Ecole Franco-Roumaine
Magnétisme des systèmes nanoscopiques et structures hybrides
Brasov, septembre 2003

Applications: Information Storage

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Laboratoire Louis Néel, Grenoble

Summary

I- Introduction to Recording

II-Media

III-Heads

IV-Drives

V- Future Developments

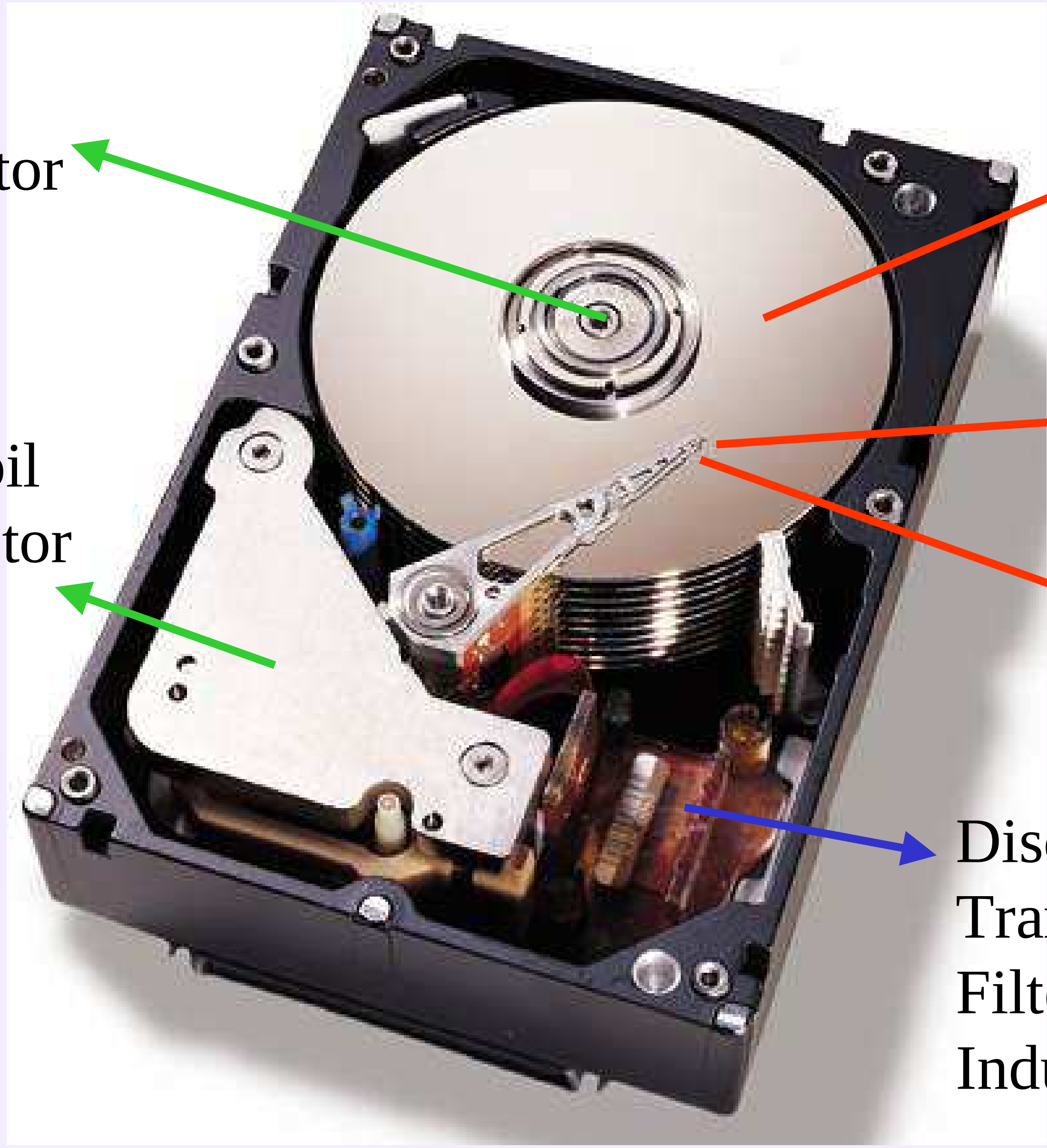
VI-MRAM

I- Introduction to Recording

Why is magnetism everywhere ?

Flat
Rotary Motor

Voice Coil
Linear Motor



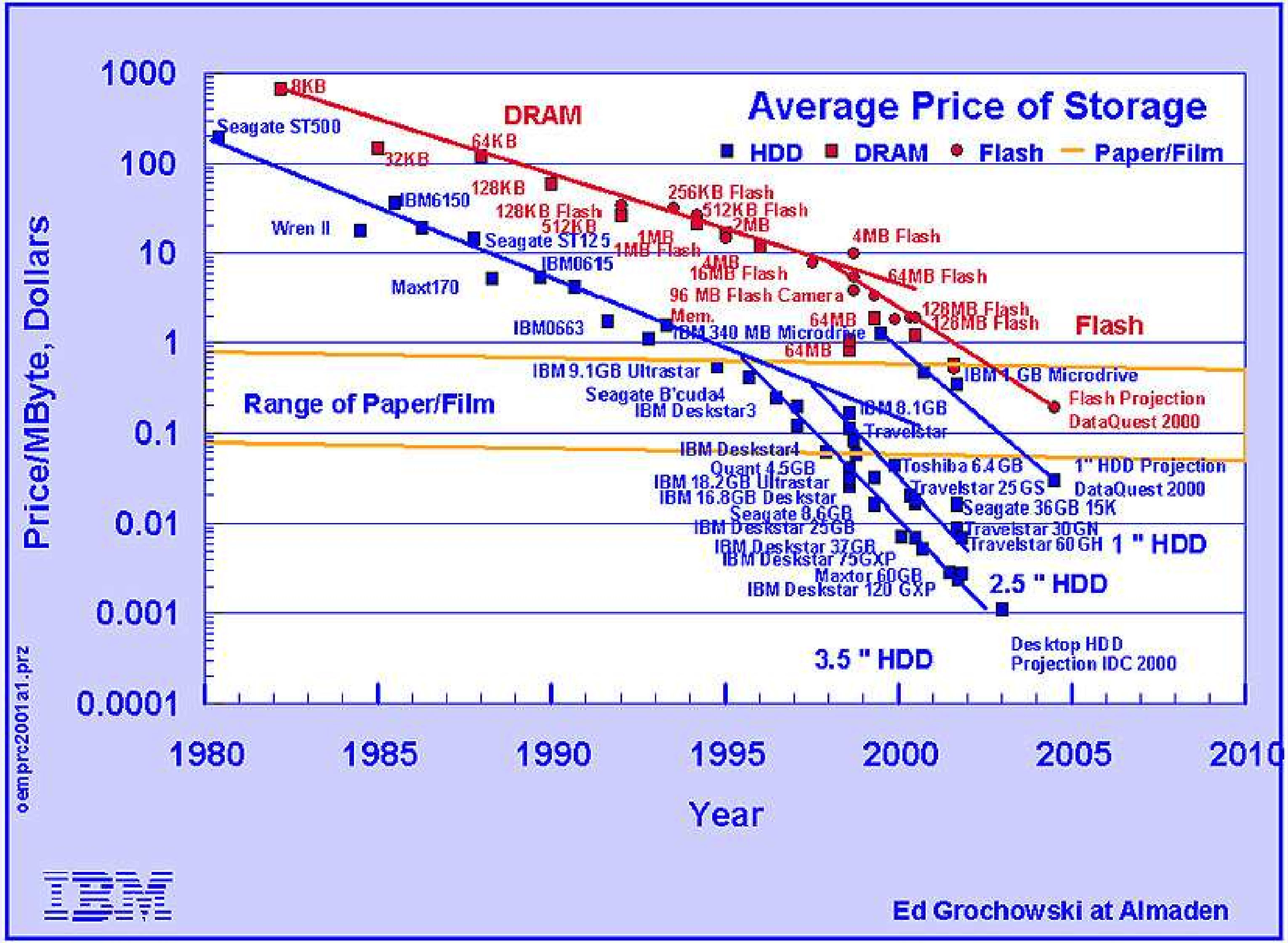
Disk

Write Head

Read Head

Discrete Components :
Transformer
Filter
Inductor

Because more €€ because of less €€



Storing information

Digital storage (binary coding)

Two states : 0 and 1 or up and down

non-binary storage will come

(new FLASH, 3 states / transitor))

(DVD 2 surfaces…)

Permanent storage : 1ms -1s-1y-10-100 years

Storage Density : 1 byte to 1 Tera byte on a given surface

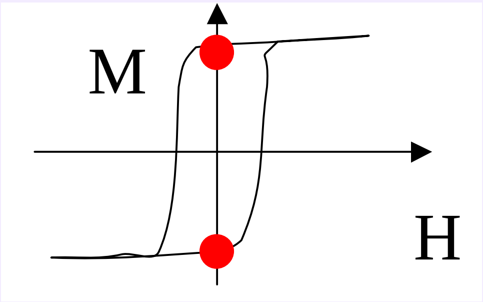
1 mm^2 memory to 1 km-long tape

Access time : Random Access / Sequential Access

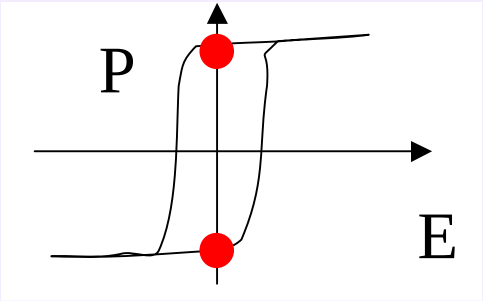
Minutes (tape), µs (FLASH) to ns (HDD)

Storing information

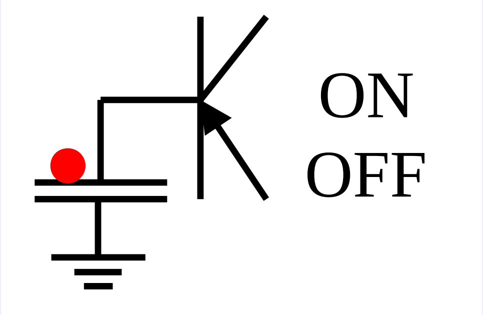
Magnetic : remanent state of
a ferromagnetic entity



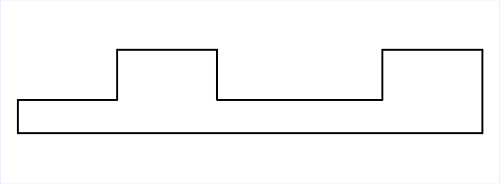
Ferroelectric : remanent state of
a ferroelectric entity



Electrostatic : presence or absence of
electrical charge



Mechanical : hole/no hole



…

Reading information

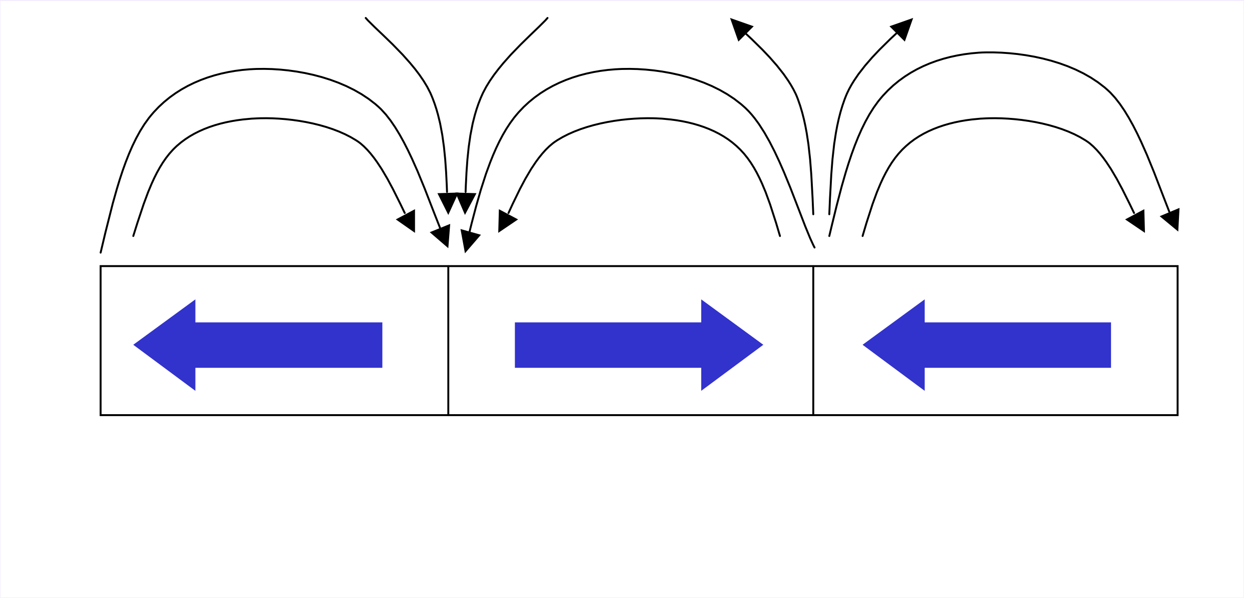
Magnetic : stray field (Floppy disk)
magneto-optical effect (M-O disk)
electrical effect (MRAM)

Ferroelectric : electric voltage

Electrostatic : electric voltage
transistor open/close FLASH
capacitor charged or not RAM

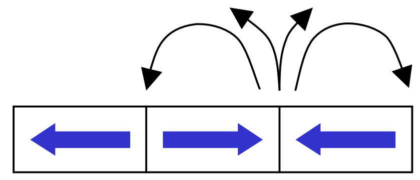
Mechanical : optical interference (CD-ROM)
heat disipation (Milipede)

Magnetic Stray Field Above a Longitudinal Media



Longitudinal recording

Reading information



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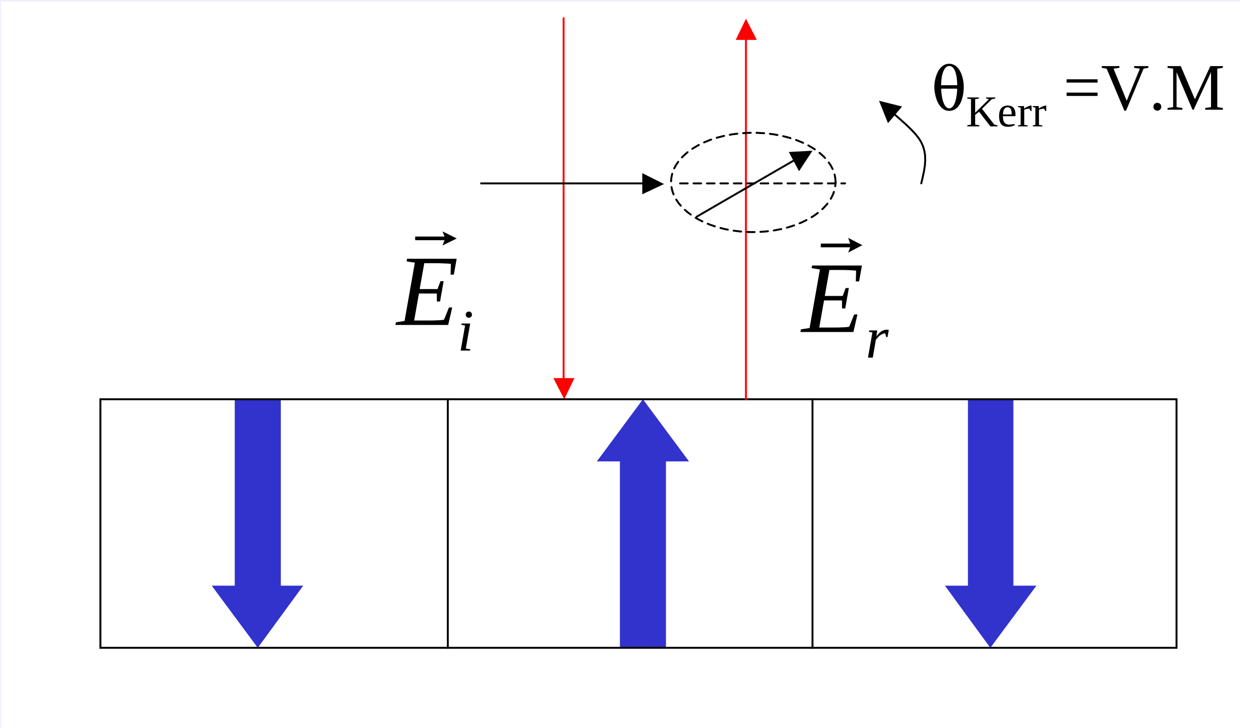
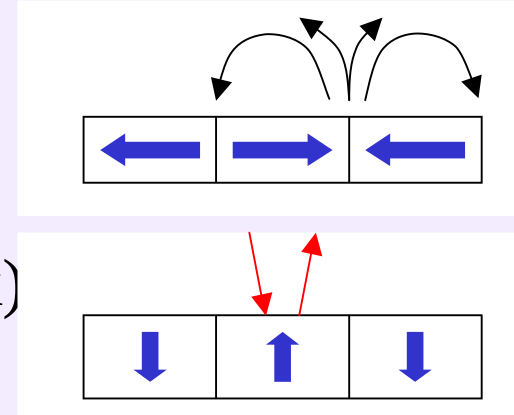
Magneto-optical effect (polar Kerr)
Perpendicular Media



Reading information



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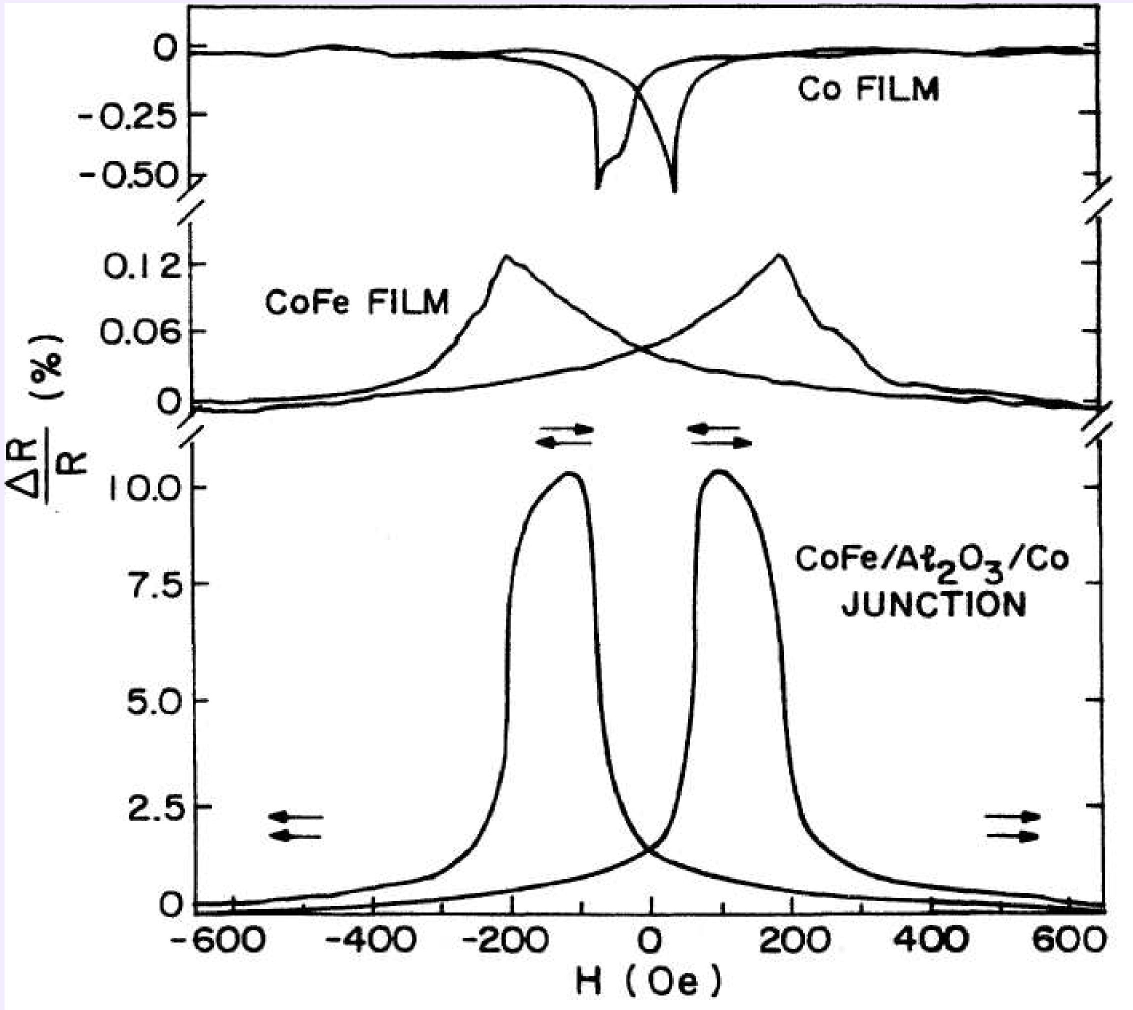
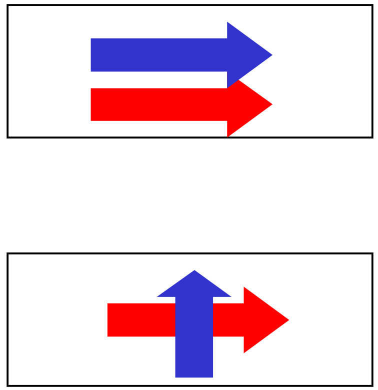
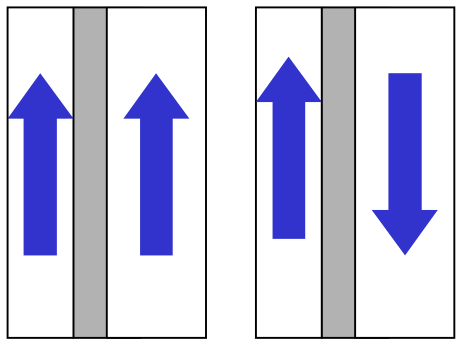


Anisotropic MR



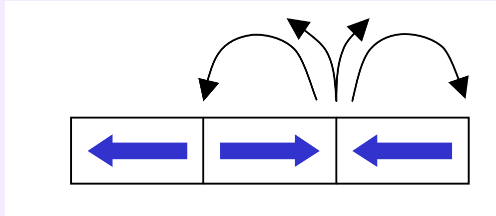
1-2%

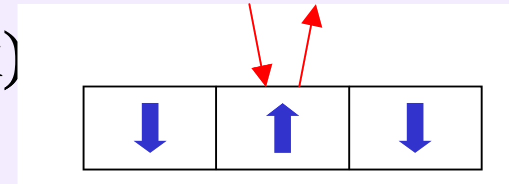
Tunnel MR

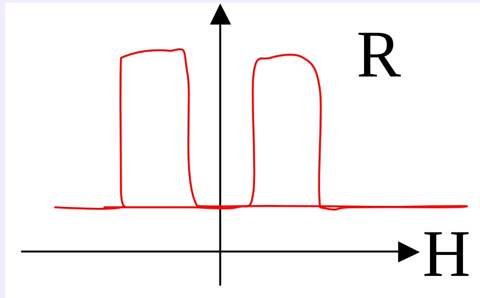


40%

Reading information







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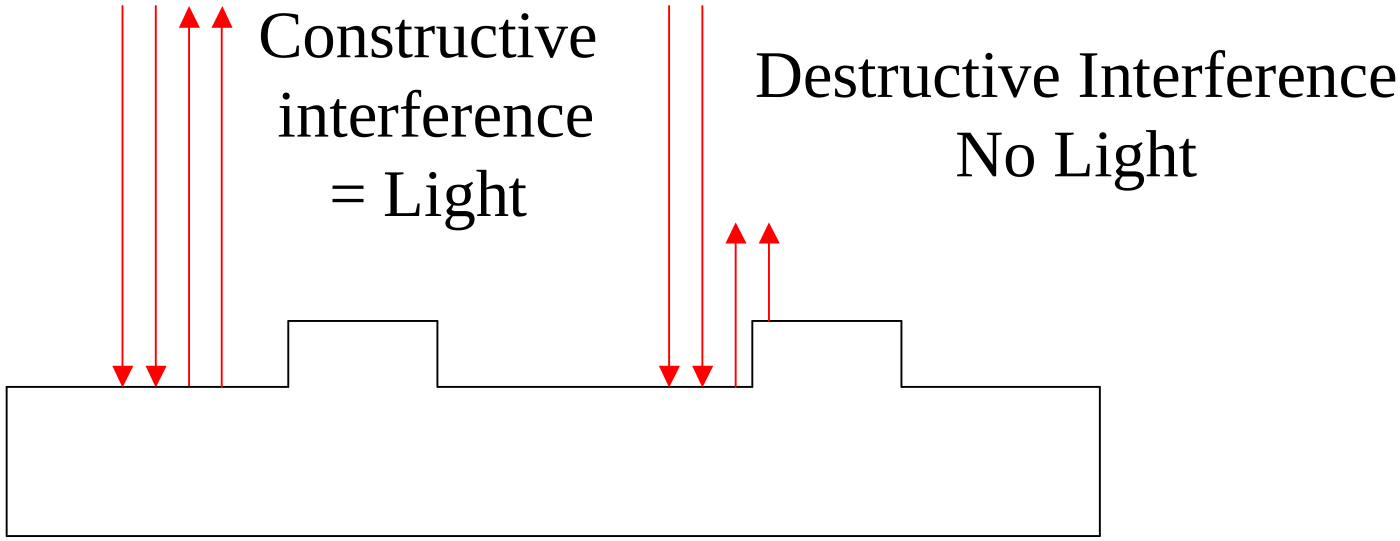
Mechanical Recording : CD-ROM



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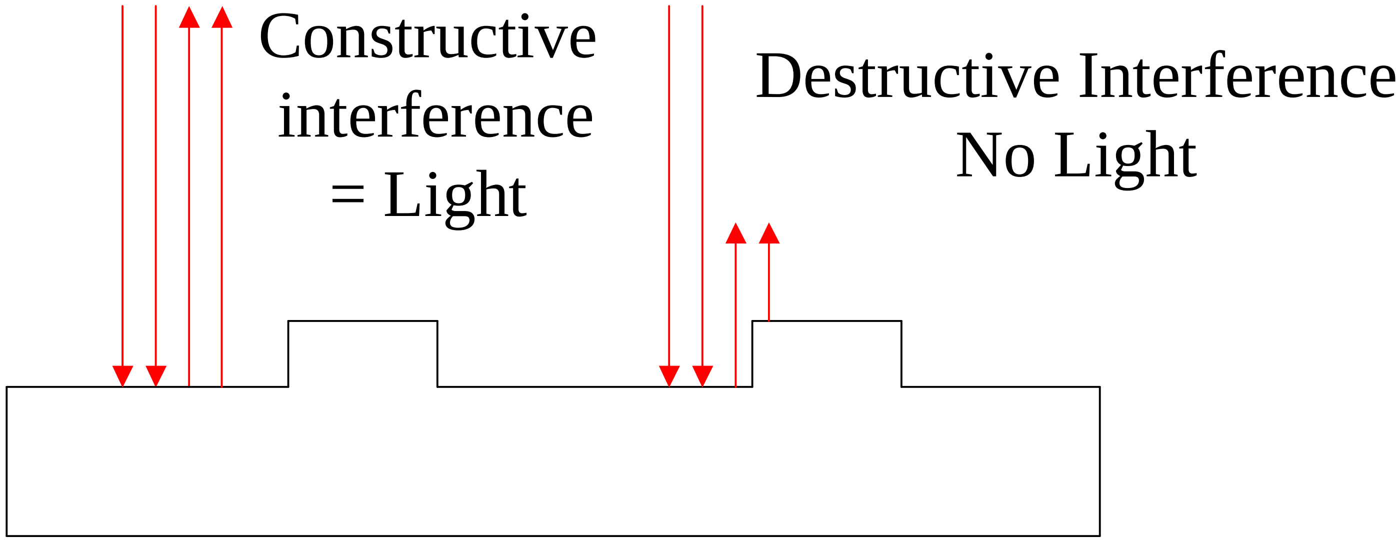


