C9 Nanoscale Magnetism

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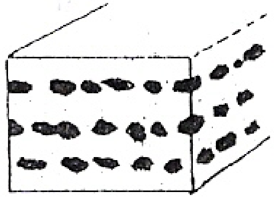
Introduction

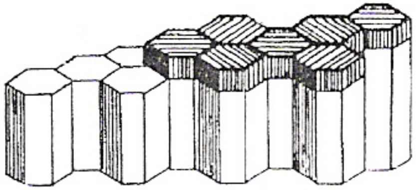
gnetic nanostructures have at least one dimension in the 1 - 100 nm size range. Magnetic properties ulk

hree small dimensions

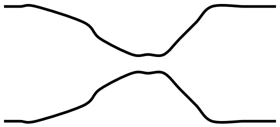
Nanoparticles



Nanocomposite

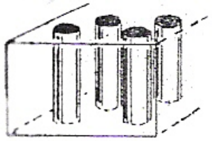


recording medium



nanoconstriction

wo small dimensions

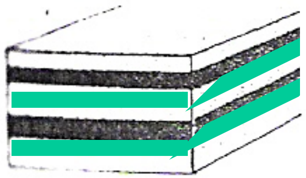


Nanowires

a

ne small dimension

in film



Thin film stack

-

Ratio of surface to volume atoms

Nanoparticle: $4\pi R^3 a/(4/3)\pi R^3 = 3a/R$

Nanowire: $2\pi Ra/\pi R^2 = 2a/R$

Unsupported film: $2a/t$

If $2R$, $t \approx 10$ nm, $a \approx 0.25$ nm surface fracti is

- 15% for a nanoparticle
- 10 % for a nanowire
- 5% for a thin film

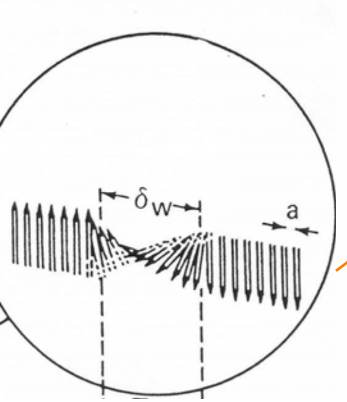
Characteristic length scales

agnetic length scales are expressed in terms of the *exchange length* ($l_{ex} \approx 2$ nm)

$$l_{ex} = \sqrt{(A/\mu_0 M_s^2)}$$

nd the *hardness parameter* (>1 for a permanent magnet; << 1 for a soft magnet)

