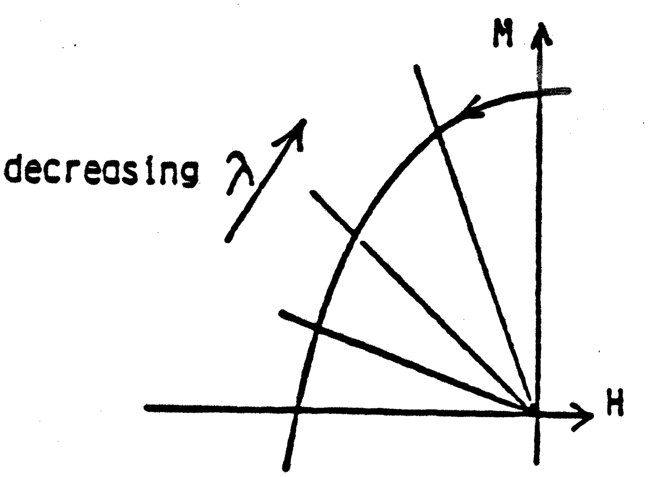


$\lambda \rightarrow 0$ $H_d \rightarrow 0$

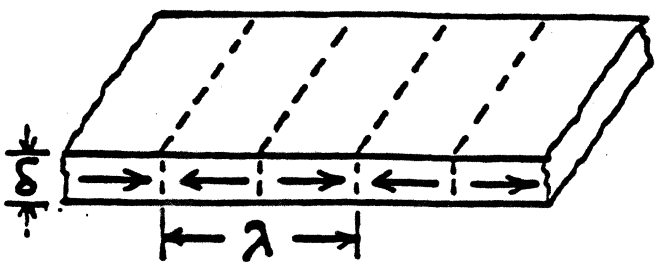
Thick δ

High M_s

High H_c



(b) Longitudinal Mode

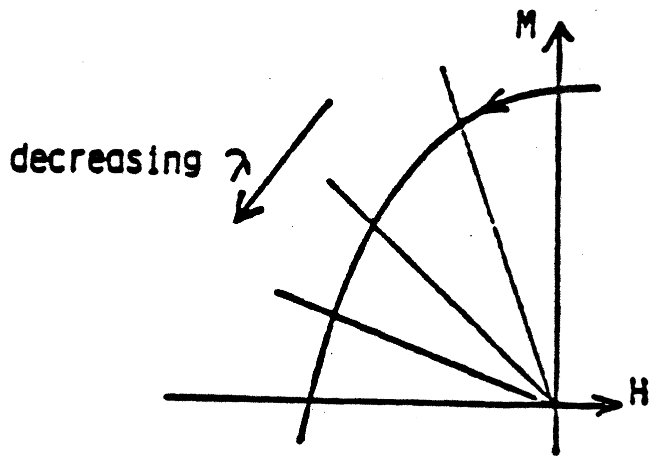


$\lambda \rightarrow 0$ $H_d \rightarrow 4\pi M$

Thin δ

Low M_s

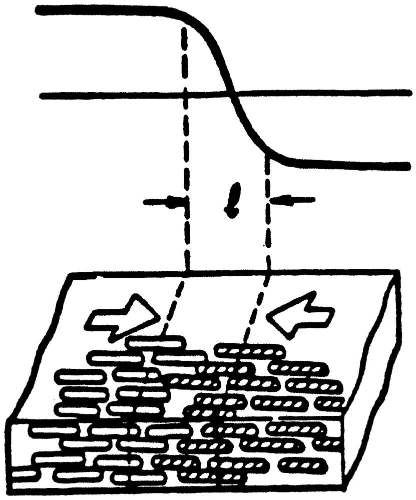
High H_c



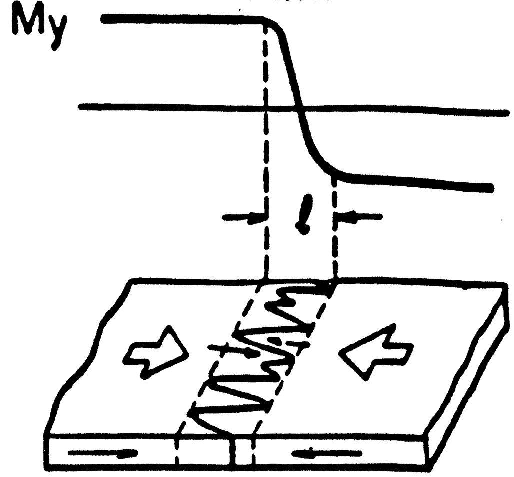
Comparison of Perpendicular and Longitudinal Recording Limit