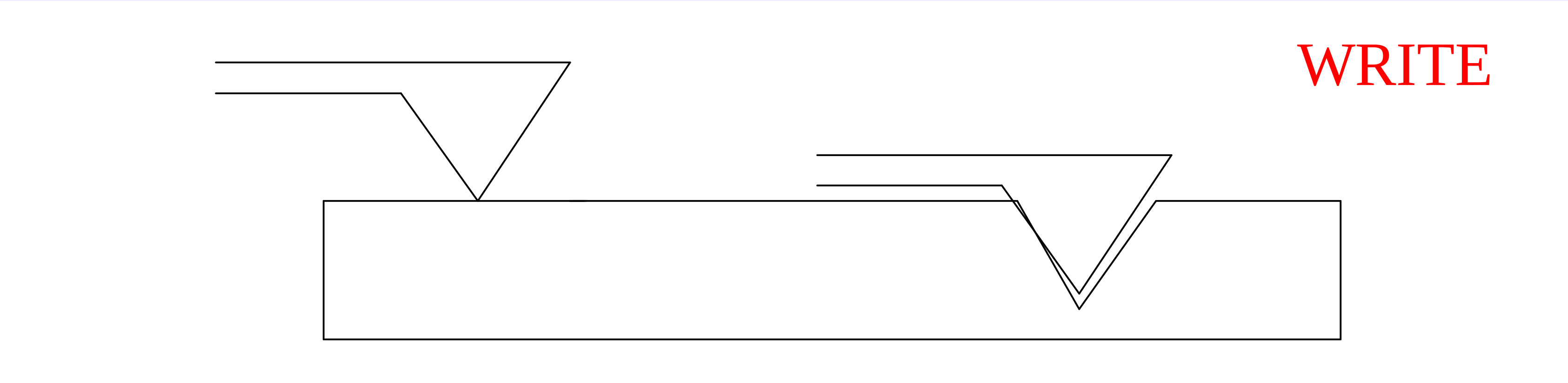
Burned / Not Burned
Black / Reflecting

CD-R

Cristallised / Amorphous
Reflecting/ Non Reflecting

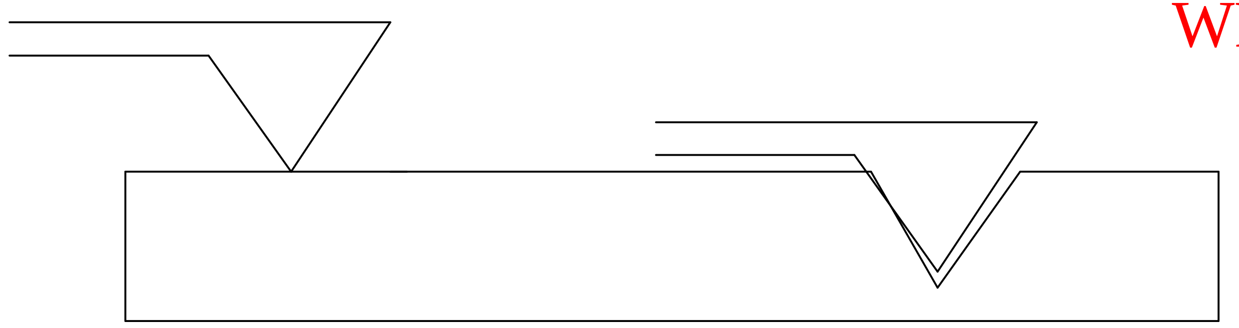
CD-RW

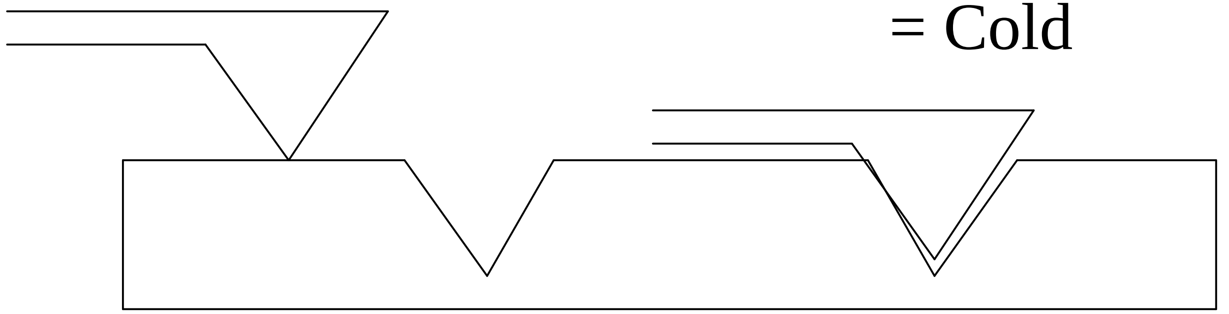
Mechanical Recording : Millipede (IBM Zurich)



40 nm hole in a polymer film

Mechanical Recording : Millipede (IBM Zurich)





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heat disipation (Milipede)

What makes the difference ?

Existing technology / not yet developped

no magnetism in Si technology --> no MRAM yet

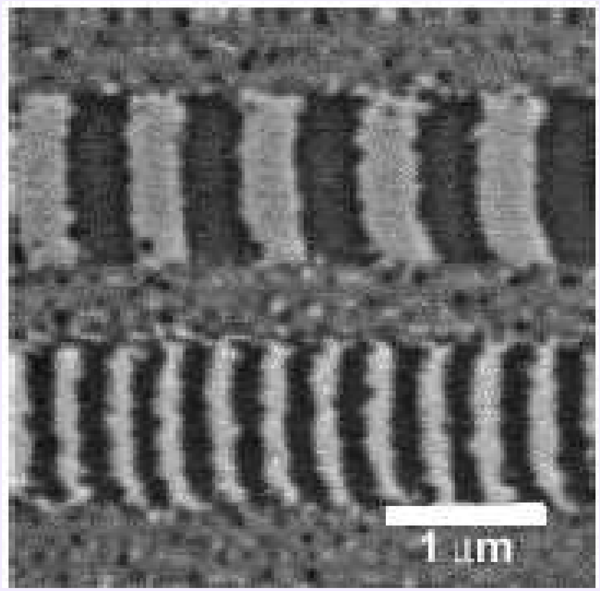
Maximum density : physical limits — Wavelength; Thermal stability

Access time / Write time / Read time

Life cycles 10^5 - 10^8 - $10^{infinity}$

II-Media

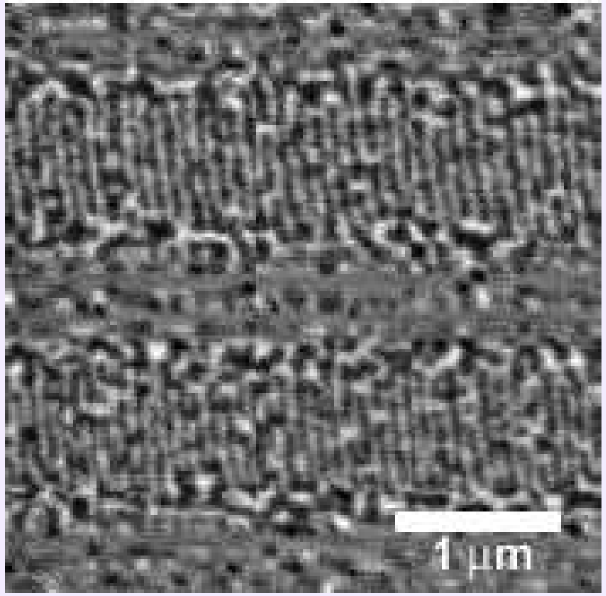
Magnetic Recording Media



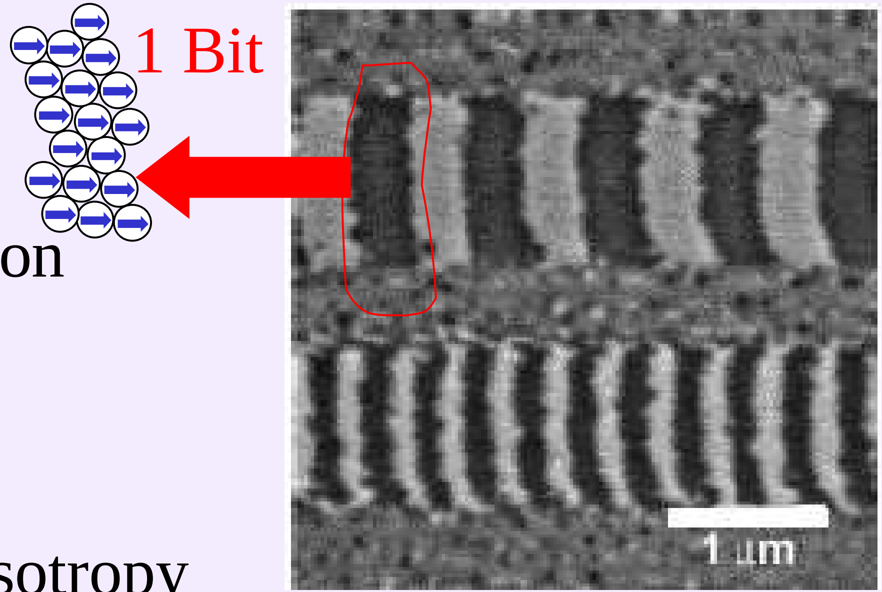
One Magnetic Bit = One information

Parameters

Two states --> uniaxial anisotropy
Stable --> anisotropy large enough
Access --> how to write/read ?



Magnetic Recording Media



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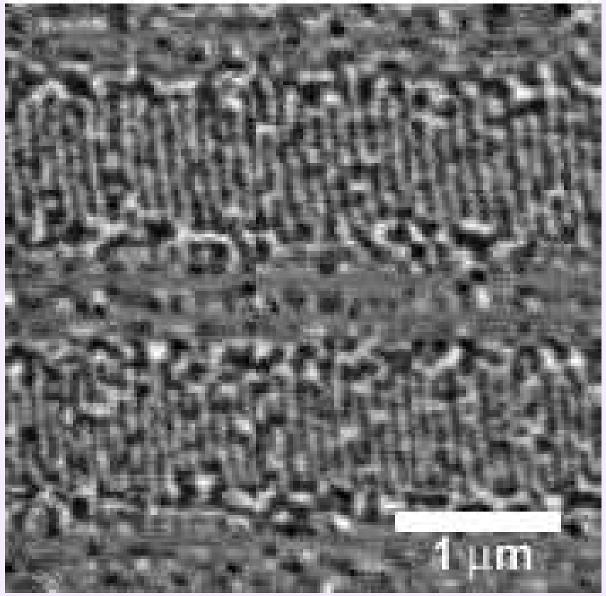
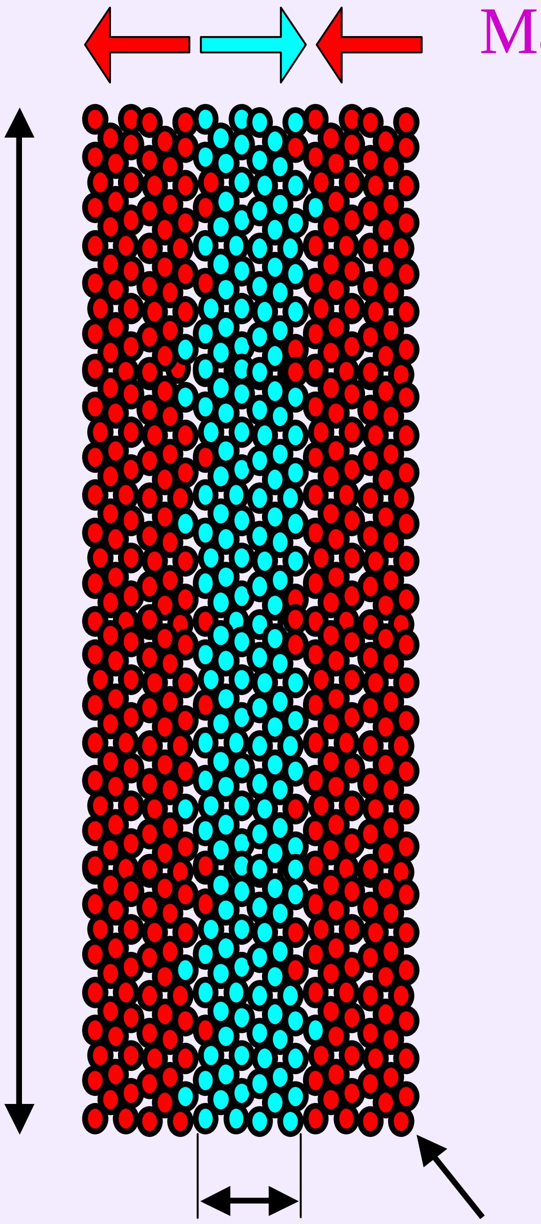
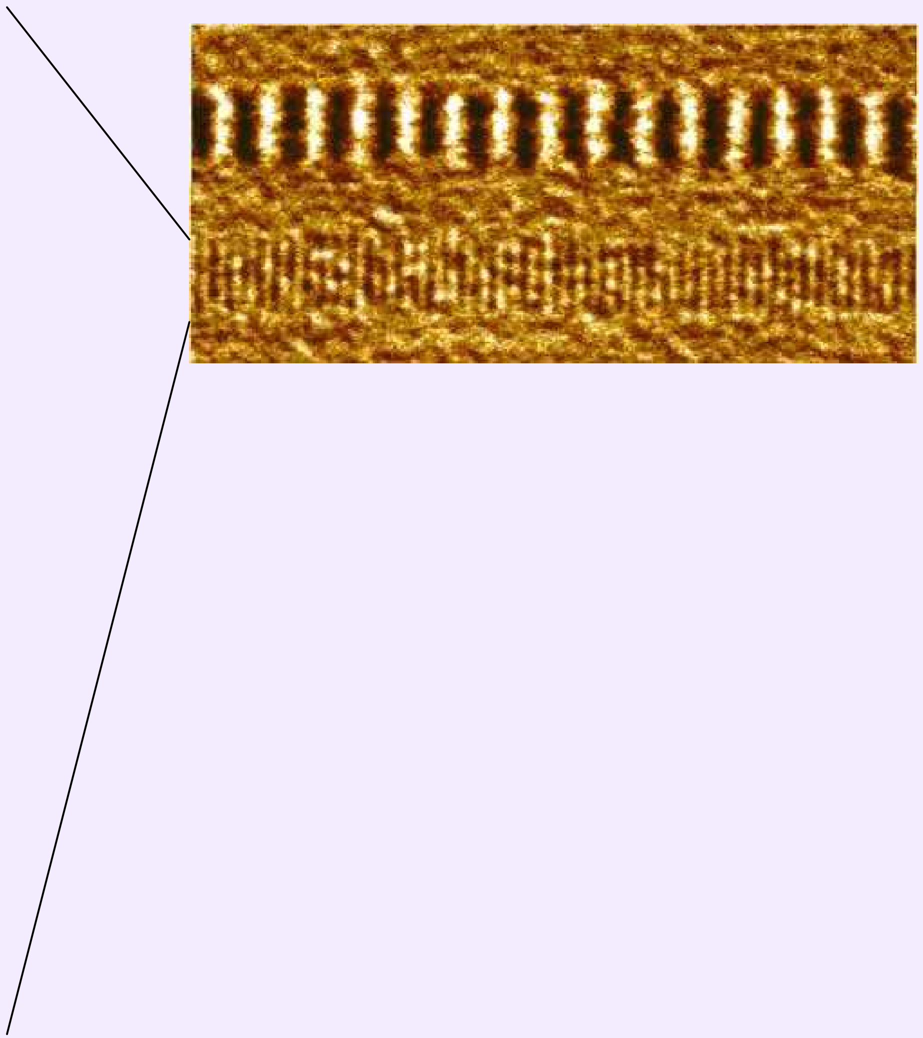


Magnetic Recording Media





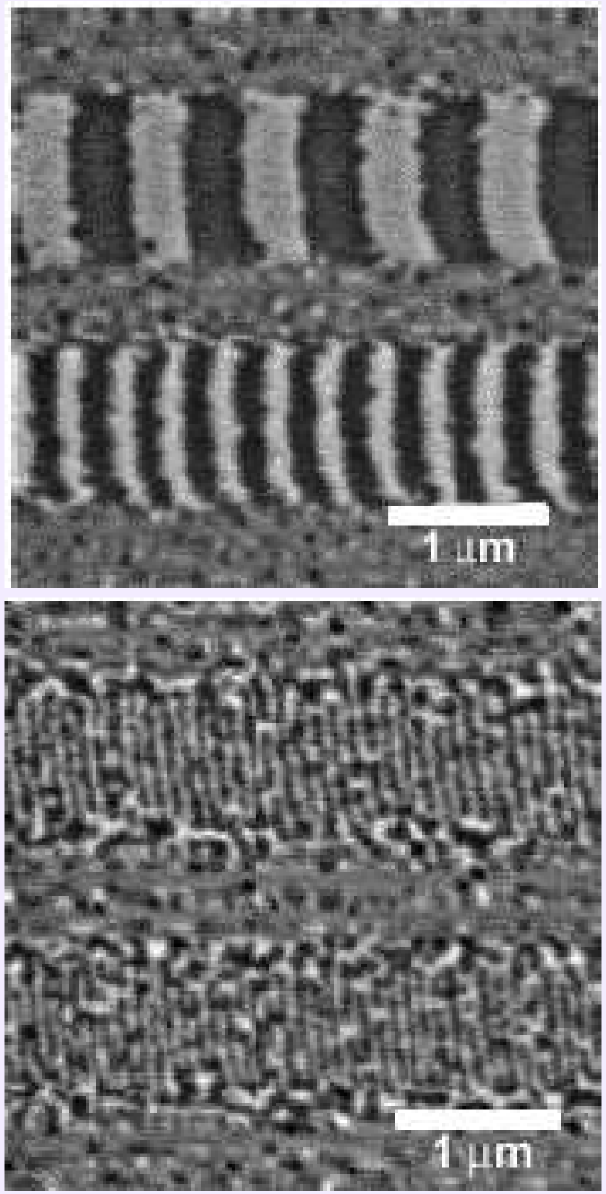
Magnetic Recording Media

One Magnetic Bit = One information

Parameters

- Two states --> uniaxial anisotropy
- Stable --> anisotropy large enough
- Access --> how to write/read ?

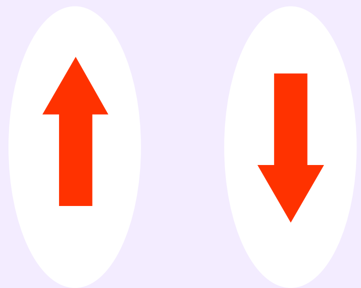
First solution : particulate media



Magnetic Recording Media : Particulate Media

Origin of the Uniaxial anisotropy

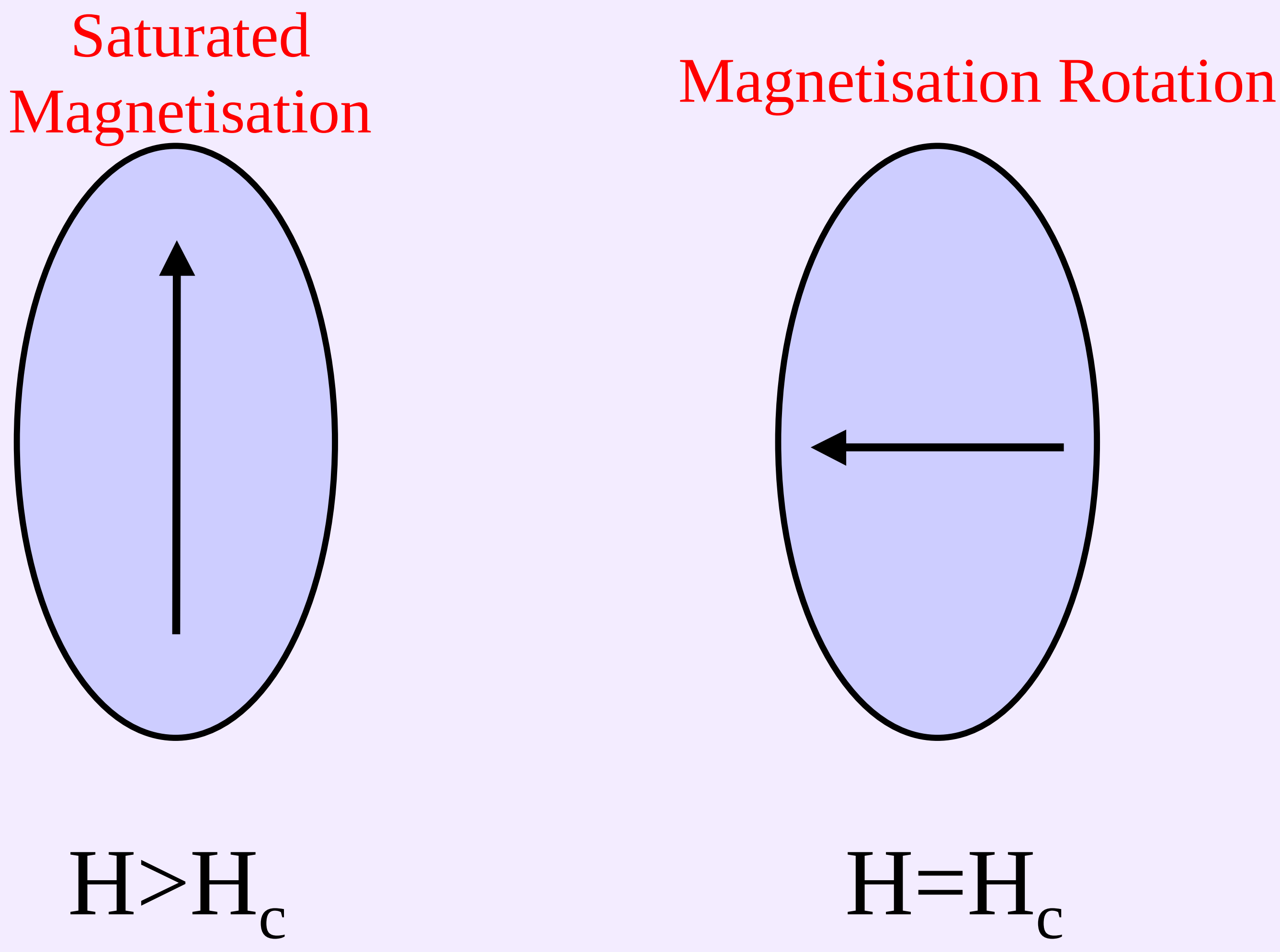
$$E = K \sin^2 \theta$$



Shape Anisotropy vs Magnetocrystalline Anisotropy

Magnetic Recording Media : Particulate Media

Coercicity : Anisotropy Field in a small particle

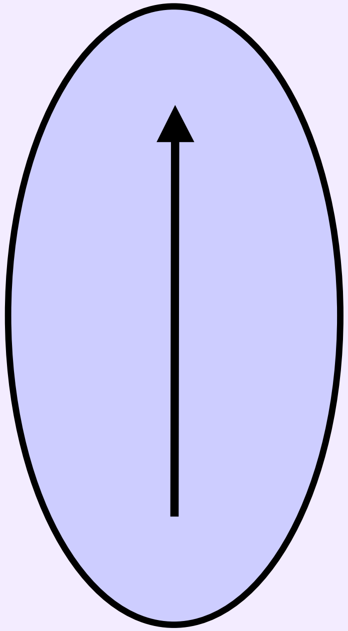


Magnetic Recording Media : Particulate Media

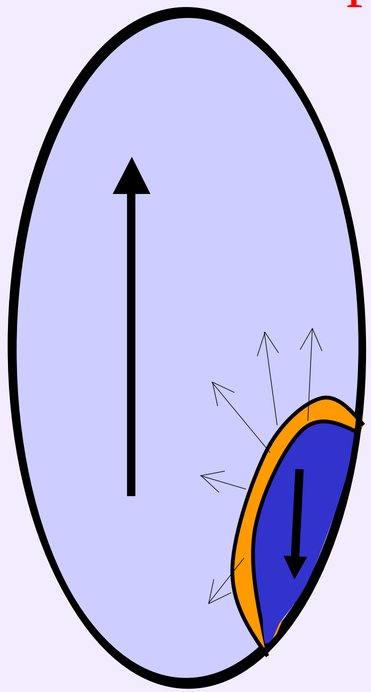
Coercicity : Much Smaller than Anisotropy in a larger particle

Saturated Magnetisation

Nucleation + Propagation



$H>H_c$



$H=H_c$

Shape anisotropy : $E = -\frac{\mu_0}{2}\vec{H}_d \cdot \vec{M} = \frac{\mu_0}{2}(N_{//}\vec{M}_{//} + N_{\perp}\vec{M}_{\perp})\cdot\vec{M}$

$$= \frac{\mu_0}{2}(N_{//}M_{//}^2 + N_{\perp}M_{\perp}^2)$$

For a needle-like particle $N_{//}=0$ and $N_{\perp}=1$

i.e. $$E = \frac{\mu_0}{2}N_{\perp}M_{\perp}^2 = \frac{\mu_0}{2}M^2\sin^2\theta$$

$\mu_0 M$ = 0.5 to 1 T for oxides, 2.2 T for Fe and 2.5 T for FeCo

maximum shape anisotropy : 400 kJ/m^3 (using 1 Tesla magnetisation)
2500 kJ/m^3 absolute maximum