$$\kappa = \sqrt{(K/\mu_0 M_s^2)}$$



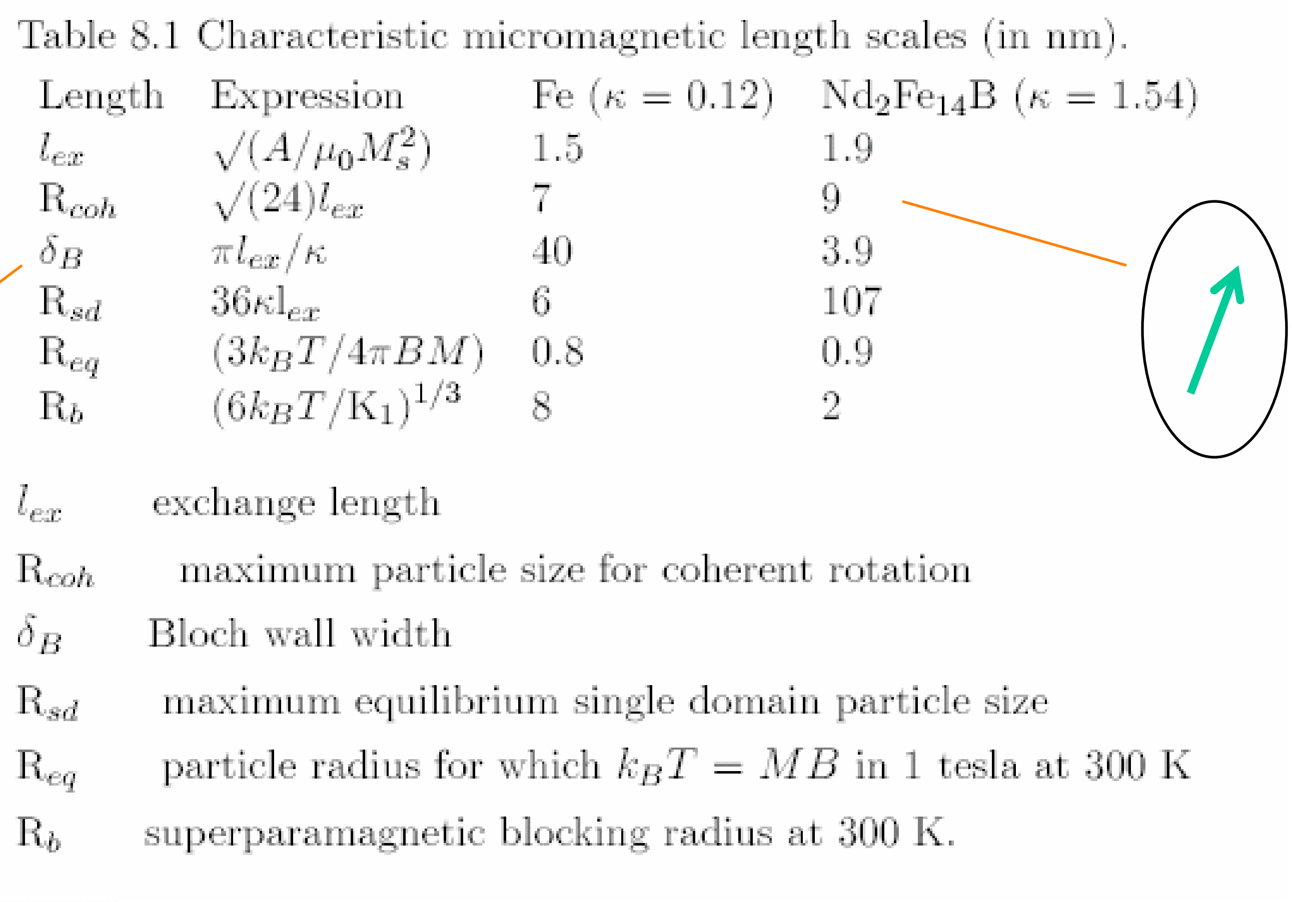


Table 8.1 Characteristic micromagnetic length scales (in nm).

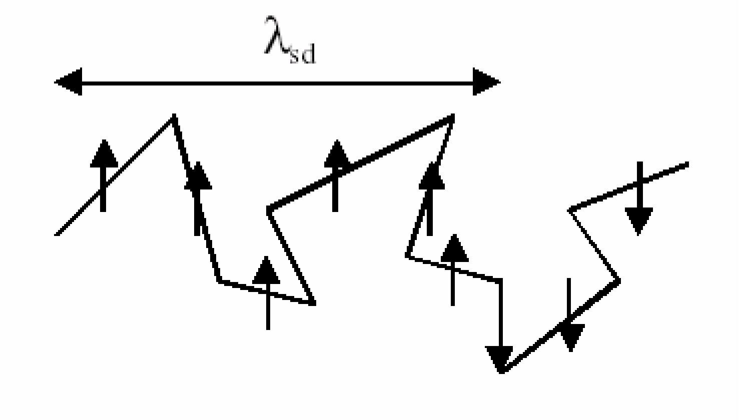
Length	Expression	Fe ($\kappa = 0.12$)	$Nd_2Fe_{14}B$ ($\kappa = 1.54$)
l_{ex}	$\sqrt{(A/\mu_0 M_s^2)}$	1.5	1.9
R_{coh}	$\sqrt{(24)} l_{ex}$	7	9
δ_B	$\pi l_{ex}/\kappa$	40	3.9
R_{sd}	$36\kappa l_{ex}$	6	107
R_{eq}	$(3k_BT/4\pi BM)$	0.8	0.9
R_b	$(6k_BT/K_1)^{1/3}$	8	2

l_{ex}	exchange length
R_{coh}	maximum particle size for coherent rotation
δ_B	Bloch wall width
R_{sd}	maximum equilibrium single domain particle size
R_{eq}	particle radius for which $k_BT = MB$ in 1 tesla at 300 K
R_b	superparamagnetic blocking radius at 300 K.

- Transport lengths:

Mean free path $\lambda_\uparrow$ $\lambda_\downarrow$ (1-10 nm, $\lambda_\uparrow/\lambda_\downarrow$ up to 5 in 3d transition metals)

Spin diffusion length $\lambda_{sd\uparrow}$ $\lambda_{sd\downarrow}$



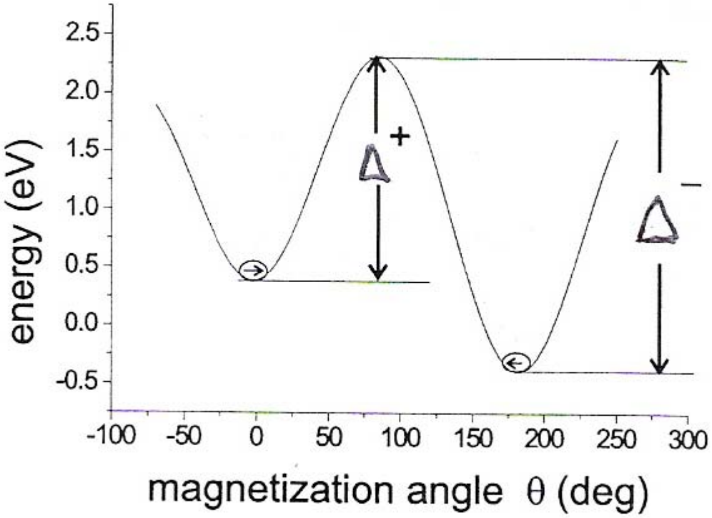
Typically an electron is scattered ~ 100 times before experiencing a spin flip, hence $\lambda_{sd} \approx 10\lambda$.