Longitudinal

Particulate



Thin Film



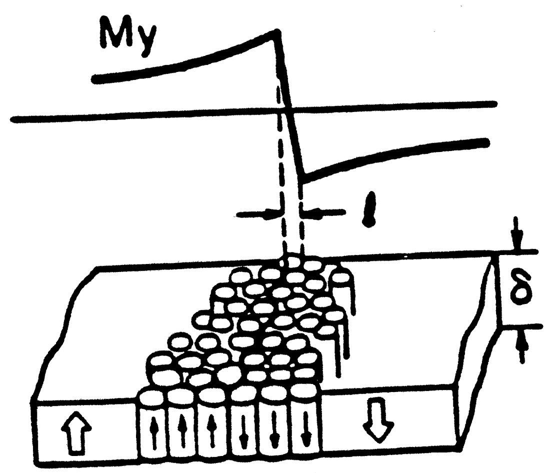
ℓ: particle assembly in transition

$\propto \left(\frac{\delta M_r}{H_c}\right)^{\frac{1}{2} \sim 1}$

ℓ: saw-tooth amplitude

$\approx \frac{\delta M_r}{H_c} \left(= \frac{\delta}{2} \sim \frac{\delta}{3}\right)$

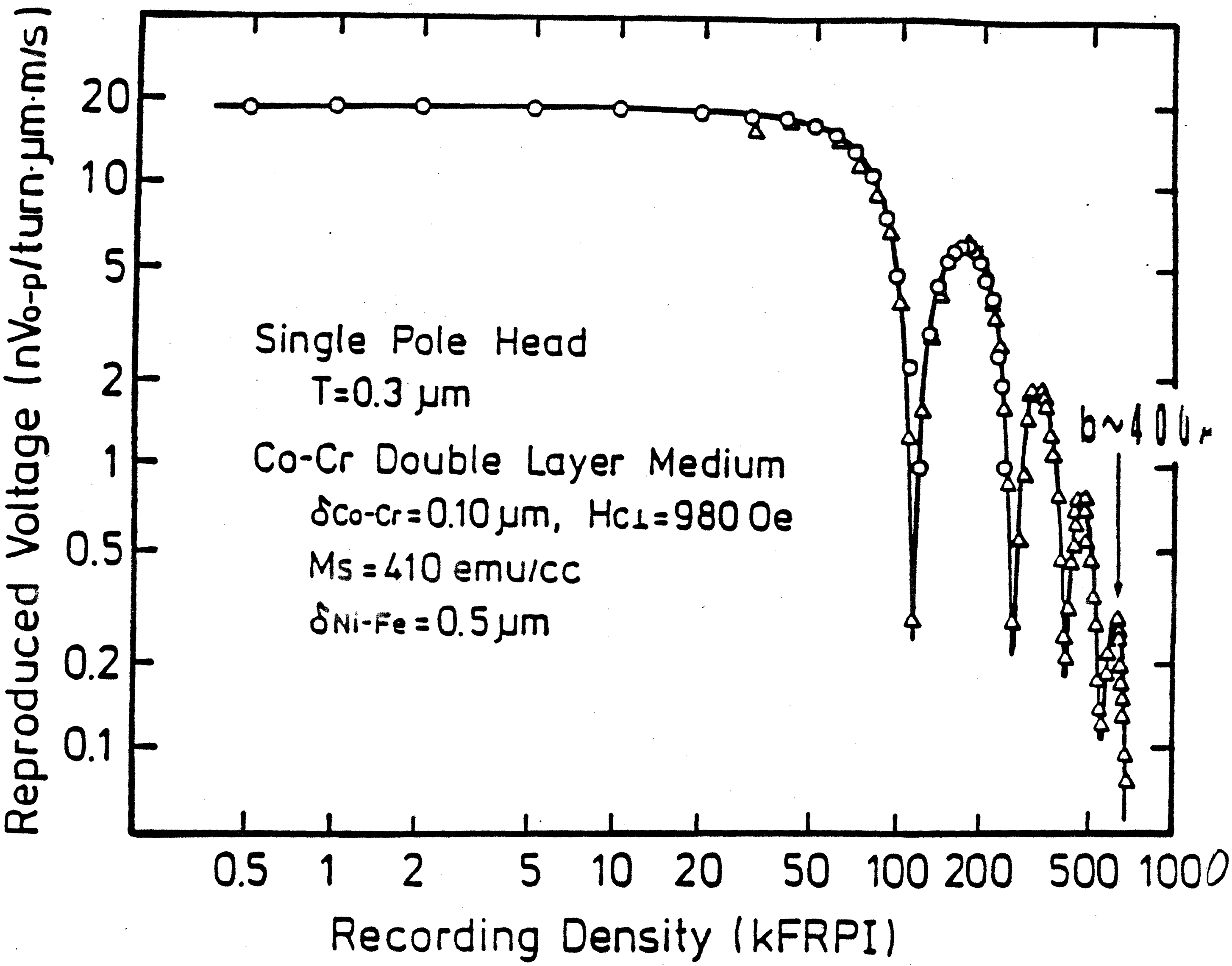
Perpendicular



ℓ: column diameter (Co-Cr)

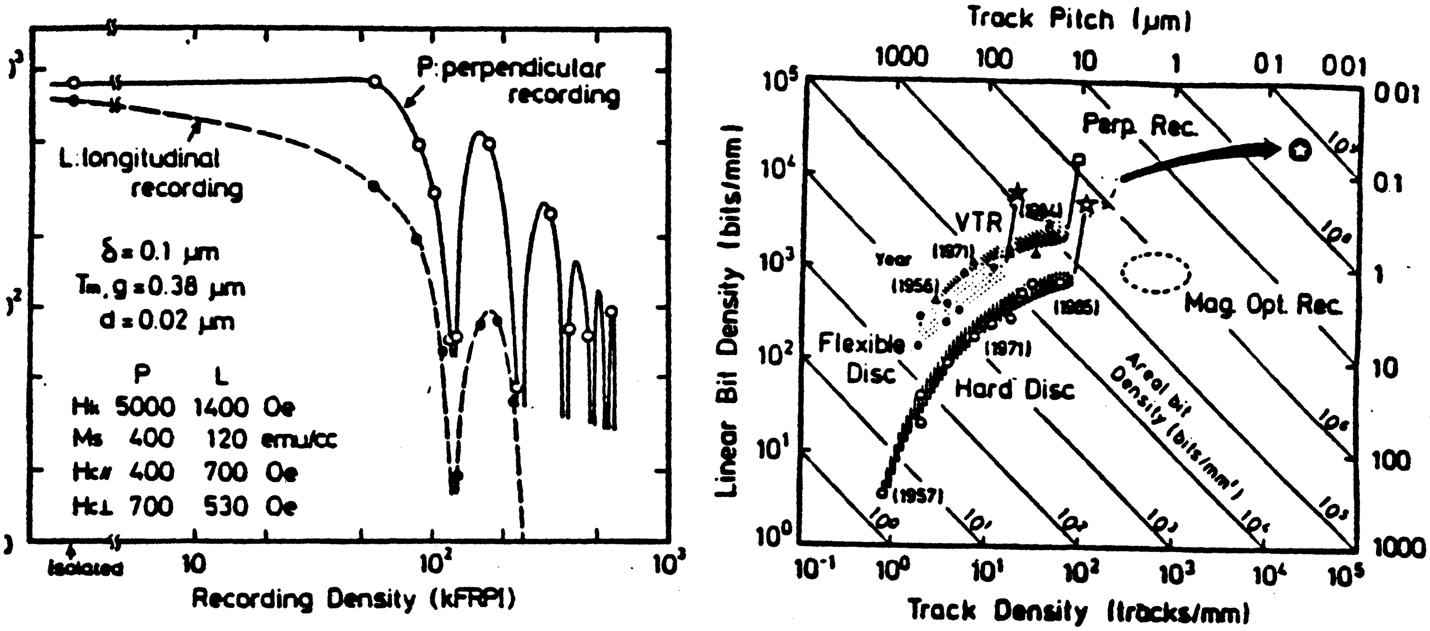
$= \frac{\delta}{10} \sim \frac{\delta}{20}$ (independent of Hc, Ms)

PERPENDICULAR RECORDING CHARACTERISTICS[21]