Magnetocrystalline Anisotropy : $E = K_1 \sin^2(\theta)$

	K_1 (kJ/m^3)
Ni	5
Fe	48
Co	530
PtFe	6 600
$SmCo_5$	17 200

Max shape anisotropy

Low symmetry structure (hexagonal, rhomb. tetragonal)
+ large spin orbit constant (rare-earth or platinium)

give MCA larger than the shape anisotropy

But Co, Pt are expensive
Rare earths are corrosive

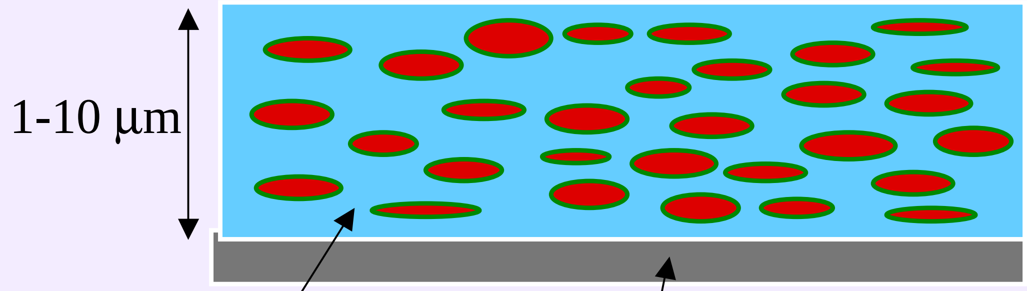
Magnetic Recording Media : Particulate Media

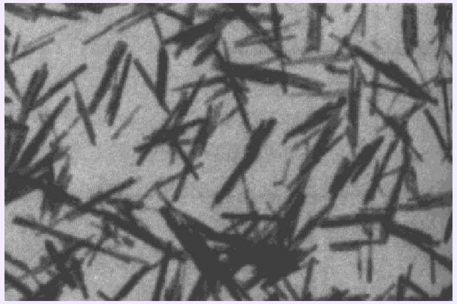
Ferro/ferrimagnetic particles in polymer binder

$\mu_0 H_C$ due to

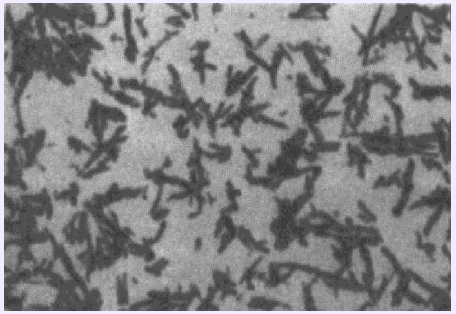
- -Shape anisotropy
  - γ-Fe_2O_3 (0.3 - 0.5 µm, 0.04 T)
  - CrO_2 (0.2 - 0.6 µm, 0.04 T)
  - $Fe_{1-x}Co_x$ (0.1- 0.3 µm, 0.25 T)
- -Magnetocrystalline anisotropy
  - $BaFe_{12}O_{19}$ (0.05-0.15 µm , 0.25T)

Packing fraction ≤ 40 vol.%

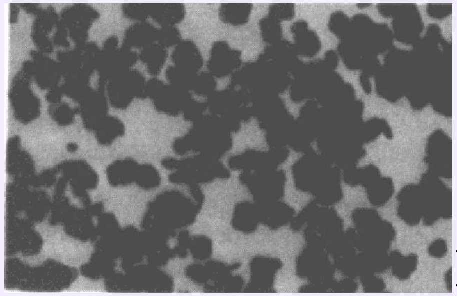




γ-Fe_2O_3



Fe



$BaFe_{12}O_{19}$

Max. storage density : 100 Megabits/in^2
Min. bit area ≈ 6.5 μm^2
Applications : Audio & video tapes, floppy disk

Floppy Disk (1984 format) :

Diameter 3.5 inch = 8.9 cm
Total thickness 77 microns
Magnetic layer 0.9 micron (iron oxide)
Rotation 300/360 rpm (HDD 10 000 rpm)

Coercive field = 12 mTesla (HDD 150 mT)

Double side recording
Tracks : 80 per side (135 tpi 0.2 mm)
Bits : 17400 bpi (1.4 micron long)

HD 100 GB/in^2
(149 000 tpi)
(680 000 bpi)

Total 1.44 MB
Transfer 500 kbit/s (HDD 100-200 Megabit/s)

ZIP : better disk (155 mT) + better head 1.44 MB --> 100/250 MB

Example (EMTEC 2003)
Tape 1/2 inch (12.5 mm)

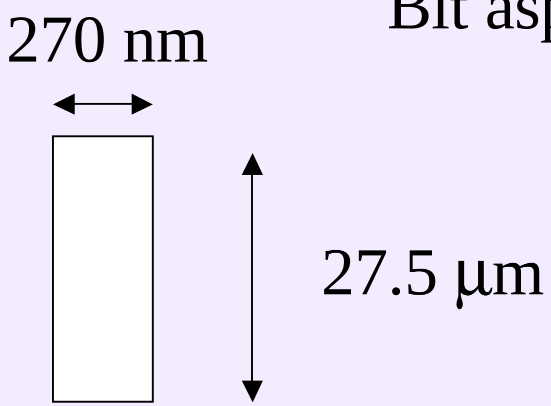
Up-to-date TAPE

1GB
417 m long
thickness : polyester (11.6 microns, total 13.7 microns)
particles : CrO_2
coercive field : 52 mTesla (+/- 5%)

20 GB
300 m long
Iron particles
coercitif field : 160 mTesla +/- 5%

100 GB
600 m (thickness 9 microns)
fine particles (iron ?)
coercive field : 185 mT
track/inch : 923 (27.5 micron)
bit/inch : 93000 (270 nm)

Bit aspect



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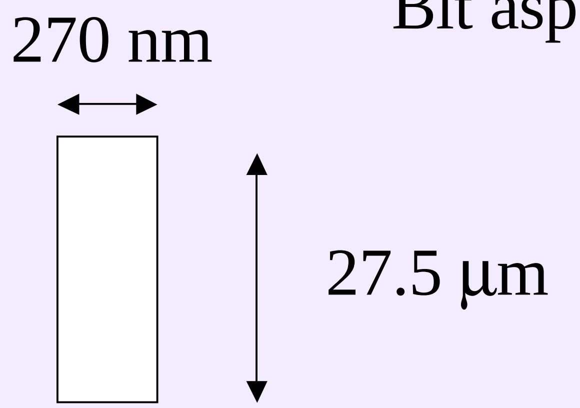


Magnetic Recording Media : Continuous Media

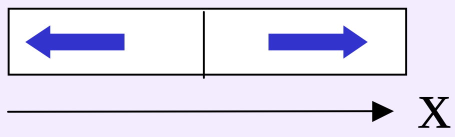
Beyond particle media

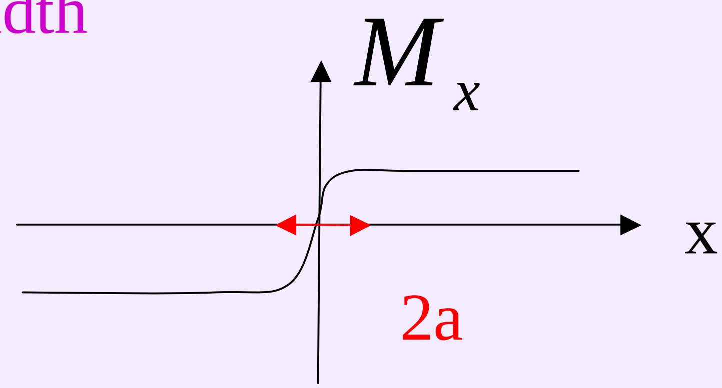
smaller particle --> continuous granular media

better materials --> cobalt based

Magnetic Recording Media : Transition Width

Longitudinal Media





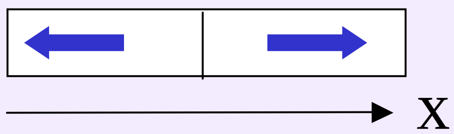
Let us suppose that M does not depend on thickness

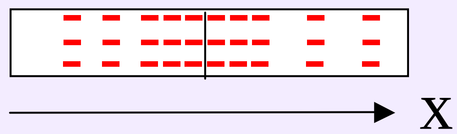
$$M_x(x) = \frac{2M_s}{\pi} \arctan \frac{x}{a}$$

The transition width is 2a

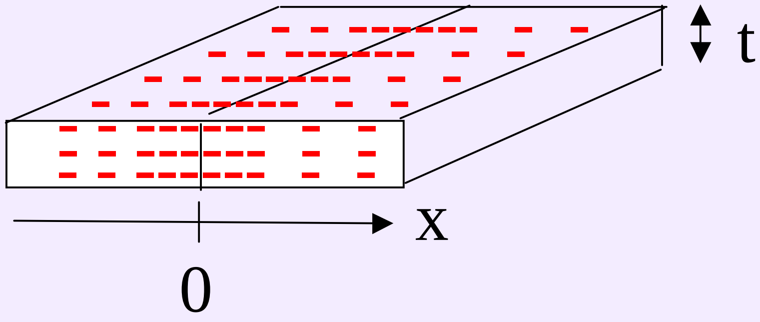
The density of « magnetic » charges is :

$$\rho = -div\vec{M} = -\frac{dM(x)}{dx} = -\frac{2M_s}{\pi \cdot a} \frac{1}{1+\frac{x^2}{a^2}}$$





Magnetic Recording Media : Transition Width



$$\vec{H}_d = \frac{1}{4\pi}\iiint \frac{\rho \cdot \vec{r}\, dV}{r^3}$$

Bit width infinite
+ 2D charge

$$\vec{H}_d = -\frac{2M_s t}{\pi \cdot a}\frac{\frac{x}{a}}{1+\frac{x^2}{a^2}}$$

Maximum Demag field $$H_d \leq \frac{2M_s t}{\pi \cdot a}\frac{1}{2} \leq H_c$$

$$a \geq \frac{M_s t}{\pi \cdot H_c}$$

$M_s t, (M_r t \text{ in fact})$ As small as possible

H_c As large as possible

Magnetic Recording Media : Transition Width

$M_r t$	As small as possible	Thin film media Small magnetisation

Signal amplitude will also decrease !!!!

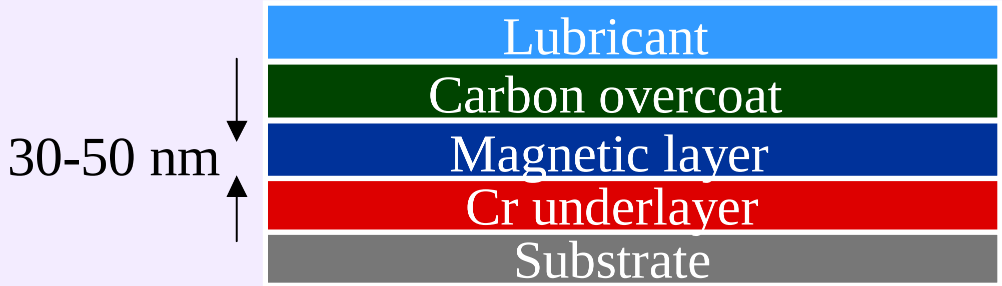
H_c	As large as possible	Hard magnetic materials

The write field should be larger than H_c !!!

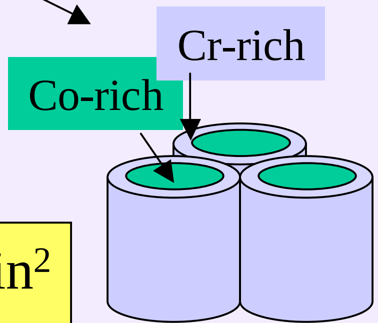
Magnetic Recording Media : Continuous Media

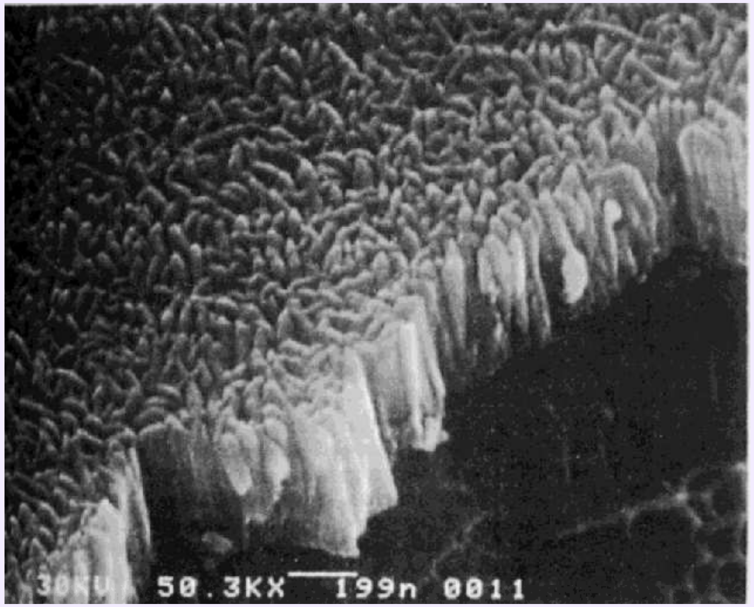
Need to reduce $M_r t$
to increase H_C
CoCrM / Cr (M=Ta, Pt)

Thin film media



Exchange coupling → transition noise
Has been limited by :
• Physical grain segregation (process / underlayer effects)
• Compositional segregation



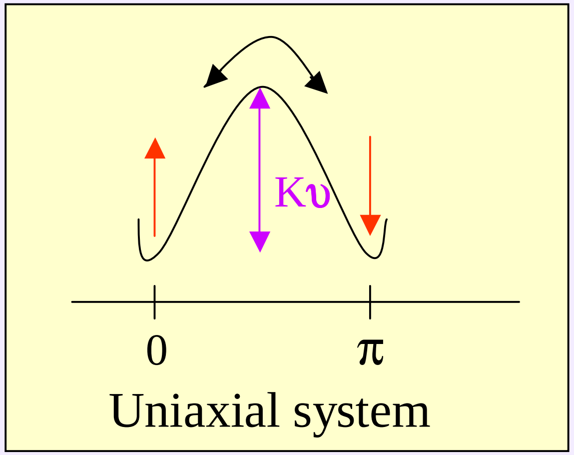


Max. storage density ≈ 30 Gbits/in^2
Min. bit area ≈ $2 \times 10^{-2}\ \mu m^2$
Applications : disk drives

Magnetic Recording Media : A physical limit : Superparamagnetism

Remanent state is bistable

if anisotropy energy < thermal energy
i.e. $K\mathbf{V} < kT$



thermal relaxation time, τ

$$\tau = \tau_0 \exp(K\mathbf{V} / kT)$$

$1/\tau_0$ is the attempt frequency ($\tau_0 \approx 10^{-9}$ s)

Superparamagnetism
lower limit to the size of a stable ferromagnetic particle

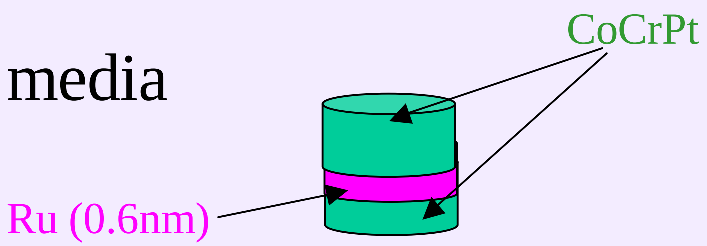
for data storage want $\tau >$ 10 years
i.e. must have $K\mathbf{V} / kT > 60$

at 300 K

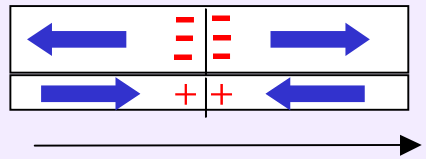
	K_1 (MJ/m^3)	ϕ_{min} (nm)
Fe	0.05	20
Co	0.5	8
$Nd_2Fe_{14}B$	5	4
$SmCo_5$	17	2

Magnetic Recording Media : Enhanced Continuous Media

AFC coupled media



RKKY AF coupled bilayer Co/Ru/Co



$M_r.t$ becomes $M_r.t_1$-$M_r.t_2$

Fullerton et al. APL 2001

Total $M_r.t$ decreases : less sensitive to demagnetising fields
but less signal also

Total $M_r.t$ decreases : but V does not, so K.V can be maintained

Max. storage density ≈ 45 Gbits/in^2
Min. bit area ≈ 10^{-2} µm^2
Applications : Ultra High Density

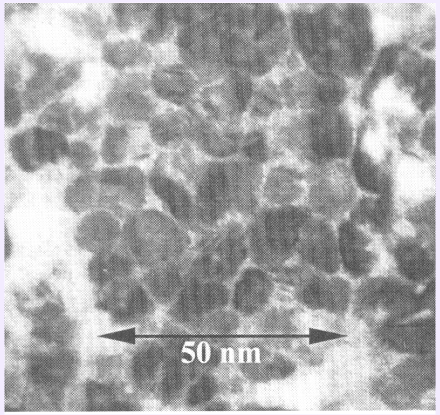
106 Gbit/in^2 in 2001 (Fujitsu)
130 Gbit/in^2 in 2002 (Read-Rite)

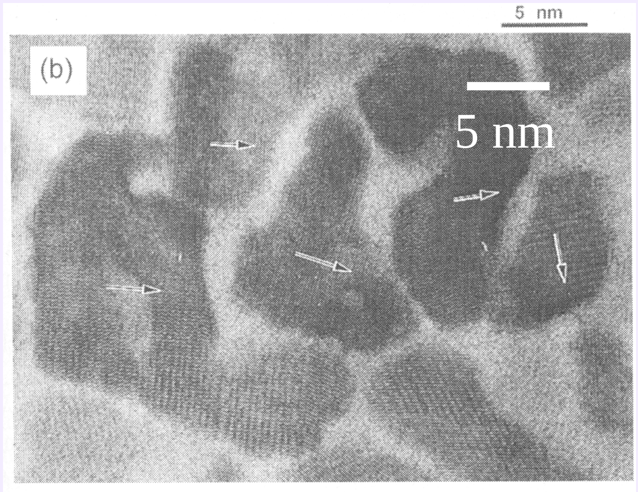
State-of-the-art longitudinal media

26.5 Gb/in^2 demonstrator

M.A. Schultz et al. (Read-Rite), IEEE Trans Mag. **36** (2000)2143

CoCrPtTaB/Cr



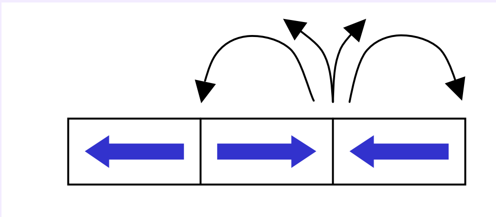


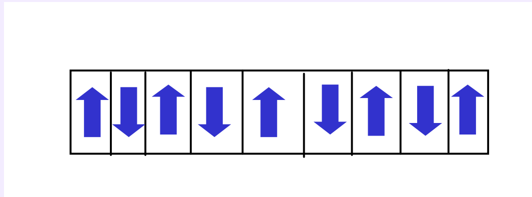
μ_0Hc : 0.25 T
M_rt : 0.4 x10^{-3} emu/cm^2
Film thickness : 19 nm
Average grain size : 11 nm
Transition parameter : 20 nm

Intermag 2002
(Seagate and Fujitsu)
100 Gbit/in^2
μ_0Hc : 0.48 T
M_rt : 0.35 x10^{-3} emu/cm^2
AFC Film
Average grain size : 9 nm

Magnetic Recording Media : Beyond Present Continuous Media

Perpendicular recording





Different aspect ratio : Decrease of demagnetising field
Thicker films allowed
SUL : Soft Underlayer to double the thickness

The write head should now provide perpendicular fields
new head design

Magnetic Recording Media : Beyond Present Continuous Media

Perpendicular recording

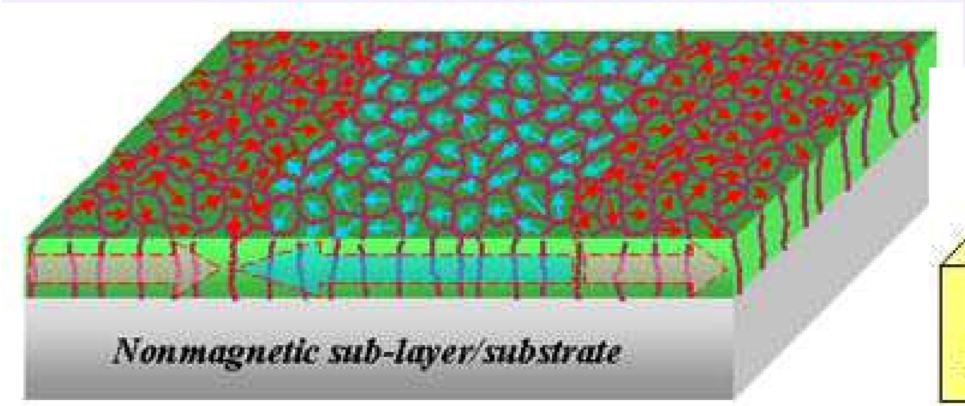
MMM 2002
(Seagate and ReadRite)
130 and 146 Gbit/in^2
μ_0Hc : 0.6 T
M_rt : 0.4 x10^{-3} emu/cm^2
Fuji film ?

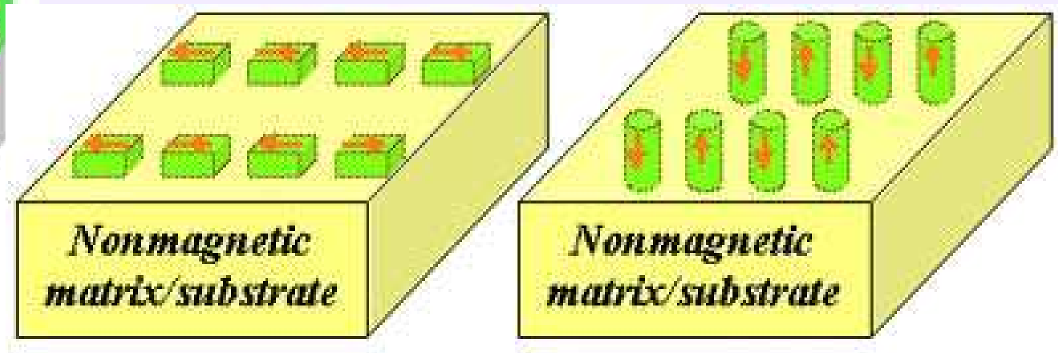
GRANULAR MEDIA

10^3-10^4 GRAINS = 1 BIT

PATTERNED MEDIA

1 GRAIN = 1 BIT





granular media give also rise to media noise (not well defined transition)

Magnetic Recording Media : Beyond Continuous Media

Patterned media : How to make them ?

e-beam lithography

Nano-imprint

self assembly + self organisation

moiré arrays

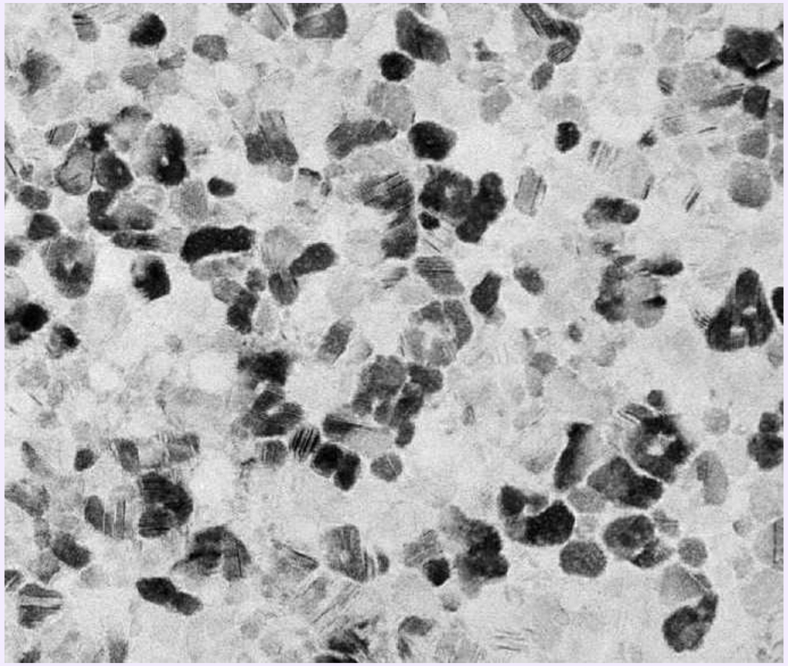
Grain Dispersion Narrowing

SOMA : Self Organised Magnetic Array

45 Gbit/in^2 demo media (Seagate)

•8.5 nm grains

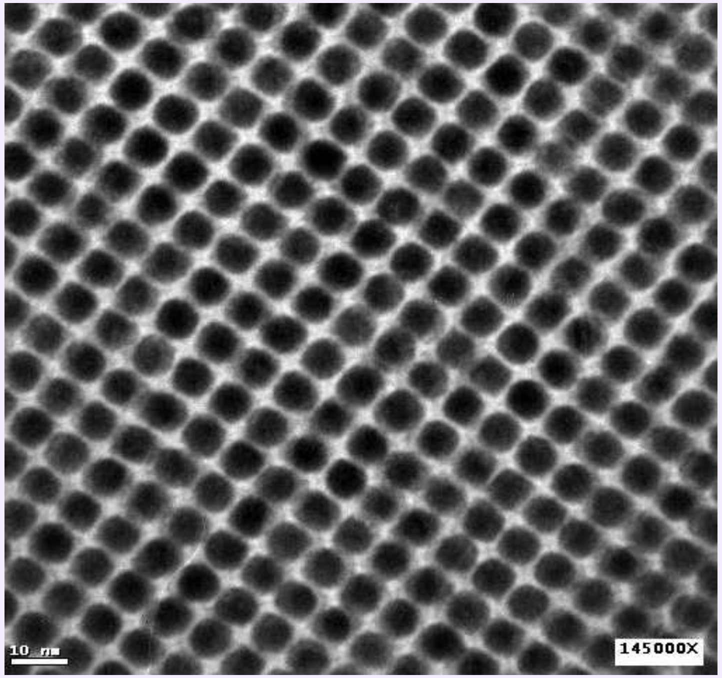
$\boldsymbol{\sigma_{area} \cong 0.5}$



Nanoparticle arrays

•6 nm FePt particles

$\boldsymbol{\sigma_{area} \cong 0.1}$



S. Sun, Ch.Murray, D. Weller, L. Folks, A. Moser, Science, 287, 1989 (2000)

(slide courtesy of D. Weller - Seagate)

APPLIED PHYSICS LETTERS VOLUME 74, NUMBER 22 31 MAY 1999

Sub-50 nm planar magnetic nanostructures fabricated by ion irradiation

T. Devolder and C. Chappert
Institut d'Electronique Fondamentale, Université Paris Sud, 91405 ORSAY Cedex, France

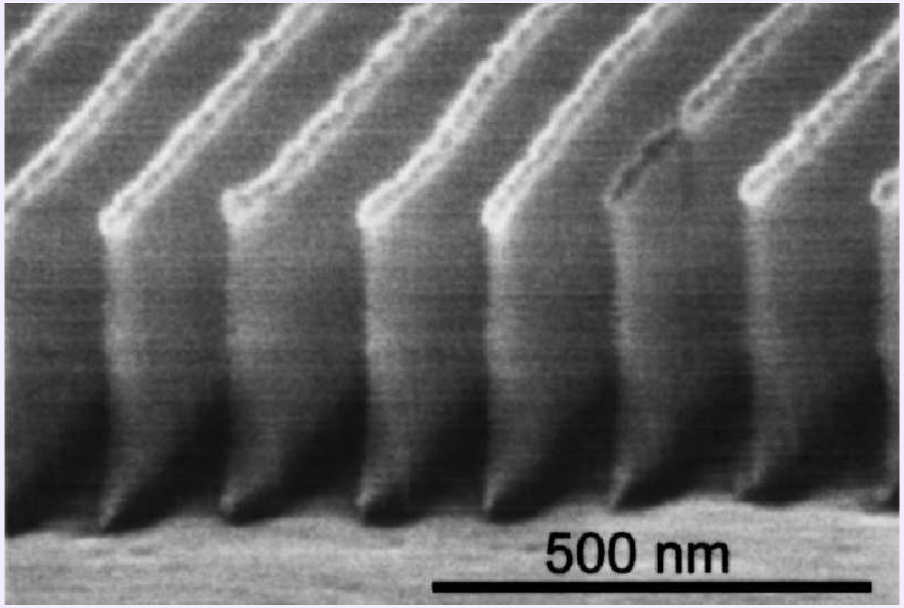
Y. Chen and E. Cambril
Laboratoire de Microstructures et Microélectronique, 196 rue H. Ravera, BP 107, 92220 Bagneux, France

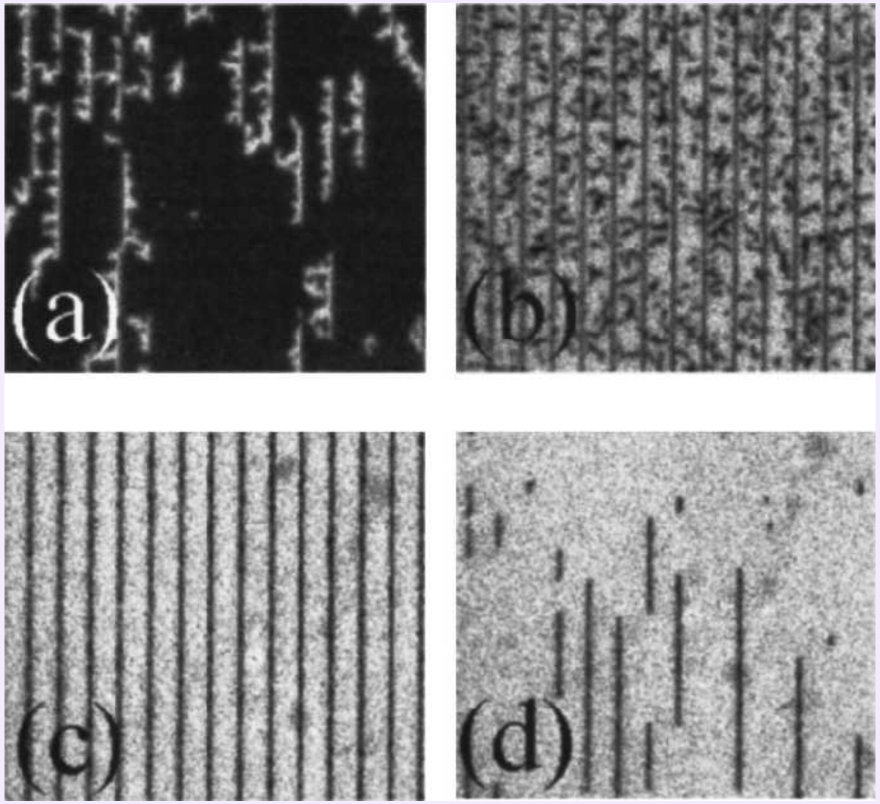
H. Bernas
Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, Université Paris Sud, 91405 ORSAY Cedex, France

J. P. Jamet and J. Ferré
Laboratoire de Physique des Solides, Université Paris Sud, 91405 ORSAY Cedex, France

Co-Pt multilayers irradiated by a He^{+} beam
Change of magnetic properties

Same idea with FePt $L1_0$ phase





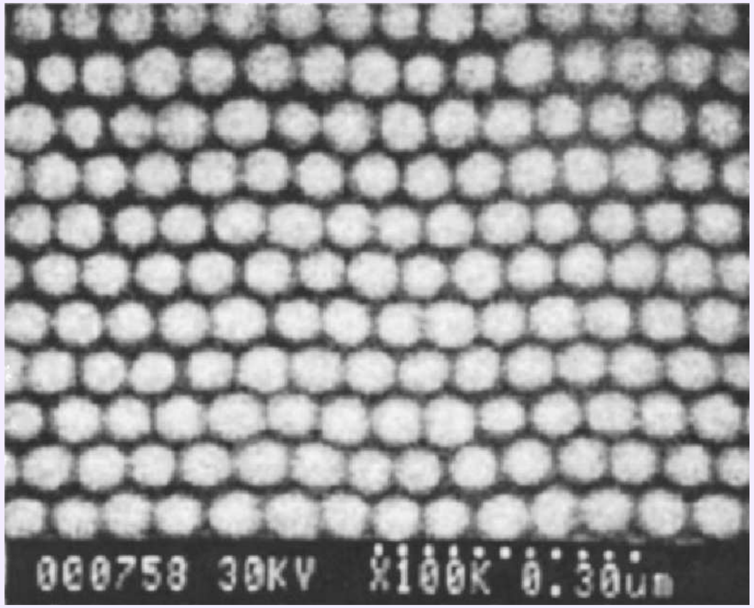
JOURNAL OF APPLIED PHYSICS VOLUME 91, NUMBER 10 15 MAY 2002

Domain structure in magnetic dots prepared by nanoimprint and e-beam lithography

J. Moritz,[a)] B. Dieny, and J. P. Nozières
CEA/Grenoble, Département de Recherche Fondamentale sur la Matière Condensée, SP2M/SPINTEC, 17 Avenue des Martyrs, 38054 Grenoble Cedex, France

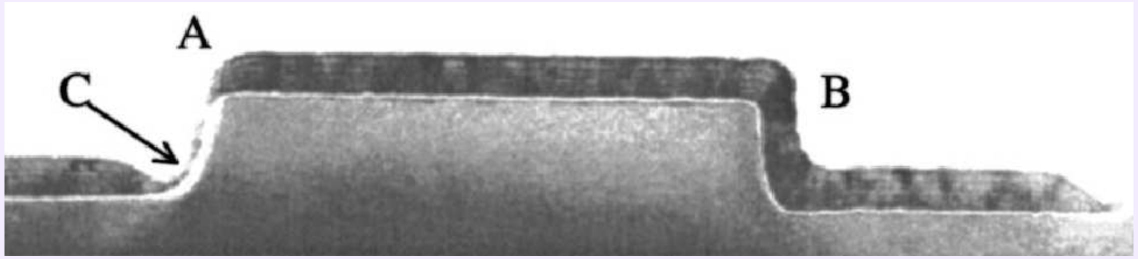
S. Landis
CEA Grenoble DTS/STME, 17 Avenue des Martyrs, 38054 Grenoble Cedex, France

A. Lebib and Y. Chen
Laboratoire de Photonique et de Nanostructures, 196 Avenue Henri Ravera, 92220 Bagneux, France



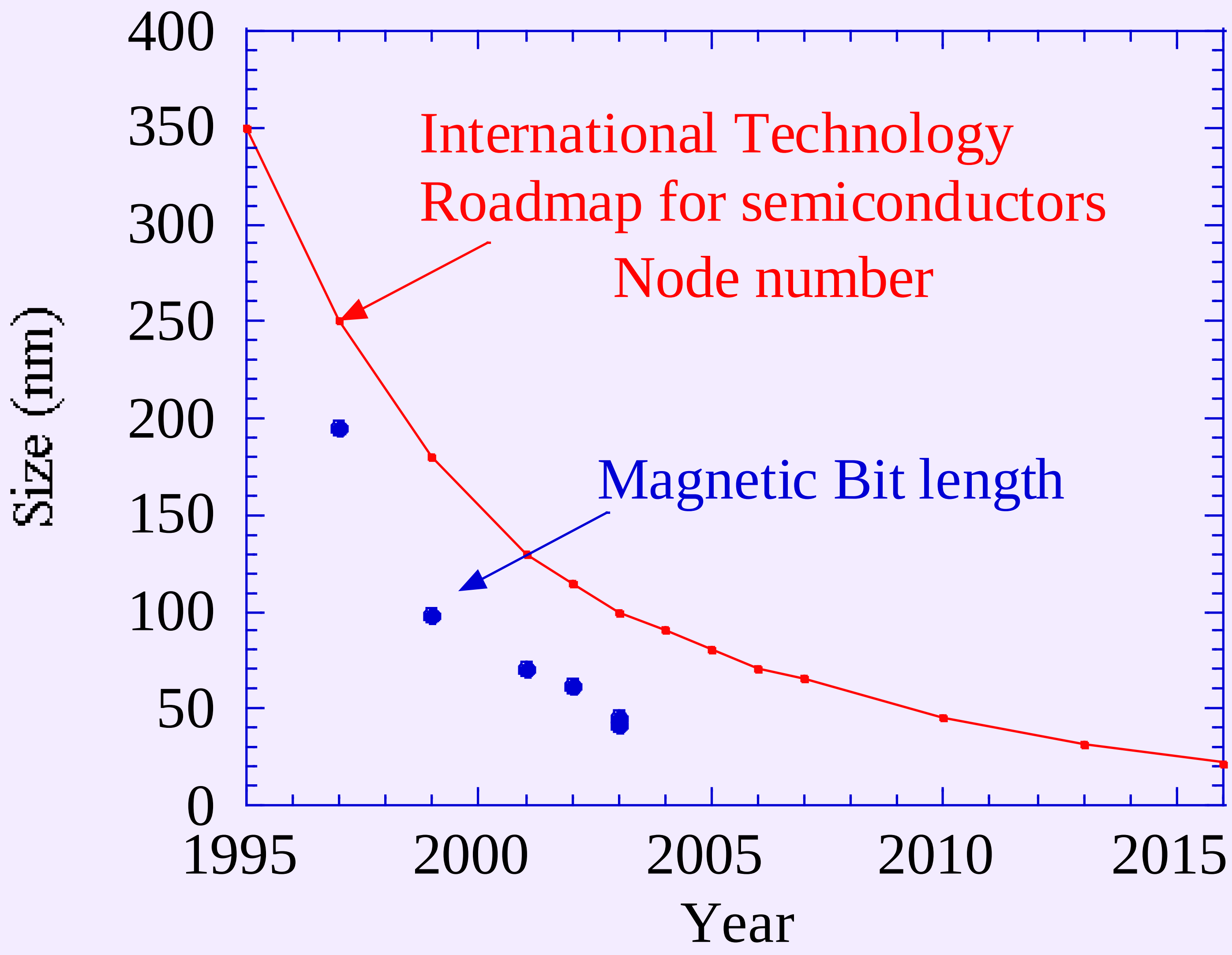
Nano-imprint + RIE + Lift-off Ni + Si RIE

+ Co-Pt mutilayers



60 nm dot array

Magnetic dimensions are smaller than semiconductor industry lithography tools



III-Heads

Magnetic Recording Heads

- Stray field measurement
  - only magnetic transition contribute
- M-O signal
  - laser wavelength limit (diffraction)
- Solid state (resistance)
  - electrical connection
  - memory matrix

Magnetic Recording Heads : inductive heads

Write head = Read head

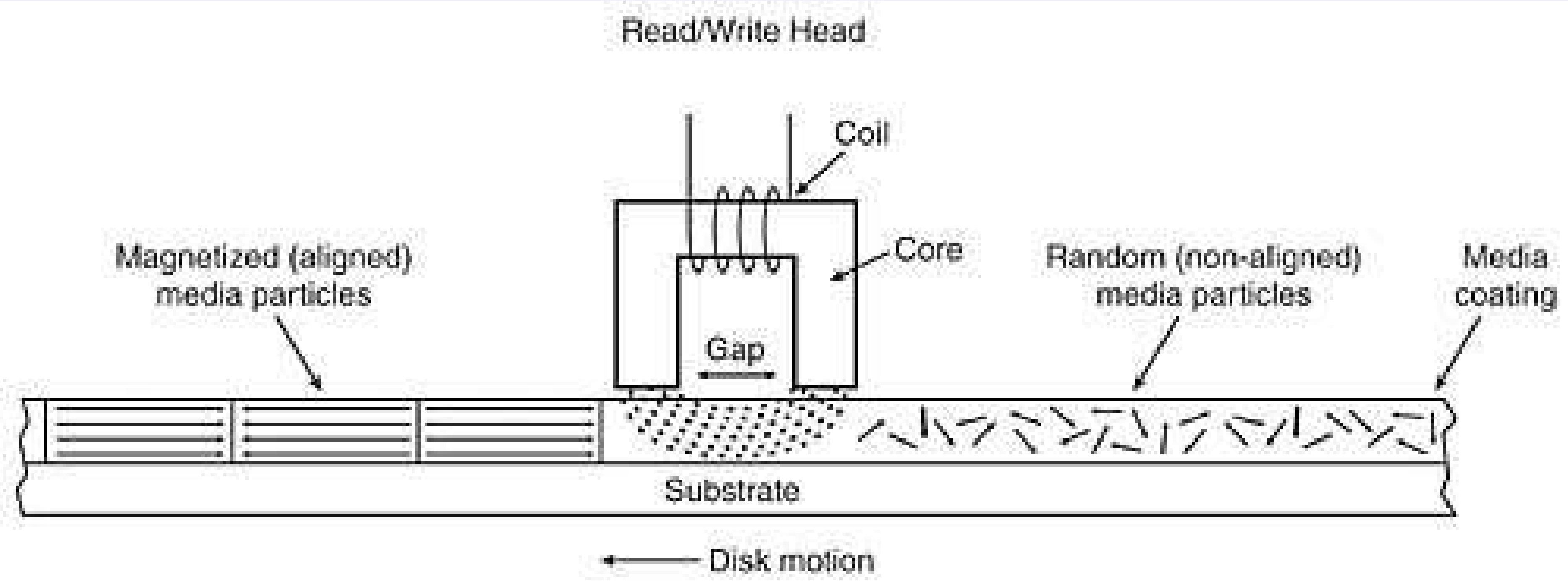
$$e = -\frac{d\varphi}{dt} = -\frac{S \cdot dB}{dt}$$

velocity : moving media and/or moving head

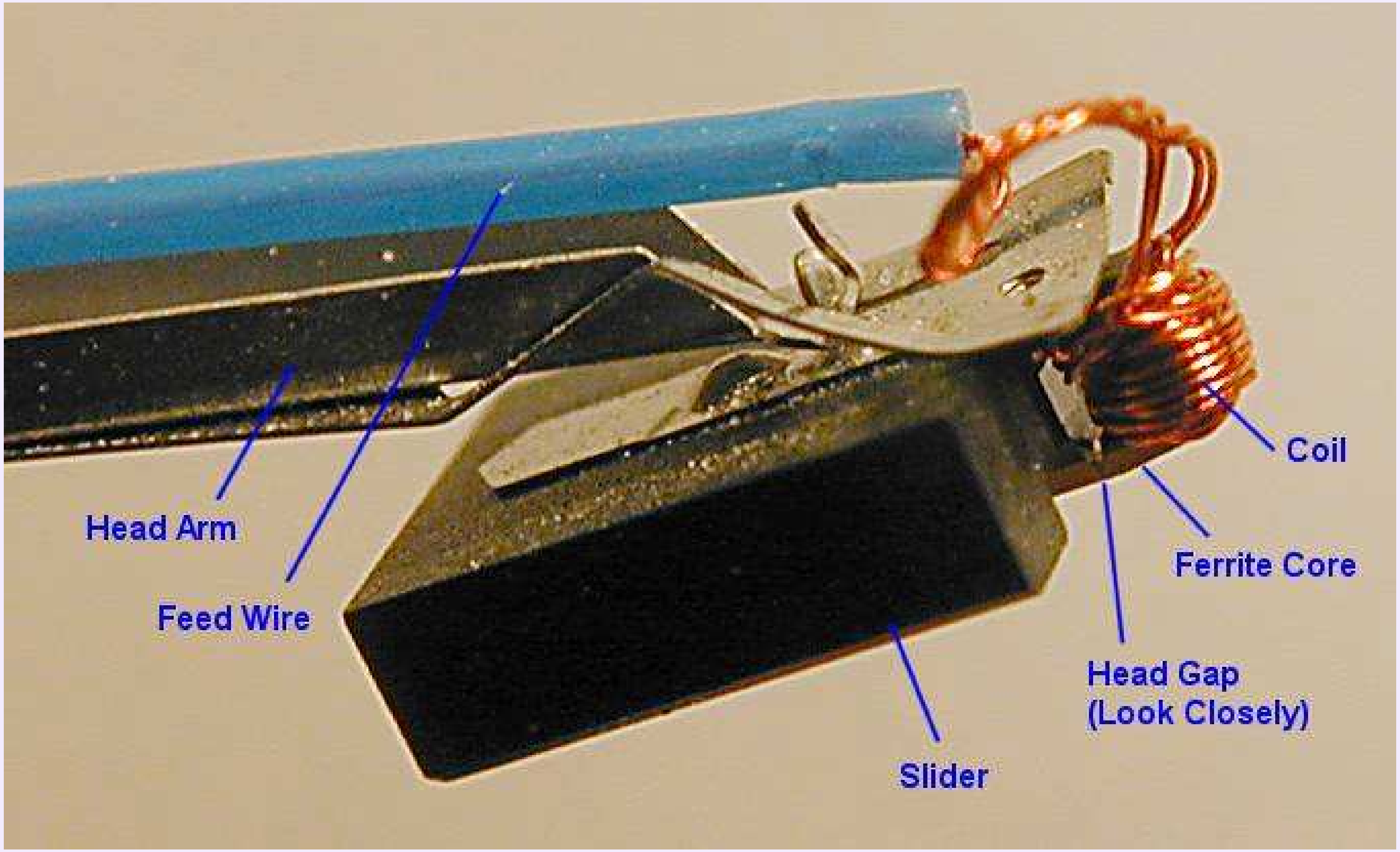
surface : signal proportional to coil area

now floppy, VHS ...

Magnetic Recording Heads : inductive heads

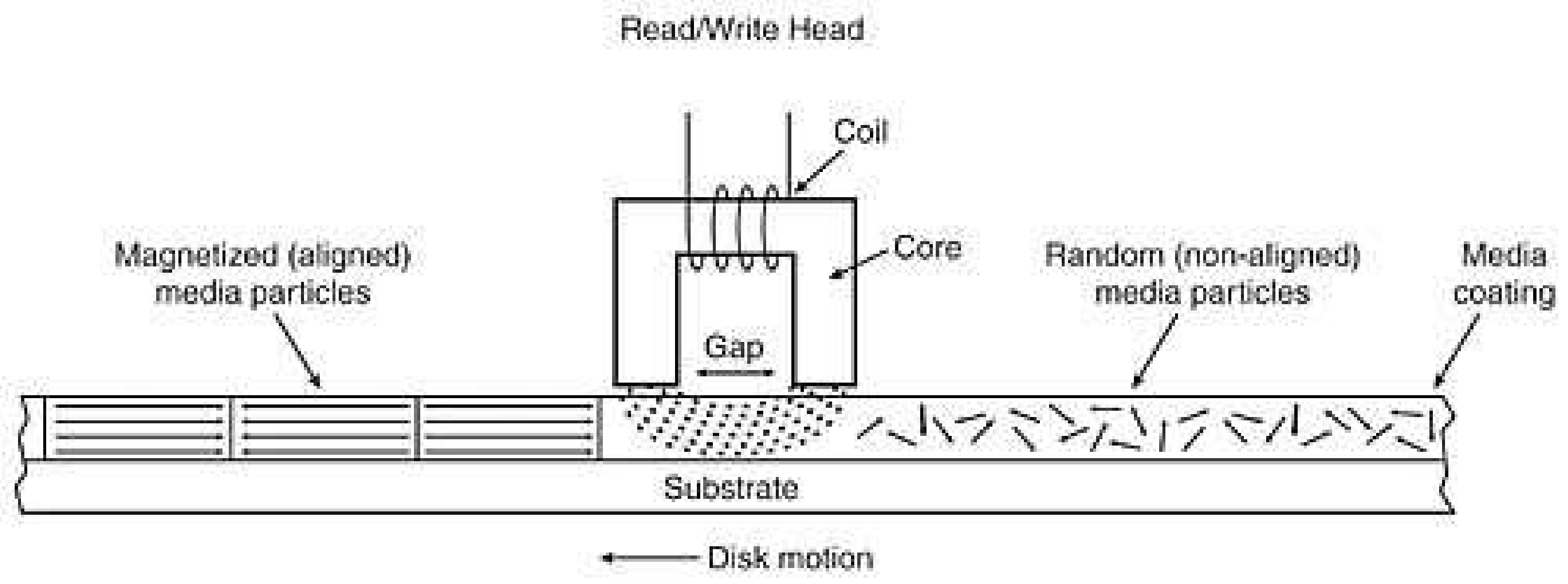


Ferrite Head (hard disk Seagate ST251 50 MB 1990, present floppy head)



MIG (Metal-in-gap) head : deposition of an iron rich alloy onto the poles to increase their magnetisation (and thus, their saturation).

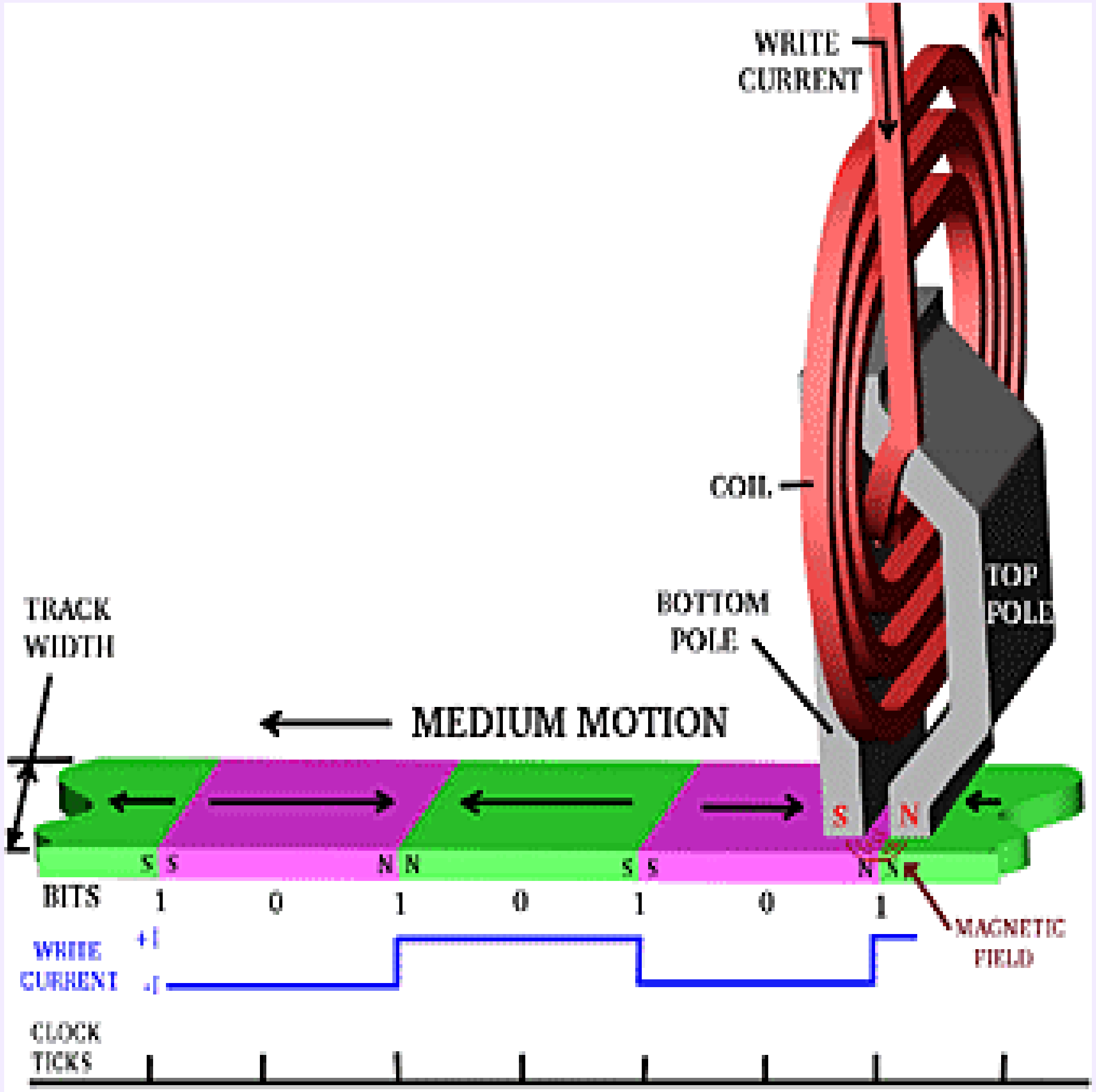
Magnetic Recording Heads : inductive heads



Space Resolution = Gap Length
Difficult to reduce the write gap down to submicron size

From Wound coils to
Thin film heads

Magnetic Recording Heads : inductive heads



Thin film head

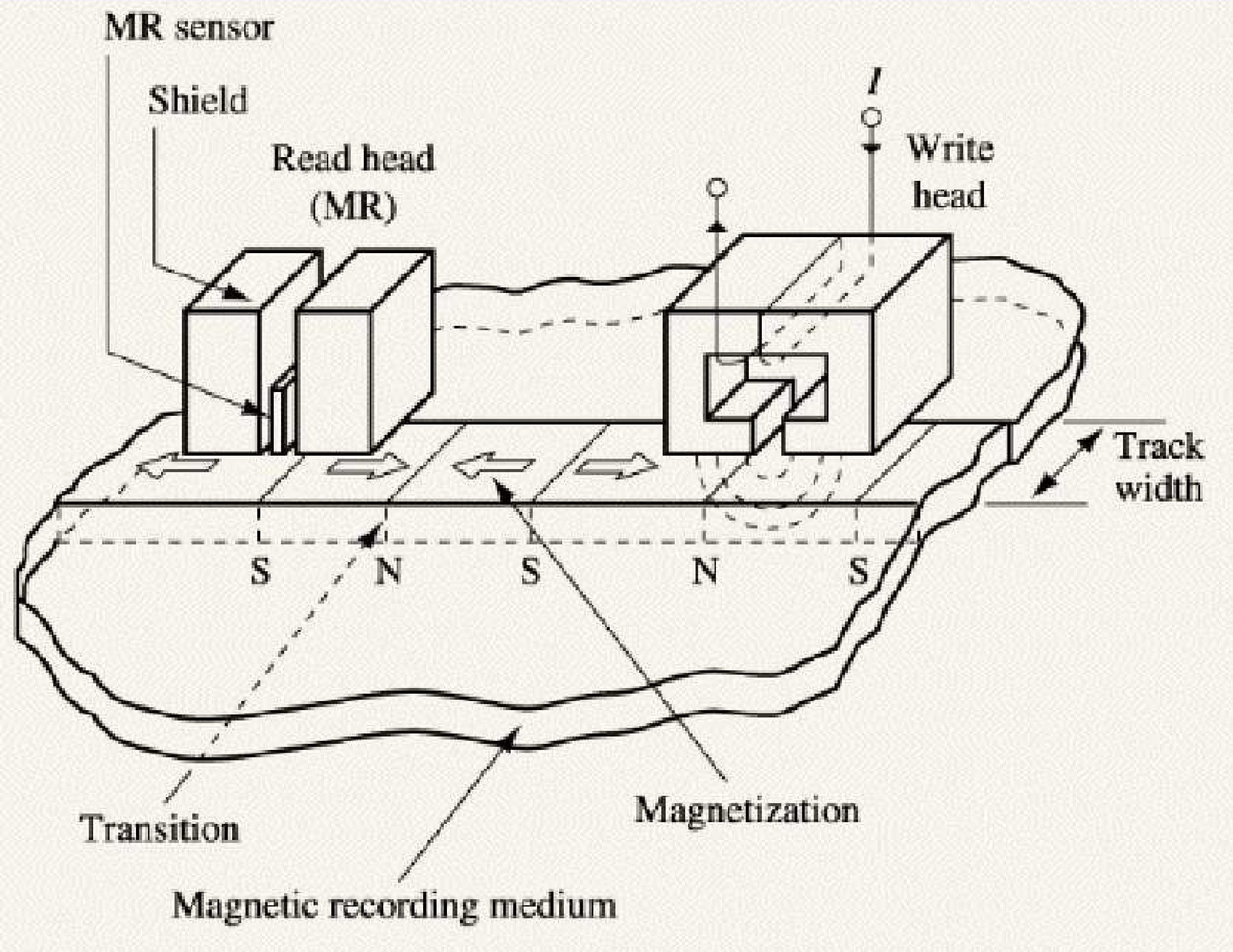
Bottom Pole (NiFe)
Copper windings
Top Pole (NiFe)