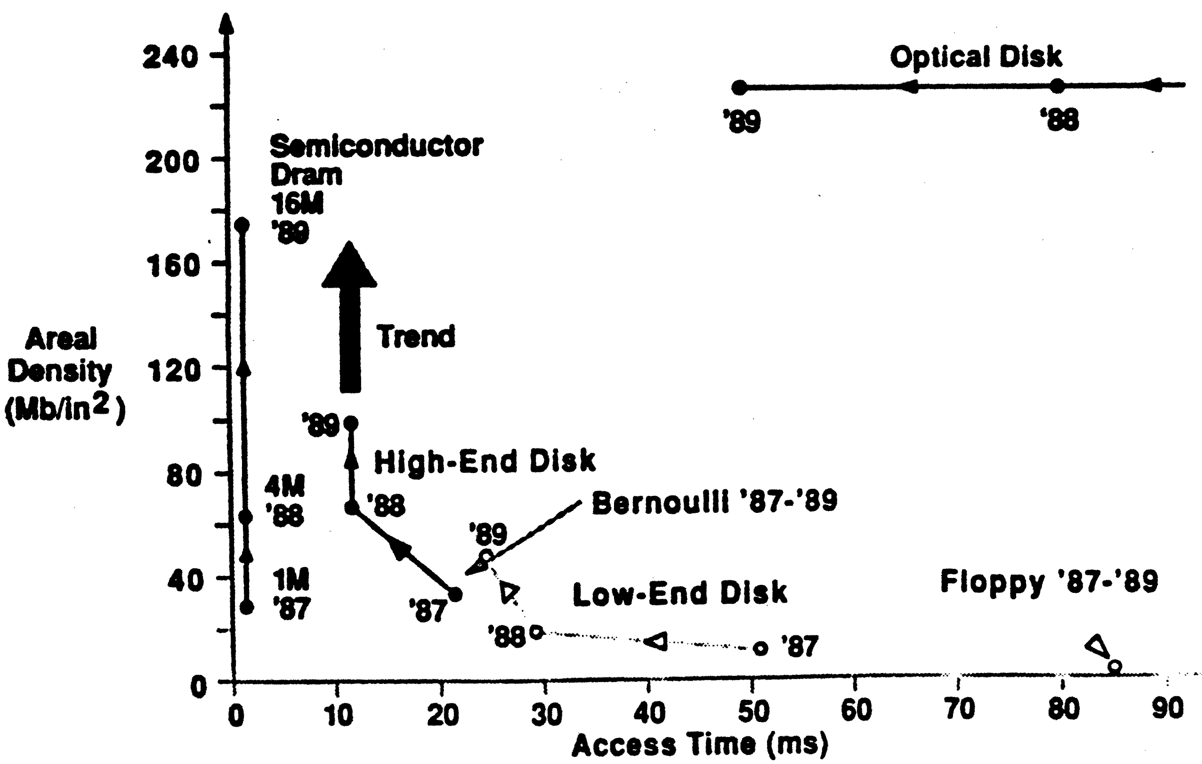


Nakamura et al (198)

COMPARISONS OF FUTURE OF LONGITUDINAL AND PERPENDICULAR RECORDING



Nakamura (1988)



George (1988)

CONCLUSIONS

1. METAL-IN-GAP HEADS WILL REPLACE FERRITE HEADS FOR HIGH AREAL DENSITY RECORDING APPLICATIONS OF RIGID DISKS
2. MIG HEADS WILL COMPETE WITH THIN FILM HEADS AS LONG AS THEIR COST IS LOWER THAN THAT OF THIN FILM HEADS
3. THIN FILM MEDIA WILL REPLACE COATED OXIDE MEDIA FOR HIGH AREAL DENSITY RECORDING APPLICATIONS OF RIGID DISKS
4. METAL EVAPORATED THIN FILM MEDIA WILL COMPETE WITH METAL PARTICLE MEDIA WHEN THE WEAR AND CORROSION PROBLEMS ARE SOLVE
5. HIGH DEFINITION VIDEO WILL BE THE DRIVING FORCE FOR USING PERPENDICULAR MAGNETIC RECORDING
6. SEMIPARTICULATE LONGITUDINAL THIN FILM MEDIA EXTEND THE LIFE OF LONGITUDINAL RECORDING FOR ANOTHER DECADE
7. PERPENDICULAR THIN FILM MEDIA WILL REQUIRE MAJOR DEVELOPMENTS IN SMOOTHER SUBSTRATES AND IMPROVED HEAD DESIGNS

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