(Read-Rite)

Higher Magnetisation Materials to create larger magnetic fields

NiFe ---> FeCo based (and soft)

Presently demonstration with 2.4 Tesla materials


MR sensor
Shield
Read head
(MR)
I
Write
head
Track
width
S
N
S
N
S
Transition
Magnetization
Magnetic recording medium

Magnetic Recording Heads : MR heads

Larger signal : electrical response to stray fields

AMR (Anisotropic Magnetoresistance) : $Ni_{80}Fe_{20}$ (permalloy) film

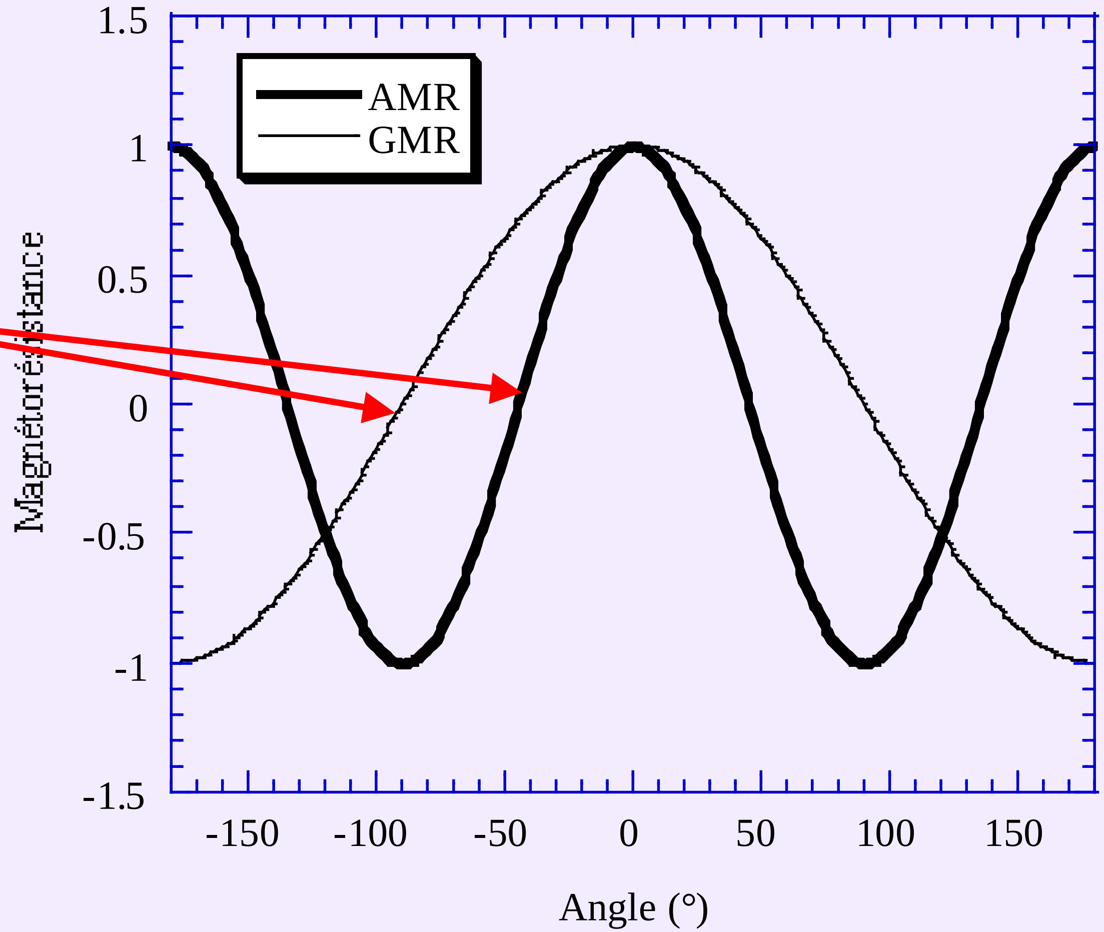
GMR (Giant Magnetoresistance) : Fe / Cu / NiFe

TMR (Tunnel Magnetoresistance) : Fe / Al_2O_3 /NiFe

Magnetic Recording Heads : MR heads

Dépendance Angulaire de la MR

Work-points

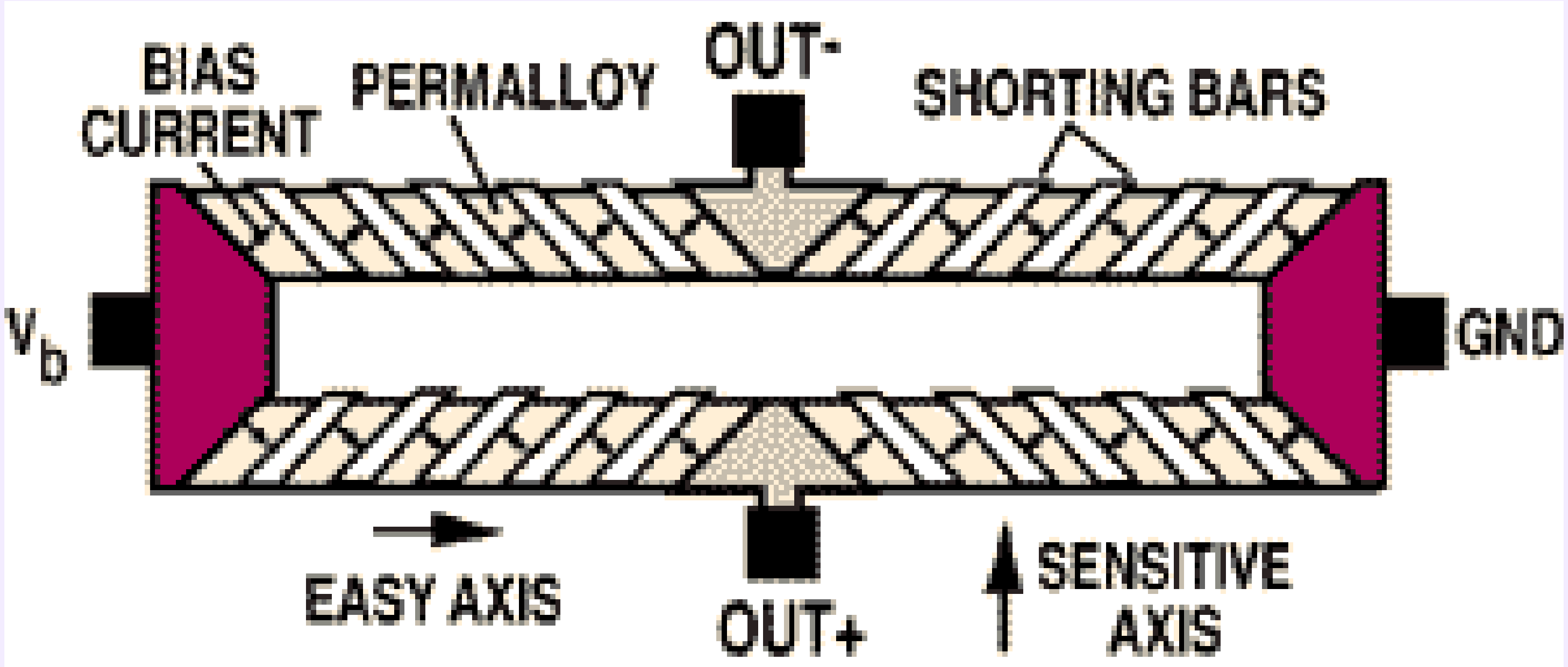


Signal processing people want linear response

Consequence for linear sensing : Angle at 45° or 90°

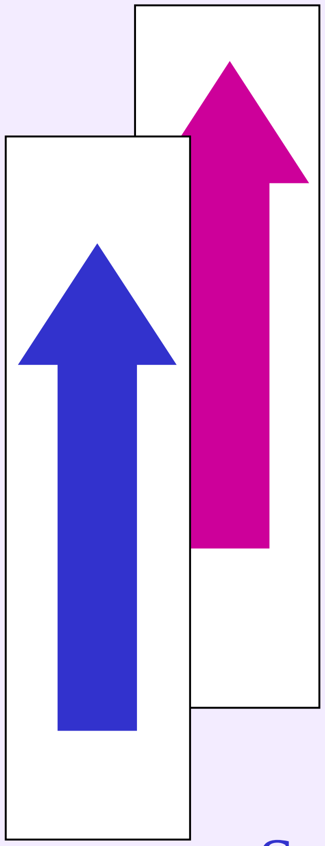
How to work 45° from current direction ?

AMR sensor : Barber pole configuration



How to work 45° from current direction ?

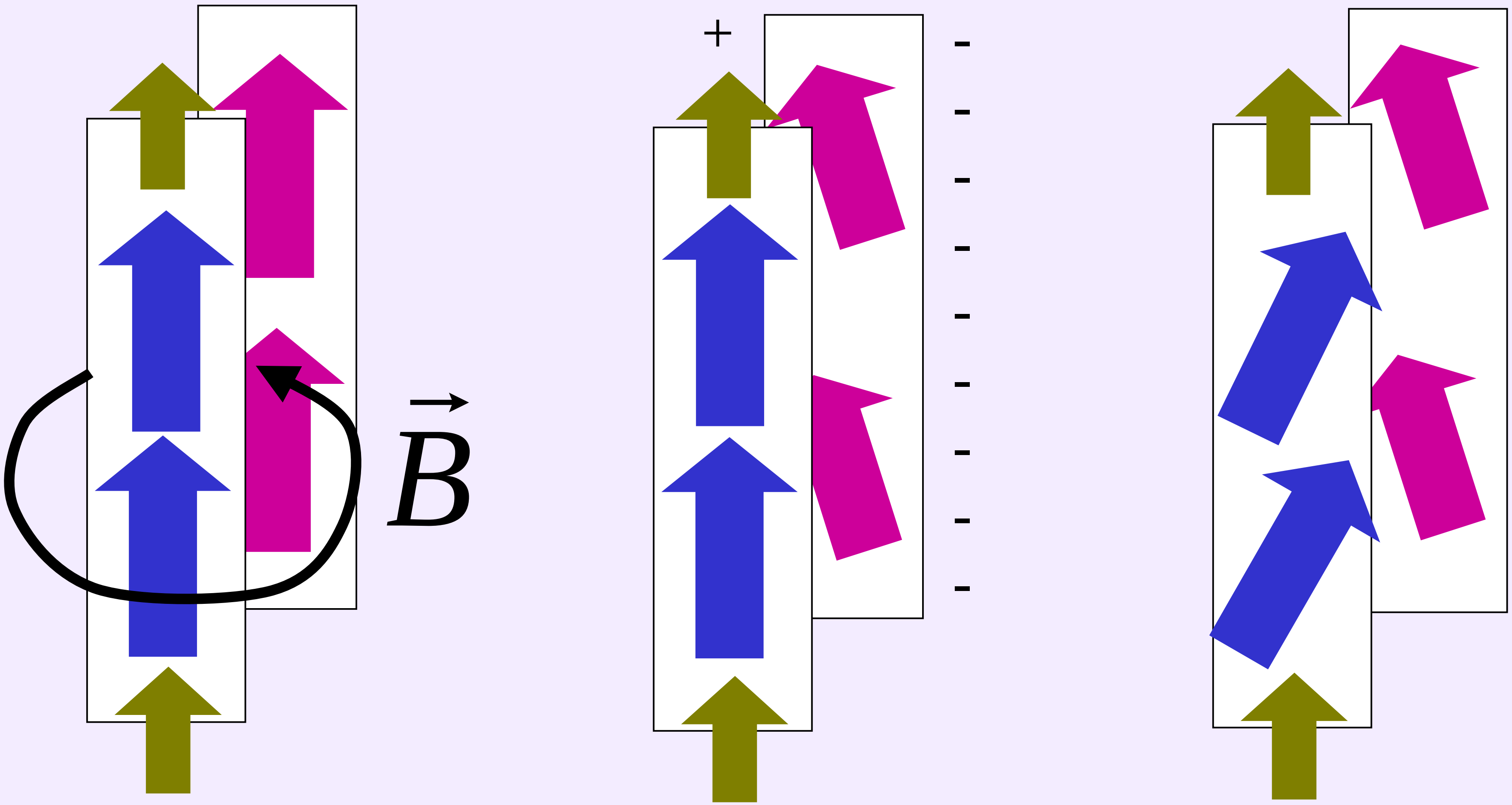
AMR sensor : Biasing using a second layer



+ current in the sensing layer

Bias layer

Sensor layer



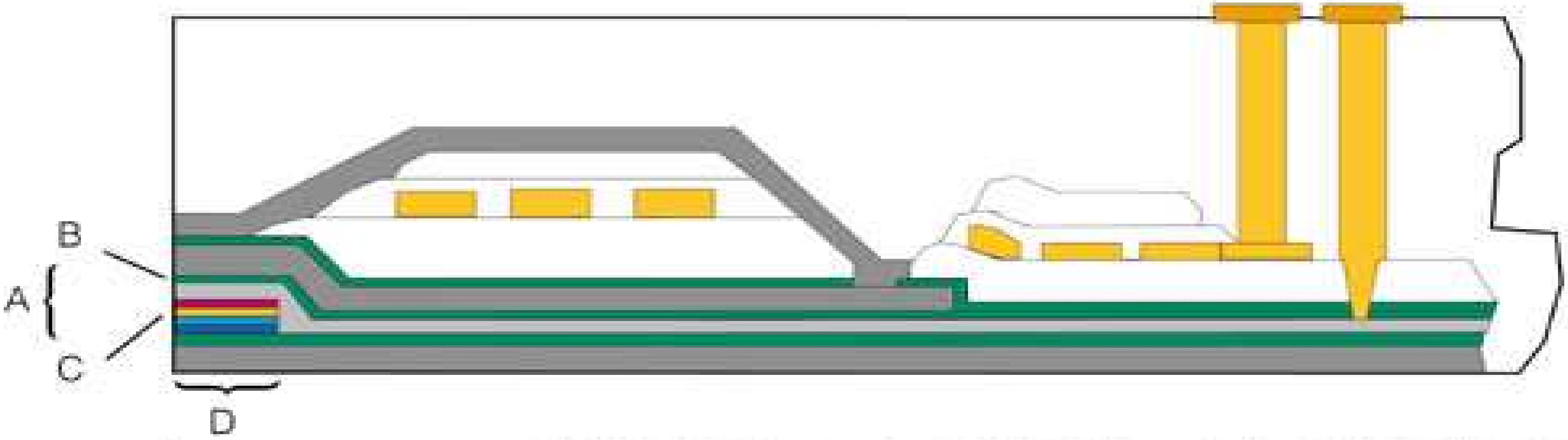
Sensing current
Magnetic field

Rotation bias layer

Rotation sensing layer

Complete MR Head

IBM's MRX D Extending Conventionsl MR Head Technology

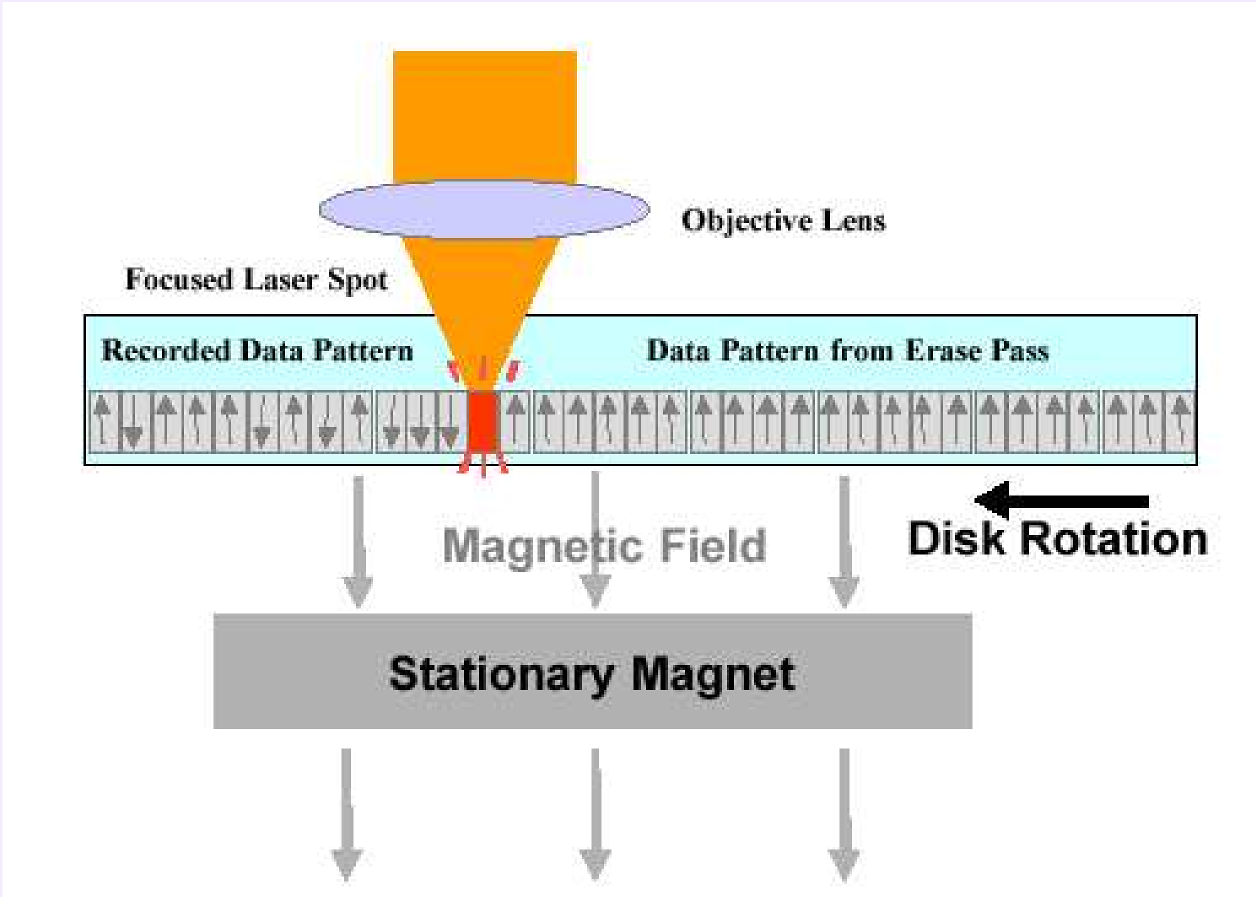


		1 Gbit/in² Head	3 Gbits/in² Head	5 Gbits/in² Head
A	Total Read Gap	0.25 µm	0.20 µm	0.20 µm
B	Sensor/Shield Spacing	<1200 Å	<1000 Å	<1000 Å
	Read Trackwidth	2.0 µm	1.1 µm	0.7 µm
C	MR Film	150 Å	120 Å	90 Å
D	Sensor Height	1.0 µm	0.5 µm	0.5 µm
	Flying Height	1.5 µ-in	1.5 µ-in	1.0 µ-in
	TAA (Signal Amp.)	300 µV/µm	600 µV/µm	900 µV/µm

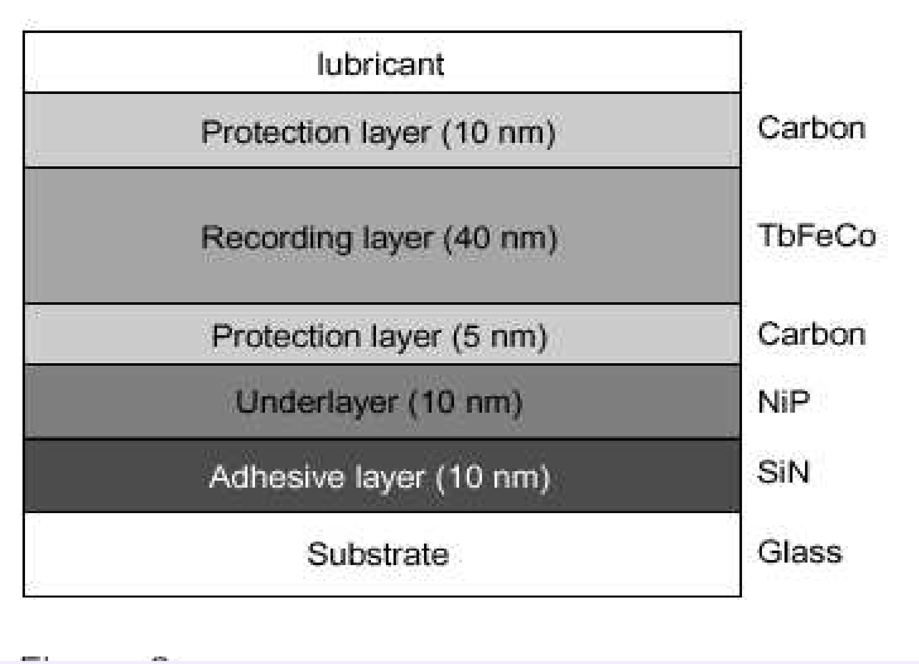
Magnetic Recording Heads : optical heads

Read (or heat assistance)

example M-O disk



Magnetic Recording Heads : optical heads



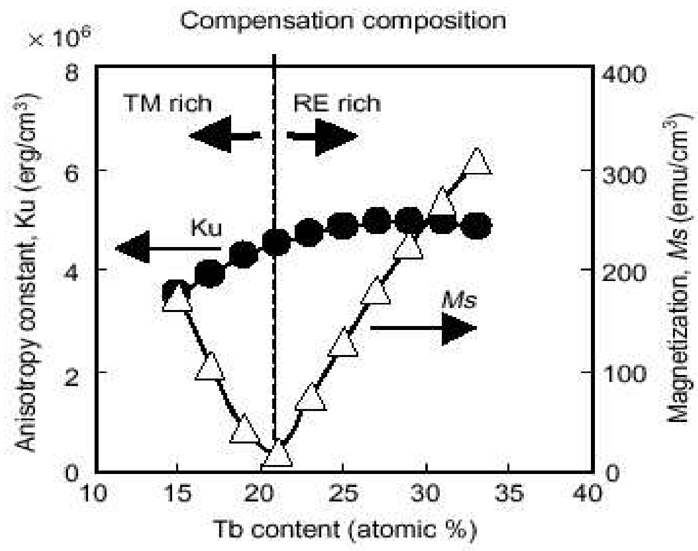


Figure 1
Composition dependence of anisotropy constant, Ku, and saturation magnetization, *Ms*, of TbFe as calculated using the molecular field model.

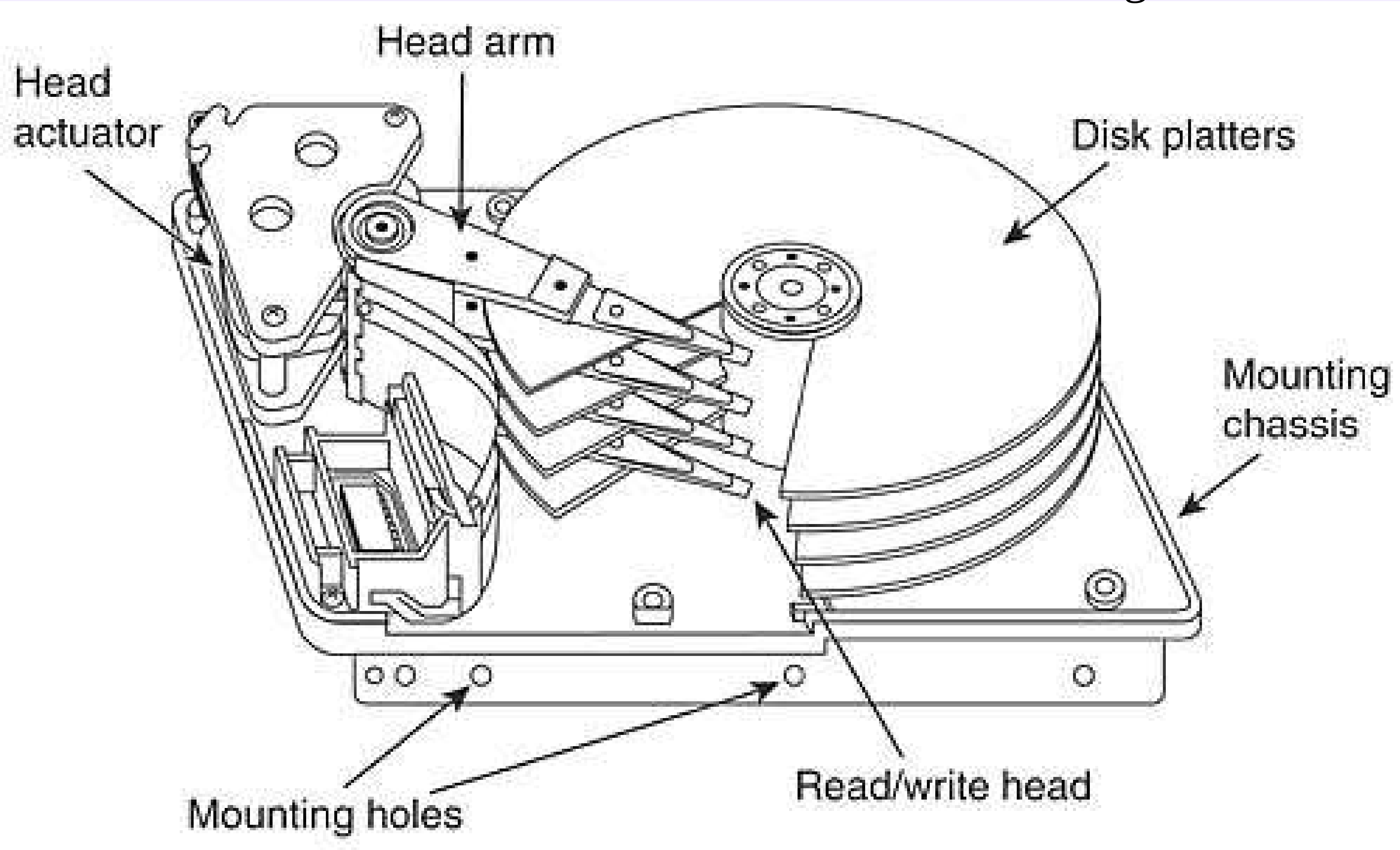
640 MB on 3,5 in (Floppy format instead of CD-ROM)
23 ktpi (1.1 micron)
53 kbpi (480 nm)
film (TbGd)(FeCo) with perpendicular anisotropy
on polycarbonate substrate or glass

IV-Drive

Magnetic Recording Drive : A hard disk

Disk Rotation : 15 000 rpm

Head-disk height : 50-15 nm



Hard disks (2003)

Hitachi (ex IBM)
147 GB (5 disks 10 heads)
30 Gb/in^2
10000 rpm
586 kbpi 51 ktpi

180 GB (3 disks 6 heads)
45 Gb/in^2
7600 rpm
632 kbpi 72 ktpi

Seagate
180 GB (12 disks 24 heads)
7400 rpm

38 GB (4 disks 8 heads)
15000 rpm

New generation is 80 GB/platter
250 GB HDD are in the shops

Magnetic Recording Drive : Data transfer, coding

Coding system

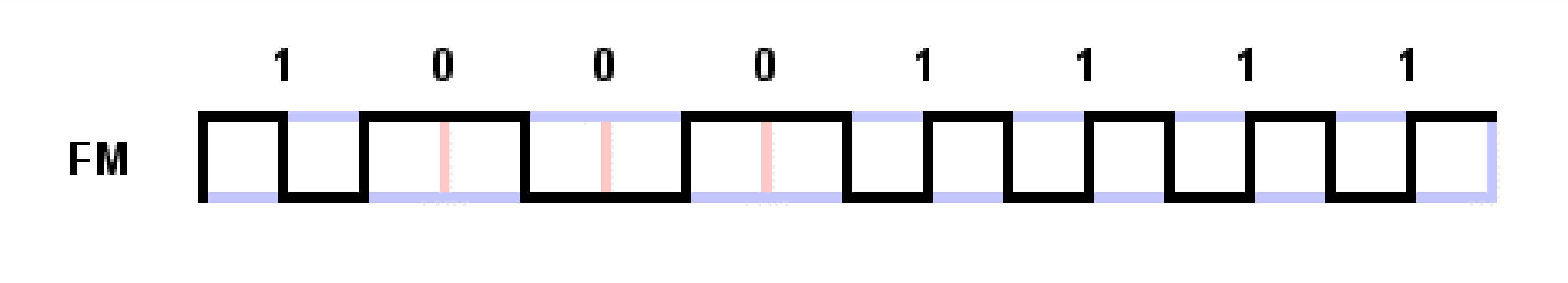
Codage floppy disk

Frequency Modulation :

1 is flux reversal + flux reversal

0 is no reversal + reversal

(simple density recording)



Magnetic Recording Drive : Data transfer, coding

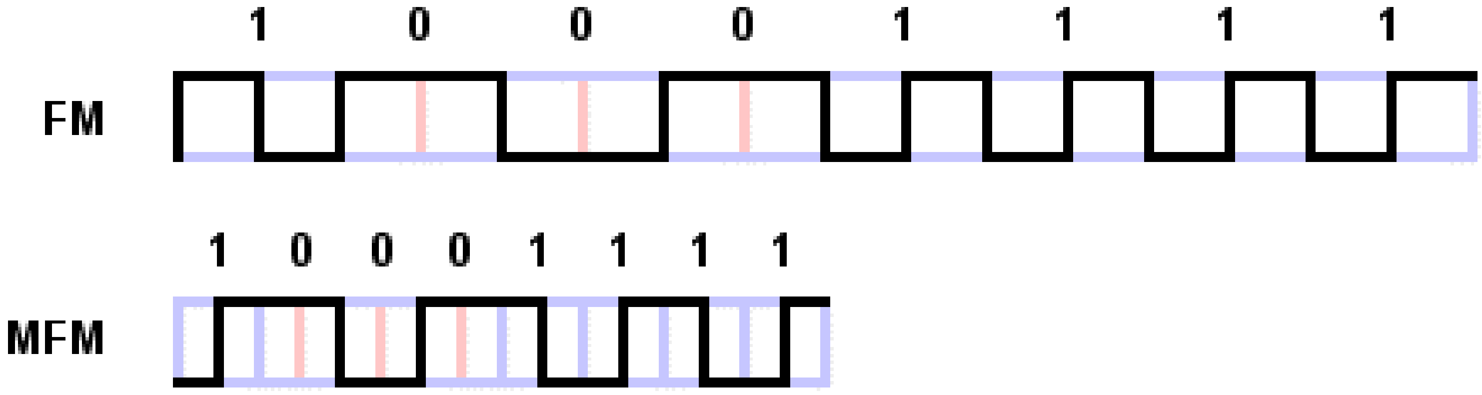
Better Coding system

Modified Frequency Modulation

1 : N R
0 after a 1 : N N
0 after a 0 : R N

(present double density Recording)

2 clock transitions /bit
but
never RR



Magnetic Recording Drive : Data transfer, coding

Hard Disk Coding

MF : 1.5 flux reversal /bit

MFM : 0.75 flux reversal /bit

RLL (Run Length Limited) 0.46 flux reversal /bit

PRML (Partial Response Maximum Likelihood) increase 30%

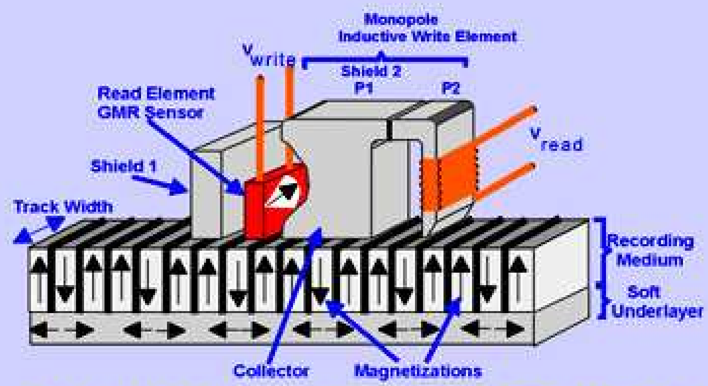
EPRML increase 20%

V - Future Developments

Advanced Technologies To Delay Superparamagnetism

1. AFC media - implemented 1Q2001

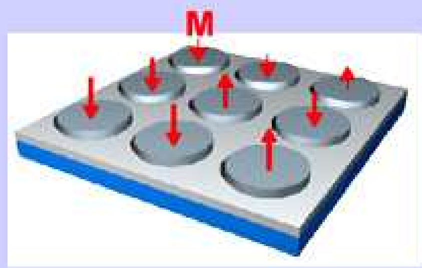
2. Perpendicular recording



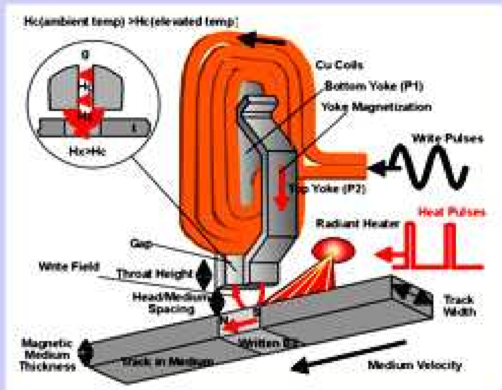
Reduces demagnetizing influence of adjacent bit fields, minimizes transition parameter. Involves new head configuration, return path soft underlayer, as NiFe, in media.

3. Reduce BAR (Bit aspect ratio)
20 ----> 4

4. Patterned media



5. Thermally assisted writing



Required because of increased media coercivity (increases K to compensate for a reduced V). Involves new magnetic materials

super2001vt.cdr

IBM

Ed Grochowski at Almaden

AMR (anisotropic magnetoresistance) heads, 1-3Gb/in^2, 1997.

Regular GMR (giant magnetoresistance) heads, 5Gb/in^2, 1998.

Synthetic anti-ferromagnetic (SAF) biased GMR heads, 6Gb/in^2 and beyond, since 1998.

Anti-ferromagnetic coupled (AFC) media, since 2000 (45 Gbit/in^2).

Seagate (2001) and Fujitsu(2002) demonstrated 100Gb/in^2 using AFC media and SAF GMR head

Perpendicular recording, may achieve areal density of 500Gb/in^2 – 1000Gb/in^2. Seagate demonstrated >100 Gb/in^2 last year.

Thermal assisting magnetic recording, proposed by Seagate Research.

* D. Thompson, J. Best, “The future of magnetic data storage technology”, IBM J. Res. Develop., Vol.44, No.3, 2000.

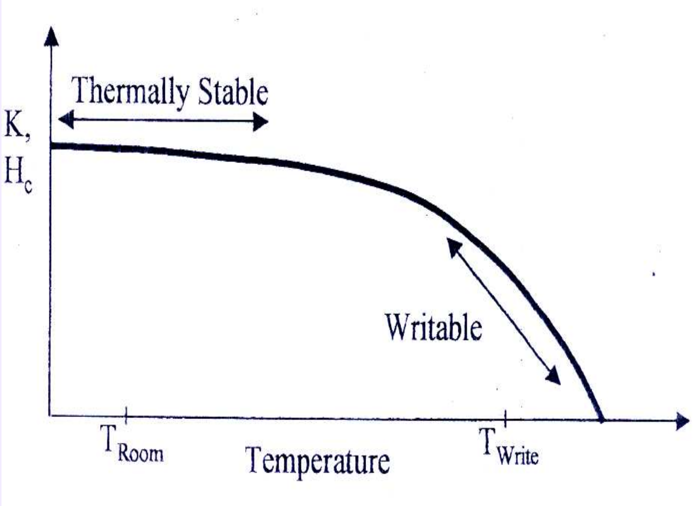
Thermally assisted writing

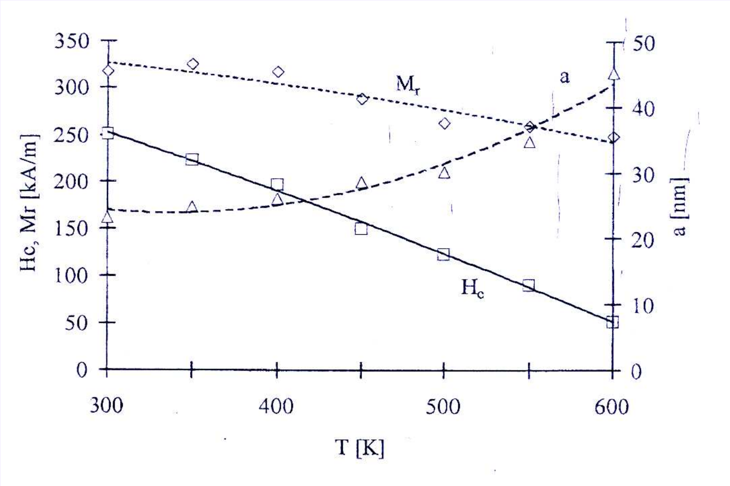
•Use of high anisotropy media with high coercivities limited by write head fields

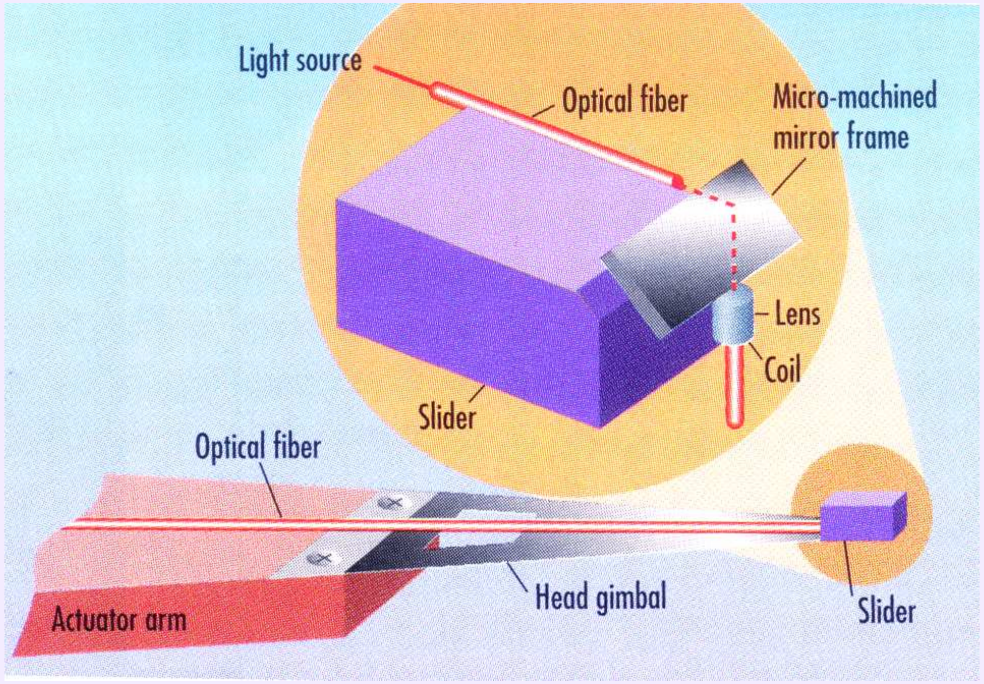
•Limitations may be eased by reducing the coercivity of the media during writing by local heating with a laser beam

"Hybrid recording"

BUT : Transition width increases if M_r and H_c change at different rates

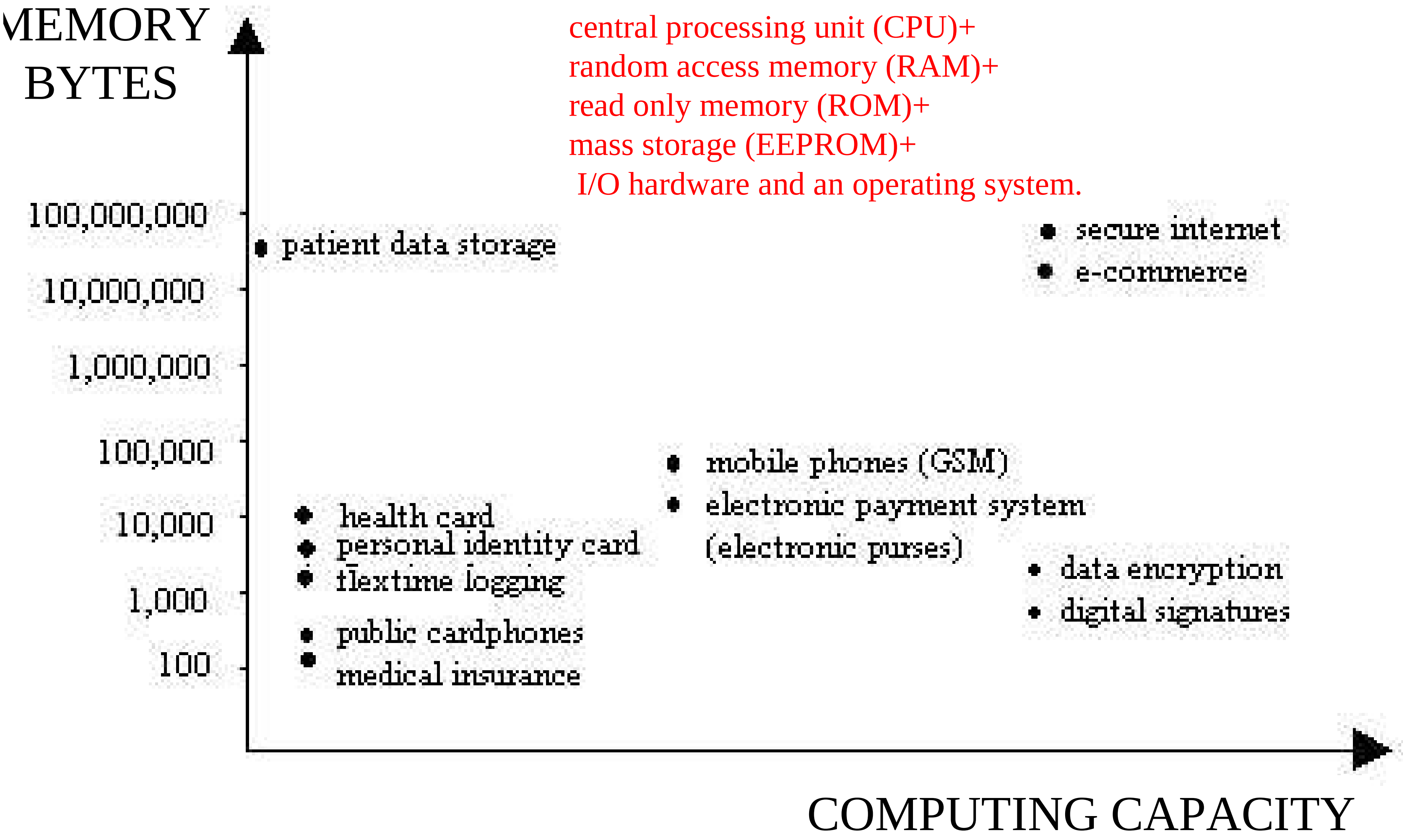






VI - MRAM

Smart cards :
central processing unit (CPU)+
random access memory (RAM)+
read only memory (ROM)+
mass storage (EEPROM)+
I/O hardware and an operating system.

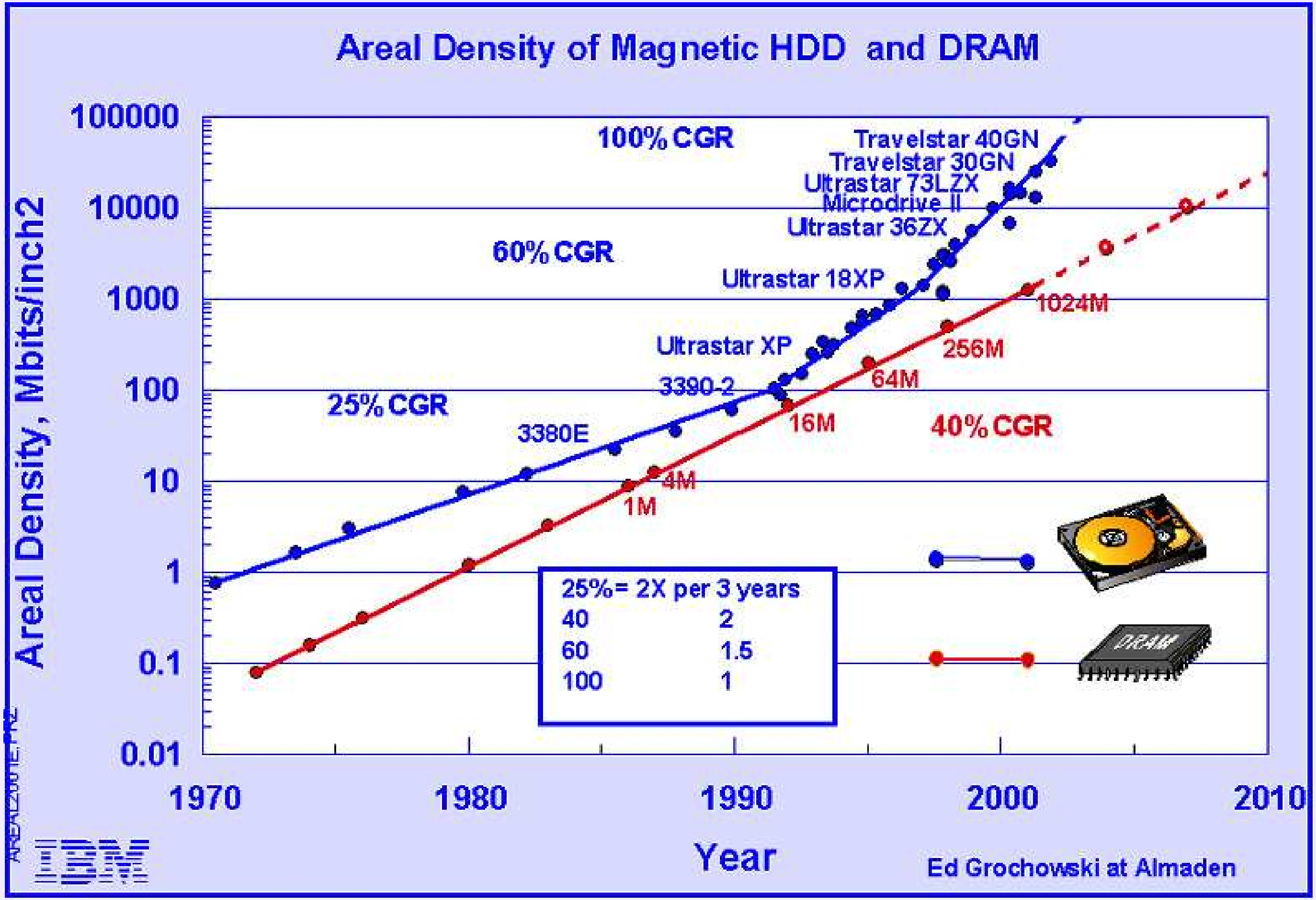


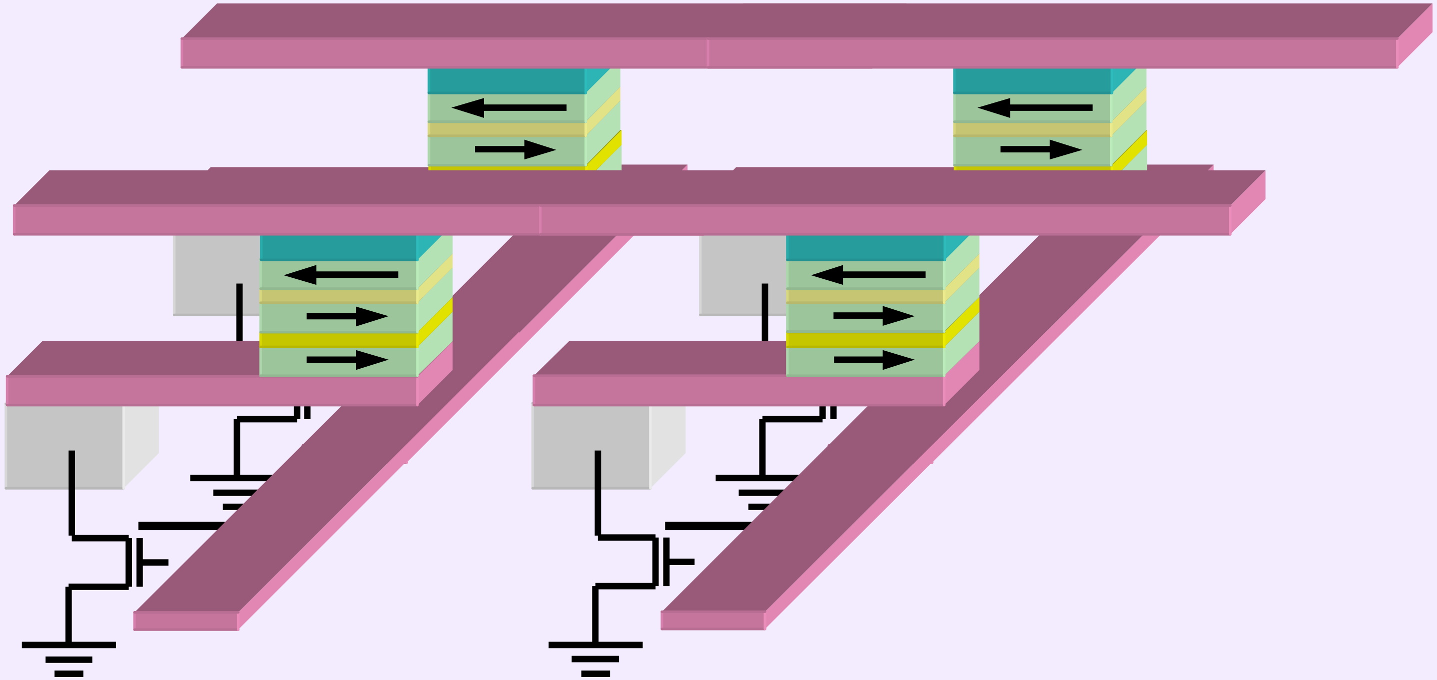
Why MRAM ?

Remanent Magnetisation is Non Volatile

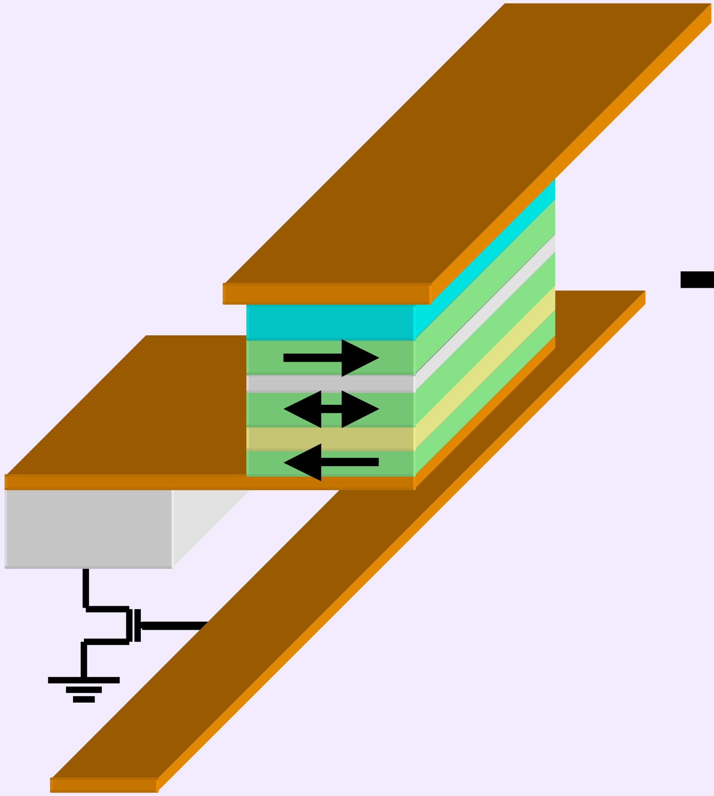
Density could compete with other RAMs

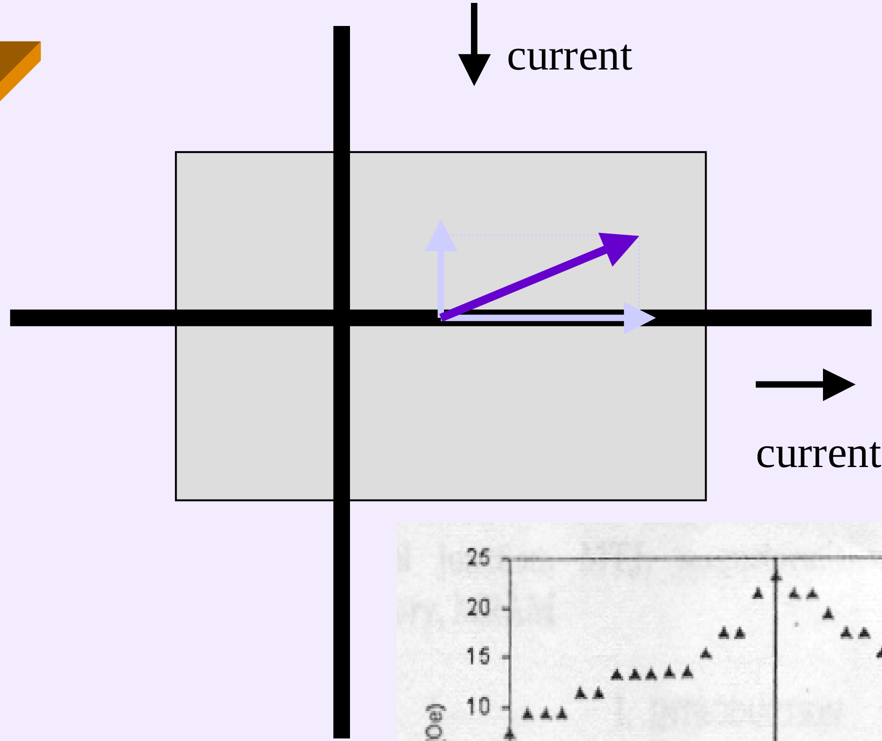
Physical limit to speed is < nanosecond

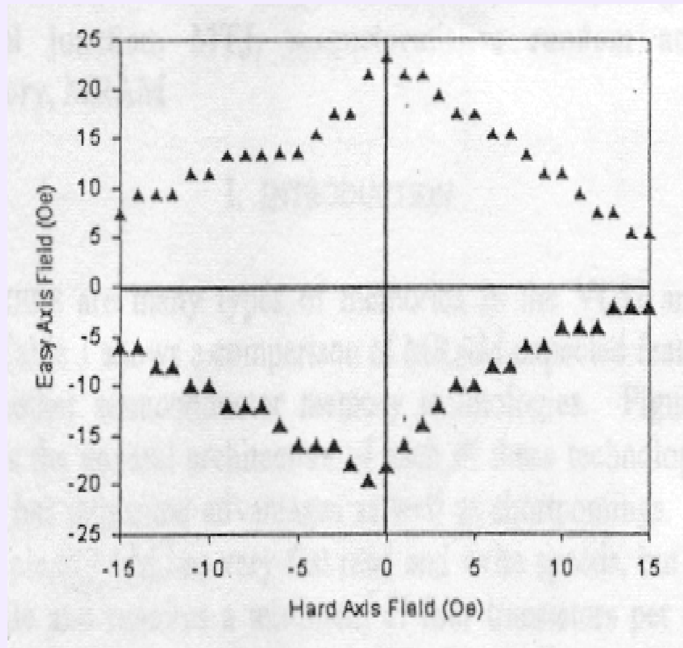

Areal Density of Magnetic HDD and DRAM
Areal Density, Mbits/inch2
100000
10000
1000
100
10
1
0.1
0.01
1970
1980
1990
2000
2010
Year
100% CGR
60% CGR
25% CGR
40% CGR
Travelstar 40GN
Travelstar 30GN
Ultrastar 73LZX
Microdrive II
Ultrastar 36ZX
Ultrastar 18XP
Ultrastar XP
3390-2
3380E
1024M
256M
64M
16M
4M
1M
25%= 2X per 3 years
40 2
60 1.5
100 1
DRAM
IBM
Ed Grochowski at Almaden



Switching Field of the free layer



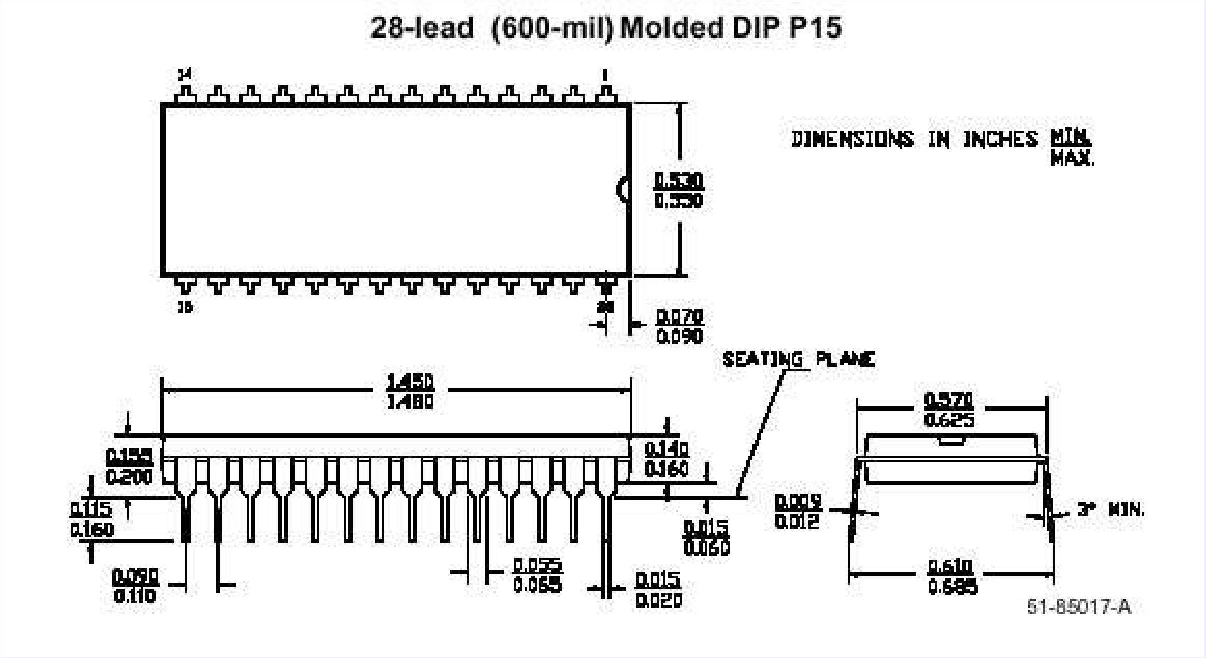




Stoner-Wohlfarth astroid
(coherent rotation of magnetisation)
(uniaxial anisotropy)

Motorola 1 Mbit (june 2002) 50 ns read/write cycle
NEC 1 Mbit (may 2003)

Cypress 256kb = 32 kB see www.cypress.com for specs



Comparison Solid State Memories (RAM)
THE COMPETITION HAS STARTED

Storage Mechanism	DRAM	SRAM	Flash	MRAM	FeRAM	PC-RAM
Date	2002	2002	2002	2004	2004	2004
Initial Size	130 nm	130 nm	150 nm	350 nm	130 nm	100nm
Structure/ cell	1T-1C	6T	1T	1T-1C	1T-1C	1T-1C
Surface/Cell	$8F^2$ $0.14\ \mu^2$	$10F^2$ $0.16\ \mu^2$	$10F^2$ $0.19\ \mu^2$	$10\text{-}20F^2$?	$20\ F^2$ $0.68\ \mu^2$	$6F^2$ $0.06\ \mu^2$
R-W time	<20ns	<10ns	~80ns (R) 1ms (W)	<25ns	<10ns	<100ns
Cycling	Unlimited	Unlimited	$>10^5$	$>10^{15}$	$>10^{13}$	$>10^{13}$
Permanent	Volatile	Volatile	>10 y	>10 y	>10 y	> 10 y

Flash : 12 Volt Write

FLASH memory Principle

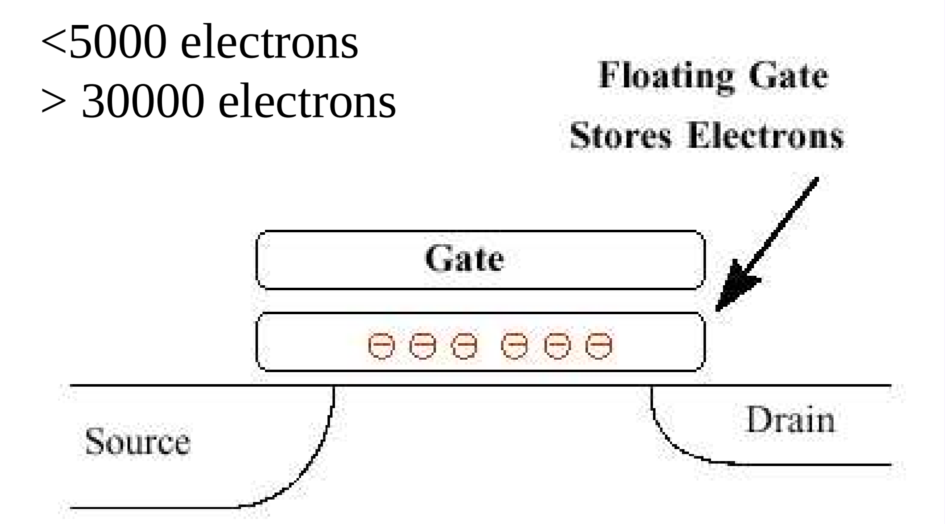


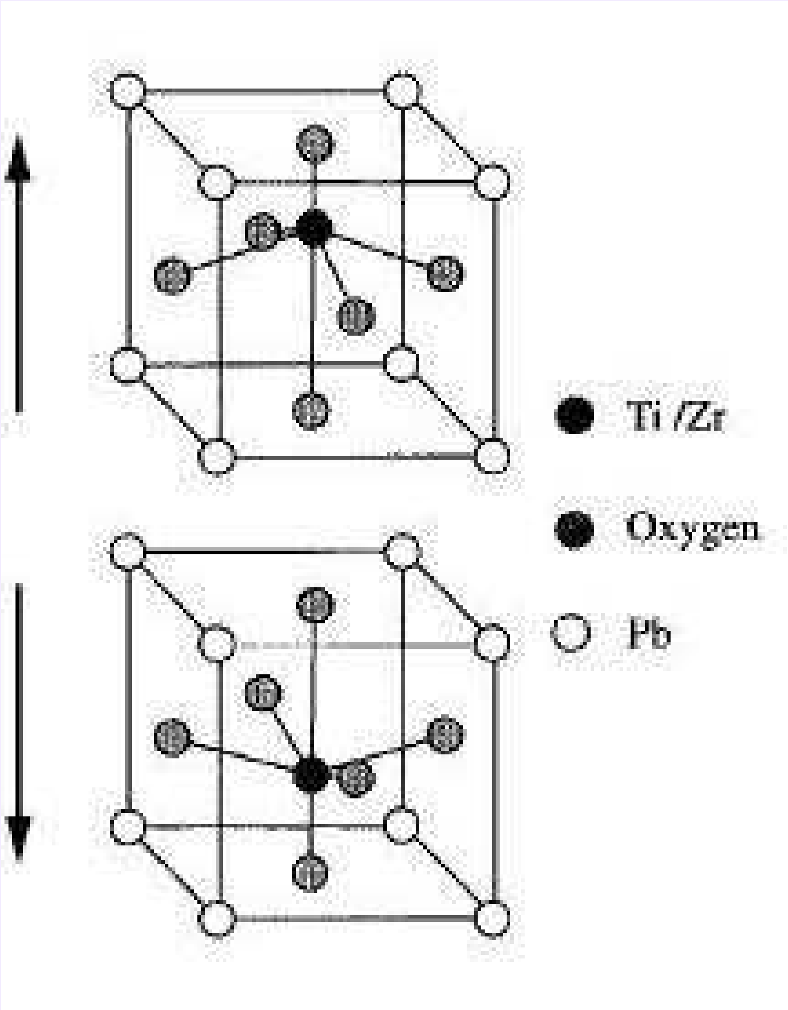
Figure 2: Single transistor flash memory cell

Leakage < 1 e /day

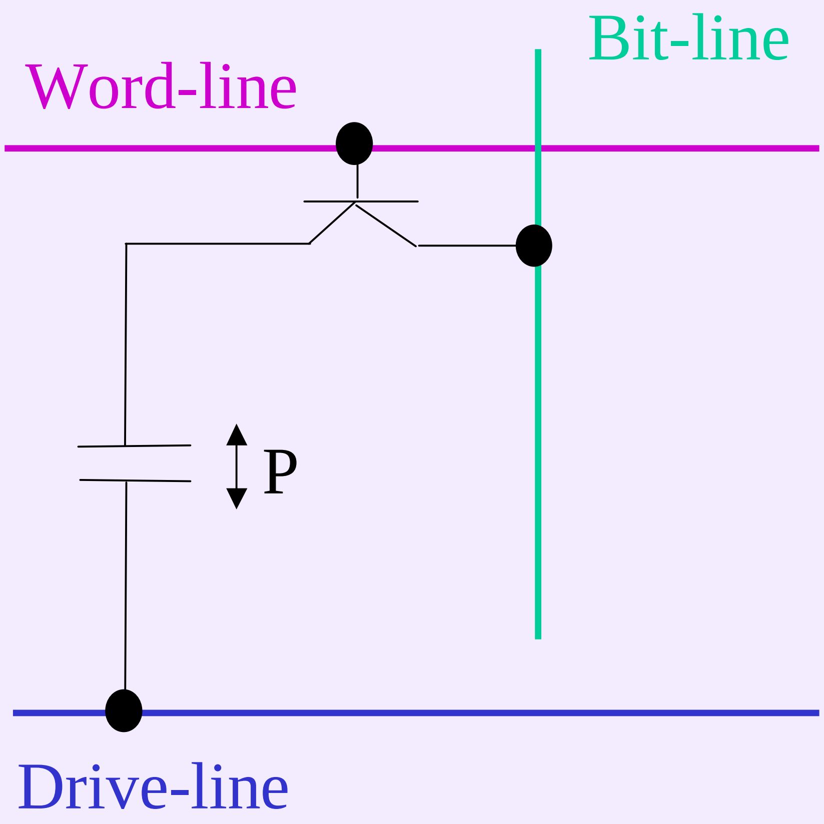
Large voltage pulse to move the charge

Ferroelectric RAM (FeRAM)

$Pb(Zr_xTi_{1-x})O_3$ or $SbBi_2Ta_2O_9$

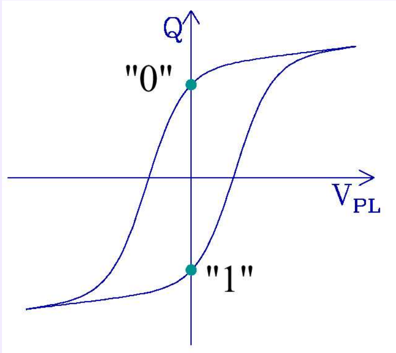


Condensator
with a ferroelectric dielectric



Reading destroys the information

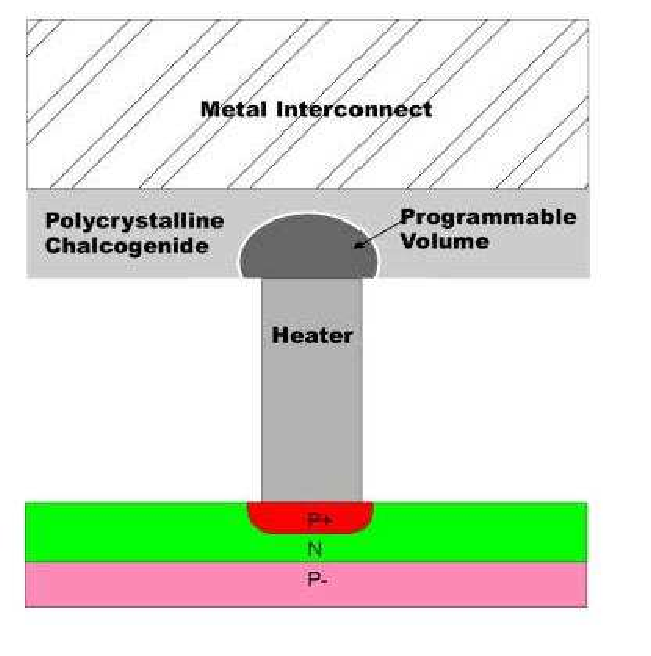
Non square loop : remanence is not well defined, the access transistor is necessary

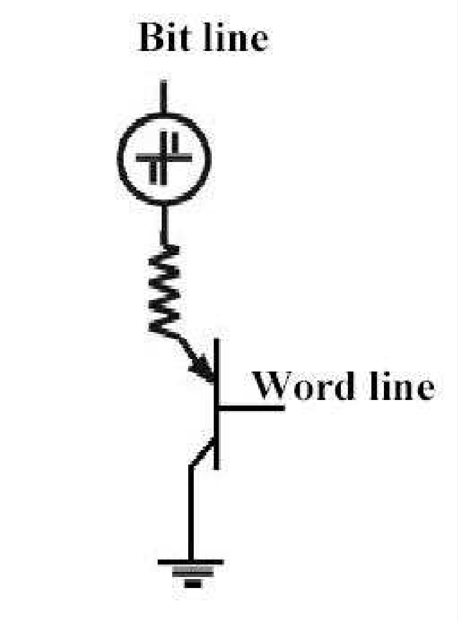


Commercial FeRAM :

RAMTRON : 256 kb
Hynix : 4 and 8 Mb (90 ns)

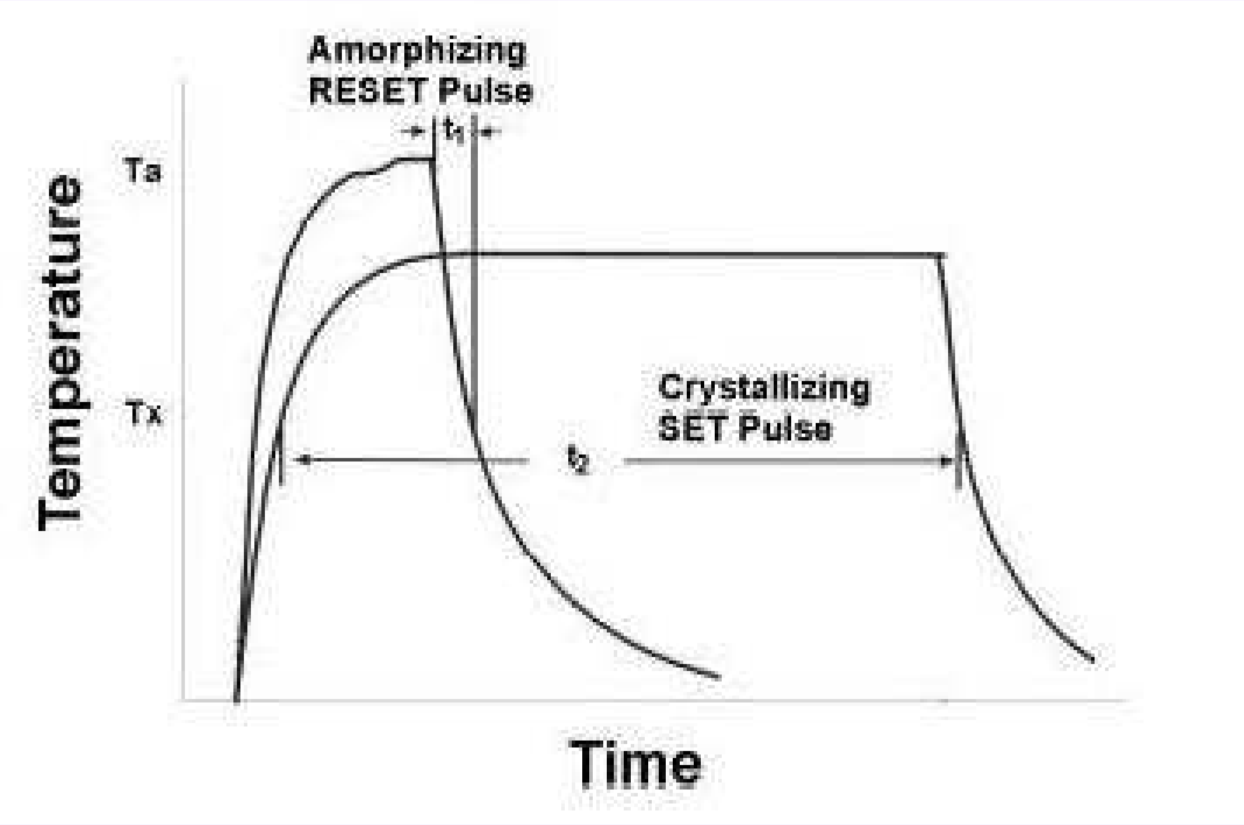
Phase Change Memory (PC-RAM)

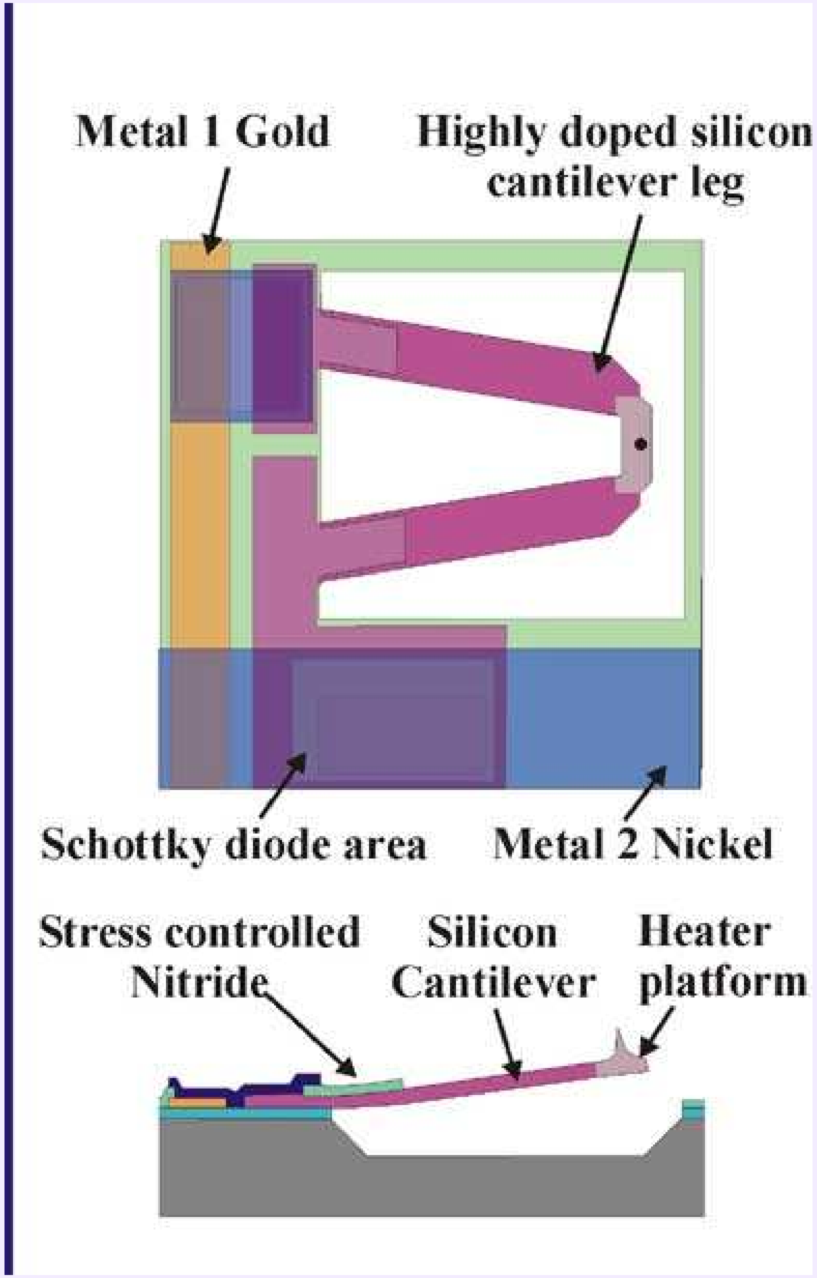




$Ge_2Sb_2Te_5$: amorphous (resistive)
crystallised 40X more conducting

PC-RAM : Writing - Erasing

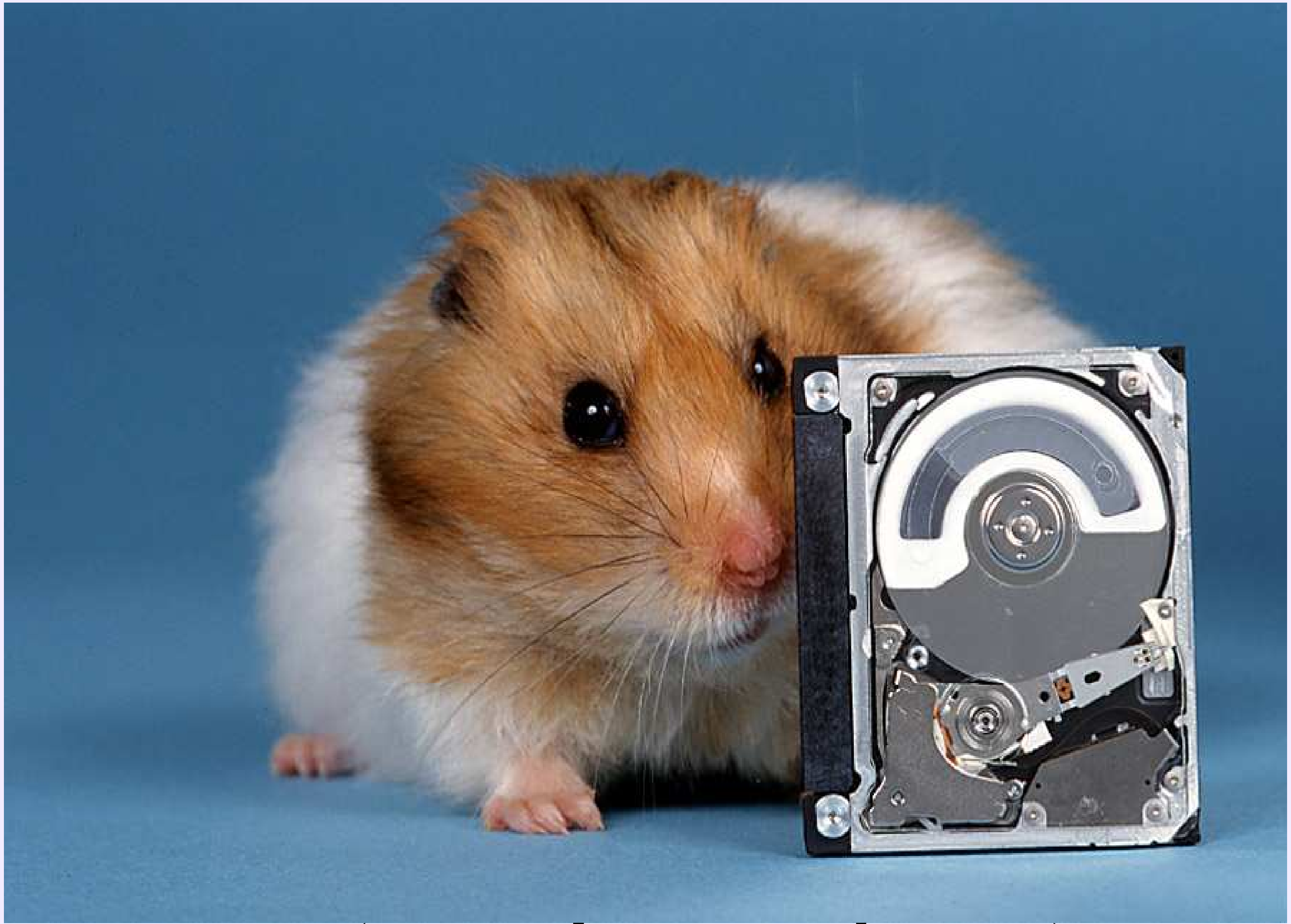




Millipede : mechanical storage

Still a laboratory toy
but very impressive prototypes

Denser, Smaller ...

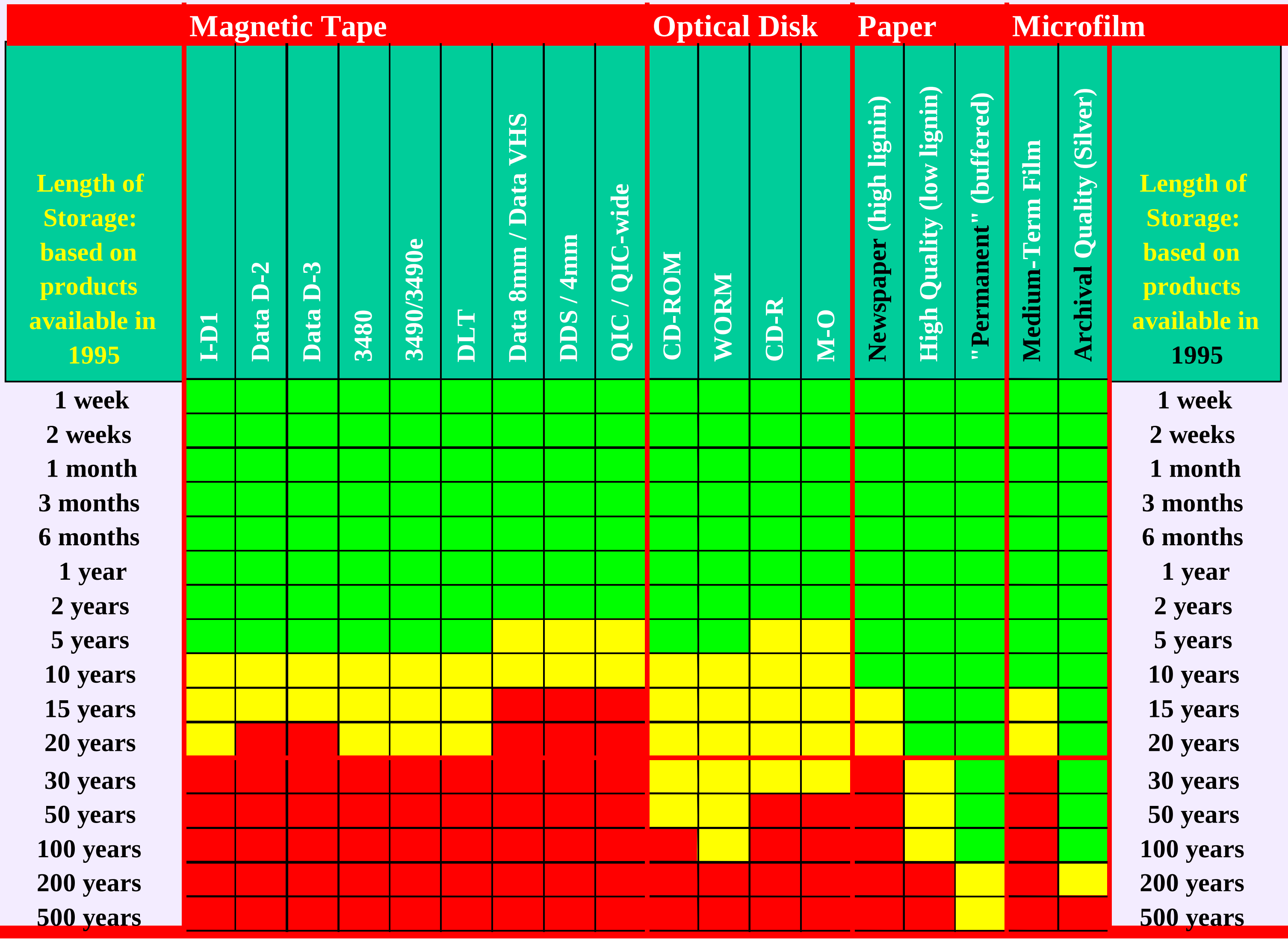


(Micro-drive Hitachi 1GB)

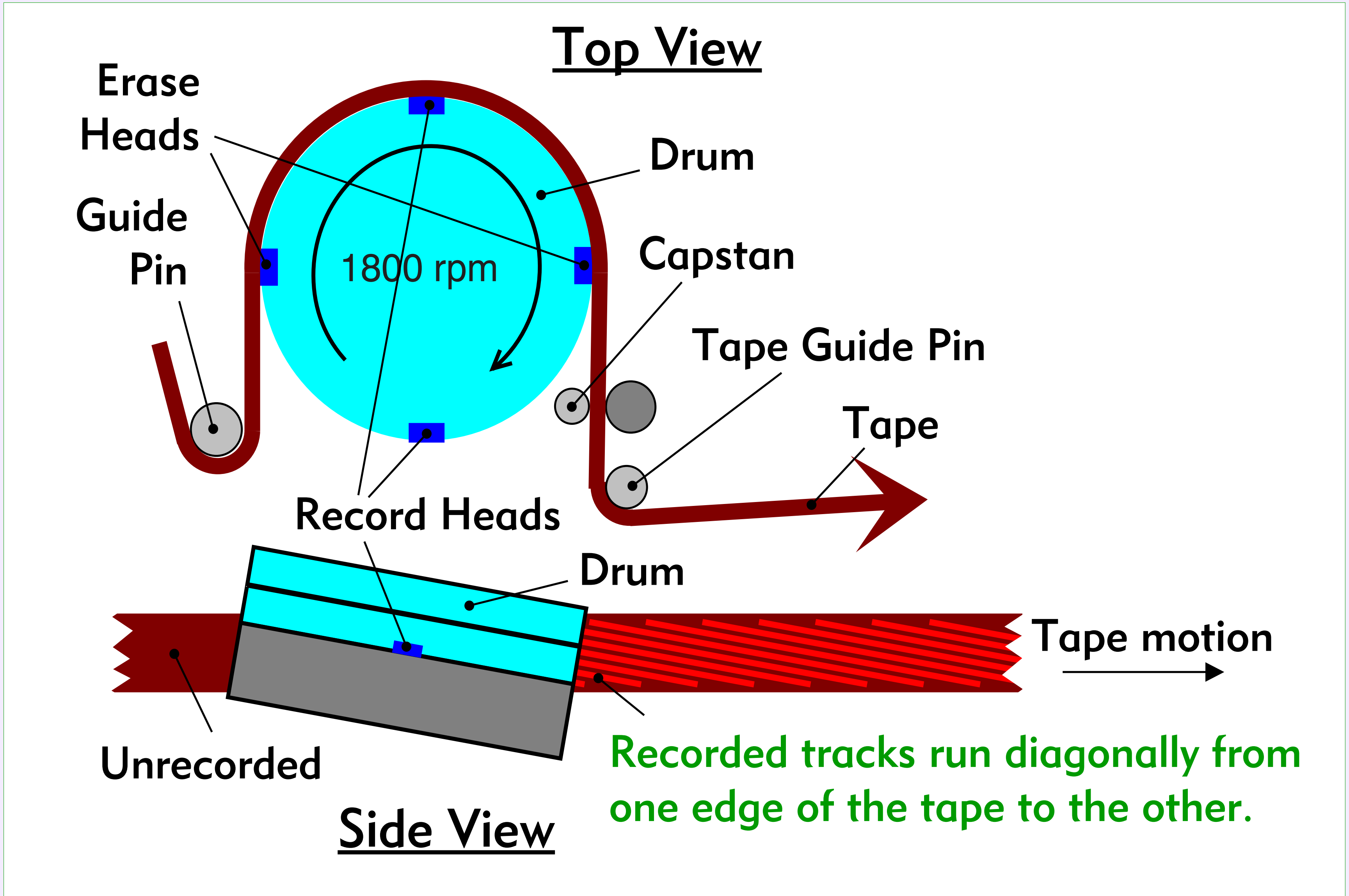
The largest Guinea Pig in the World

FIN

68 Degrees, 40% RH



VHS-storage (helicoidal storage)

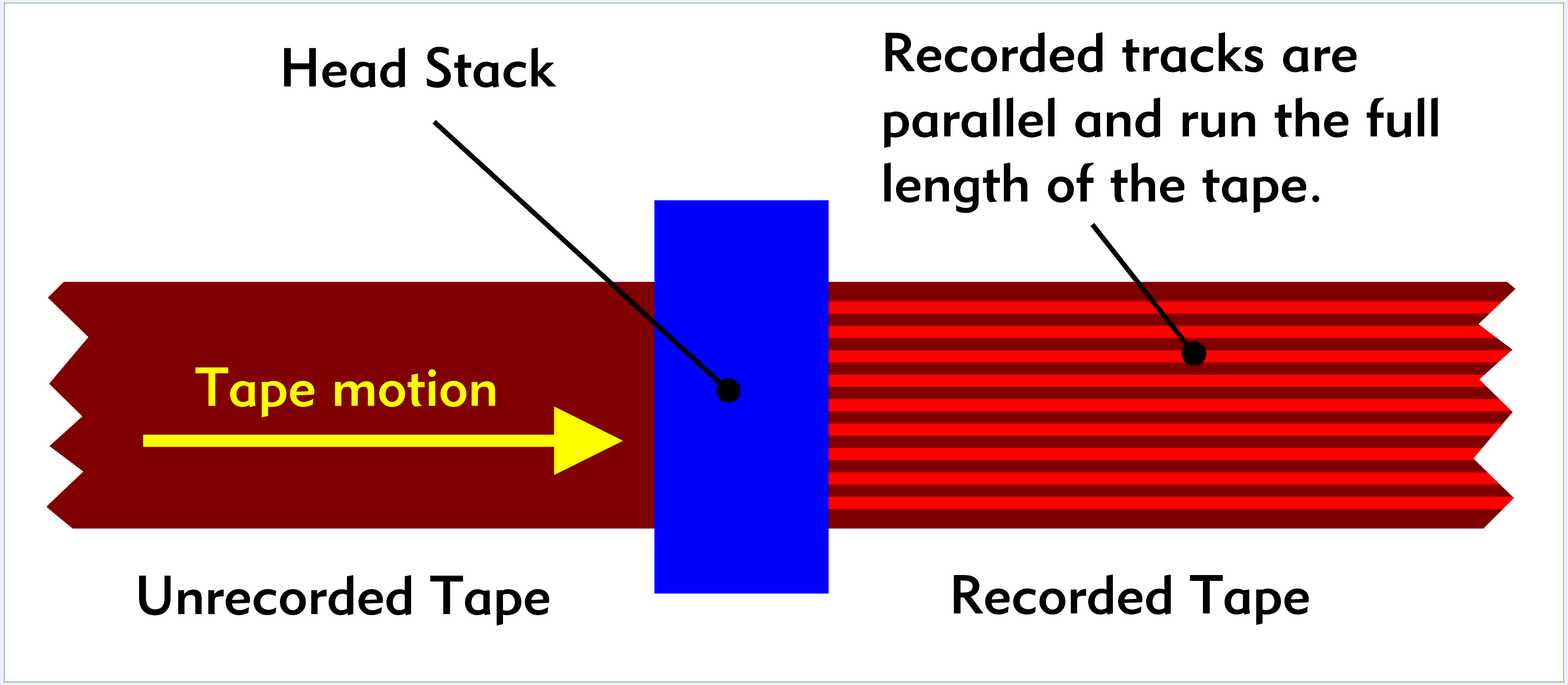


	1b/c Flash Memory	Intel StrataFlash[tm] 2b/c Memory	
Density	16Mbit	32Mbit	64Mbit
Read Speed	100 ns	120 ns	150 ns
Block Size	64KByte	128KByte	
Architecture	x8	x8 / x16	
V_{cc} Power Supply (+/-10%)	5V	5V	
V_{pp} (Program/Erase Voltage)	5V or 12V	5V	
Effective Write Speed	6 µS/Byte	6 µs/Byte	
I_{ccr} (Read Current)	35 mA	55 mA	
I_{ppw} + I_{ccw} (Write Current)	75 mA	90 mA	
Endurance	100,000 Cycles	10,000 Cycles	
Operating Temperature	Extended	Comercial	

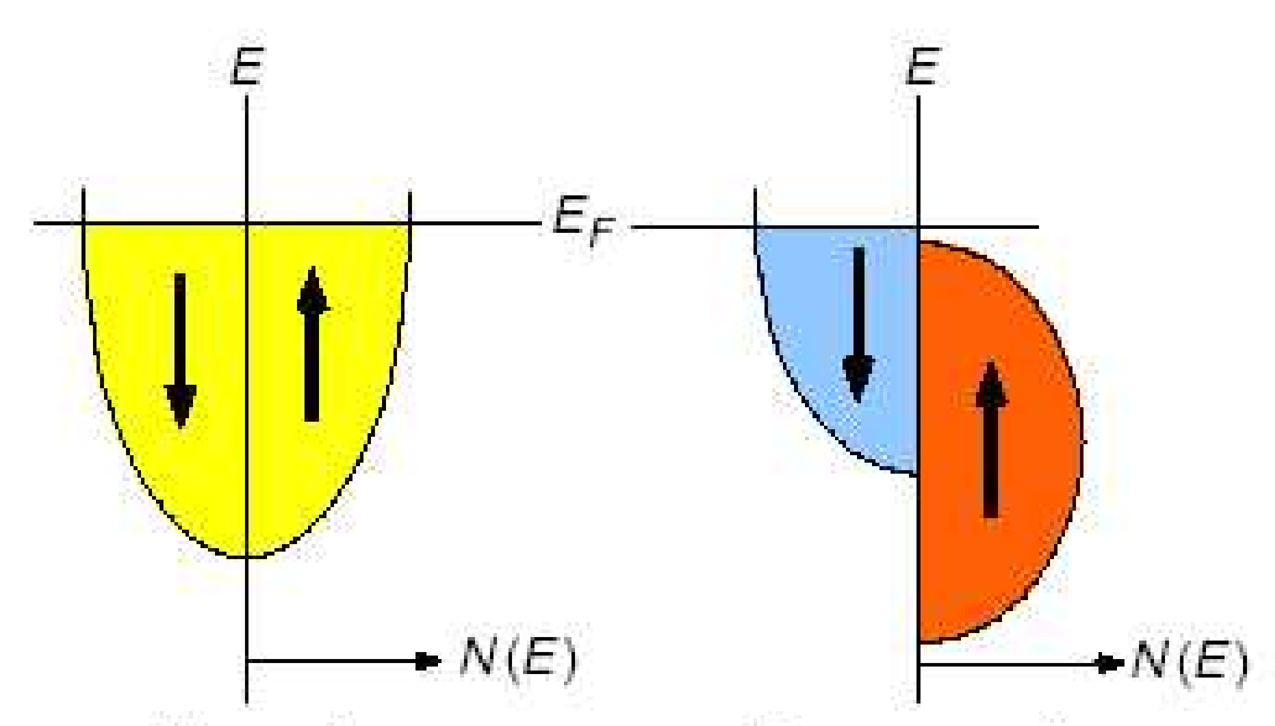
Figure 9: Comparison of 1b/c and 2b/c product features

Intel 1998

Parallel storage

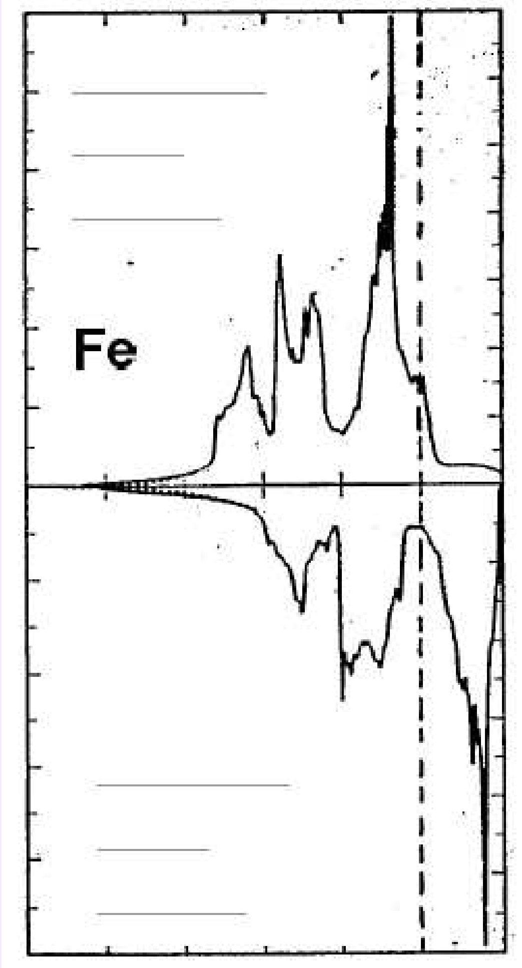


Structure électronique d 'un métal ferromagnétique

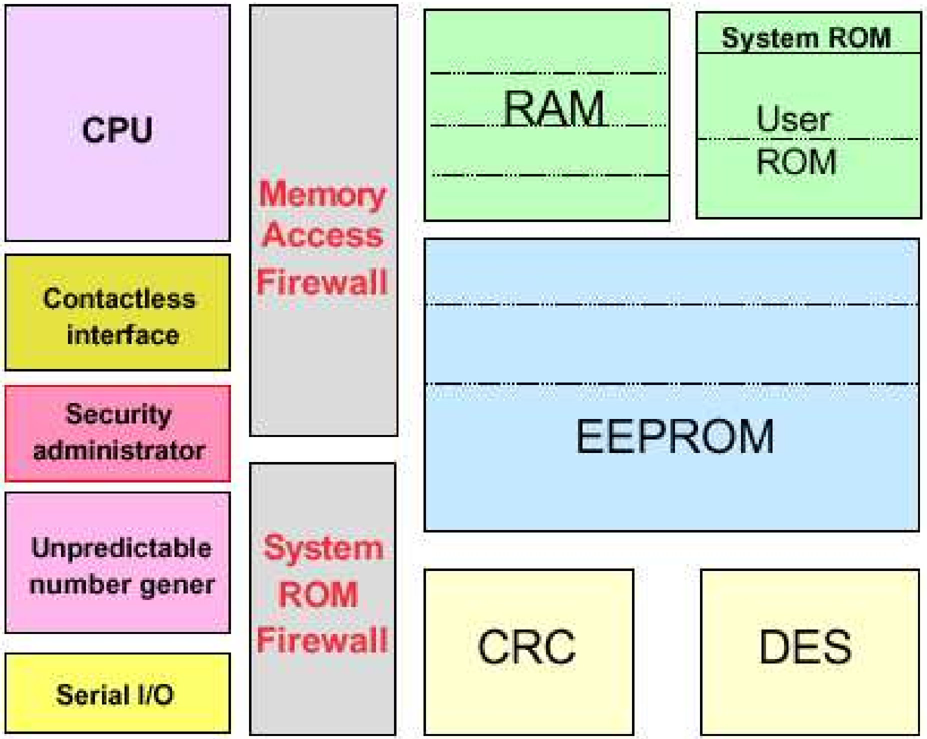


Métal normal

Métal ferromagnétique



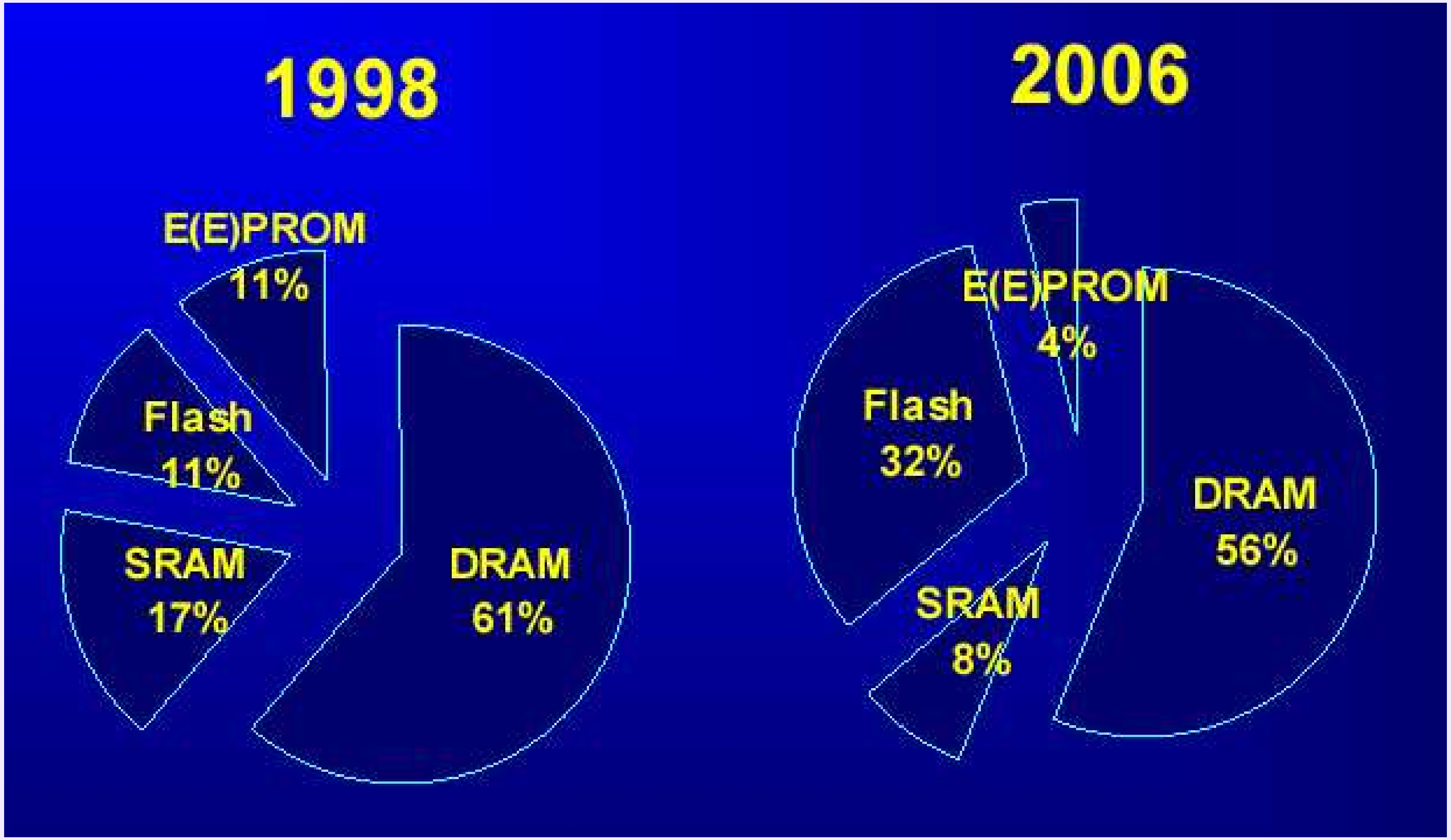
Secure MCU-based Smart Card



Minimum system requirements

	1999	2001	2003
CPU	8 bit	8 bit	32 bit
ROM	23 KBytes	70 KBytes	90 KBytes
EEPROM	8 KBytes	16 KBytes	64 KBytes
RAM	256 Bytes	1 KByte	4 KBytes

Different memory types
Emphasis on security


1998
E(E)PROM
11%
Flash
11%
SRAM
17%
DRAM
61%
2006
E(E)PROM
4%
Flash
32%
SRAM
8%
DRAM
56%

There is a ITRS roadmap for FeRAM

Table 55a FeRAM Technology Requirements—Near-term

Year of Production	2001	2002	2003	2004	2005	2006	2007
DRAM ½ Pitch (nm)	130	115	100	90	80	70	65
MPU / ASIC ½ Pitch (nm)	150	130	107	90	80	70	65
MPU Printed Gate Length (nm)	90	75	65	53	45	40	35
MPU Physical Gate Length (nm)	65	53	45	37	32	28	25
Feature Size (µm): F [A]	0.5	0.35	0.25	0.18	0.18	0.18	0.13
FeRAM Generation (Mass production)[B] Standard memory (bit) Embedded memory (Byte)	1Mb 32KB (256Kb)	4Mb 128KB (1Mb)	16Mb 512KB (4Mb)	64Mb 2MB (16Mb)	64Mb 2MB (16Mb)	128Mb 4MB (32Mb)	256Mb 8MB (64Mb)
Access time (ns) [C]	80	65	55	40	30	30	20
Cycle time (ns) [D]	130	100	80	70	50	50	32
Cell area factor a [E]	60	40	24	16	10	10	10
Cell size (μm^2) [F]	15.000	4.900	1.500	0.518	0.324	0.324	0.169
Total cell area (mm^2) for standard memory [G]	15.73	20.55	25.17	34.79	21.74	43.49	45.37
Total cell area (mm^2) for embedded memory [H]	3.93	5.14	6.29	8.70	5.44	10.87	11.34
Projected capacitor size (μm^2)[I]	2.00	0.98	0.50	0.26	0.13	0.13	0.07
Capacitor area (μm^2) [J]	2.00	0.98	0.50	0.26	0.13	0.13	0.09
Cap area/proj cap size[K]	1.00	1.00	1.00	1.00	1.00	1.00	1.34
Height of bottom electrode/F (for 3D capacitor)[L]	n/a	n/a	n/a	n/a	n/a	n/a	0.17
Capacitor structure [M]	planar	planar	stack	stack	stack	stack	3D
T2C or 1T1C [N]	2T2C	1T1C	1T1C	1T1C	1T1C	1T1C	1T1C
Vop (Volt) [O]	3.0	3.0	2.5	1.8	1.5	1.5	1.2
Minimum switching charge density ($\mu C/cm^2$) @Vop[P]	4.4	7.1	11.2	17.2	34.5	34.5	40.0
Minimum switching charge per cell (fC/cell) @Vop[Q]	88.5	69.8	55.8	44.8	44.8	44.8	36.1
Retention @85 ℃ (Years)[R]	10 Years	10 Years	10 Years	10 Years	10 Years	10 Years	10 Years
Fatigue with assuring retention[S]	1.0 E12	1.0 E13	1.0 E14	1.0 E15	>1.0 E16	>1.0 E16	>1.0 E16