- Quantum length $l_B = \sqrt{(\underline{h}/eB)} = 26/\sqrt{B}$ nm (B in tesla)

Arises in quantum phenomena such as Landau diamagnetism

3 Superparamagnetism

Tiny particles (≈ 10 nm) are unstable when the barrier to magnetization reversal is comparable to k_BT

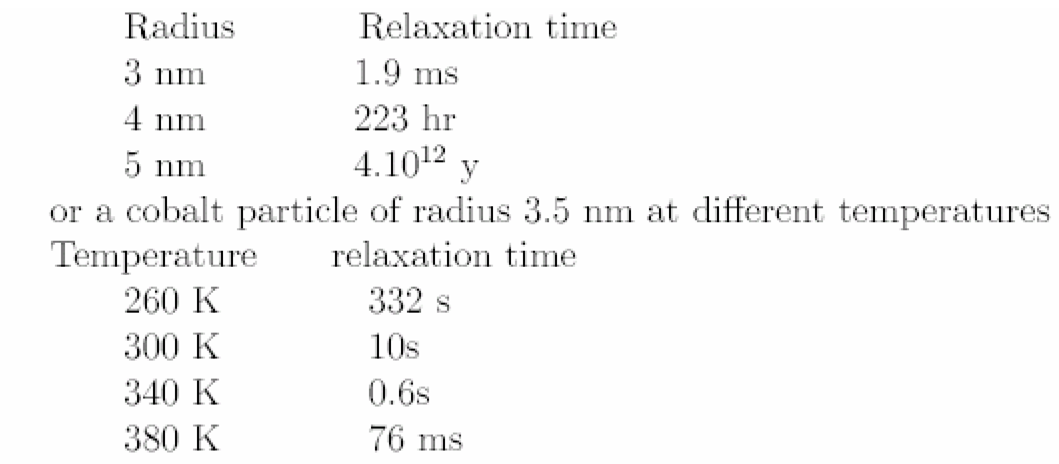


$$\Delta \rightarrow \Delta \pm \mu_0 m H \cos\theta$$

$$\tau = \tau_0 \exp(\Delta/k_BT)$$

~10^{-10} s

ΔMay originate from magnetocrystalline anisotropy K_1V, shape anisotropy K_dV, or surface anisotropy K_sA.



Radius	Relaxation time
3 nm	1.9 ms
4 nm	223 hr
5 nm	4.10^{12} y

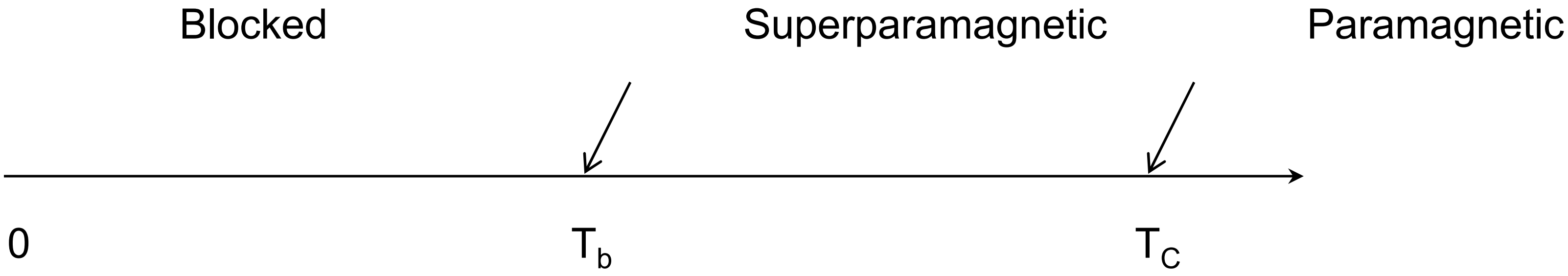
or a cobalt particle of radius 3.5 nm at different temperatures

Temperature	relaxation time
260 K	332 s
300 K	10s
340 K	0.6s
380 K	76 ms

The magnetization decays exponentially,

$$M(t) = M(0)\exp(-t/\tau)$$

Blocking



Blocked Superparamagnetic Paramagnetic

0 T_b T_C

Criteria for blocking $\Delta/k_B = 25 \Rightarrow \tau \approx 100\text{s}$

$\Delta/k_B = 40 \Rightarrow \tau \approx 10\text{y}$

In the superparamagnetic region the particles behave like a classical paramagnet with a giant classical moment *m*. The superparamagnetic susceptibility is

$$\chi=\mu_0 N m i^2/3k_B T$$

, where *N* is the number of particles perp cubic meter.

n cooling basalt in the Earth's magnetic field H_e, tiny superparamagnetic particles of magnetite block elow $T_{B,}$, thereby acquiring a *thermoremanent magnetization*.

$$M_{tr} = \mu_0 N m^2 H / 3 k_B T_b$$

Polarity of earth's field changes randomly every ≈ 100,000 y

Plates move at about 1 cm y^{-1}.

The ocean floor is like a giant tape recorder

Latitude is deduced from magnetic colatitude θ

$$\tan I = 2 \cot \theta.$$

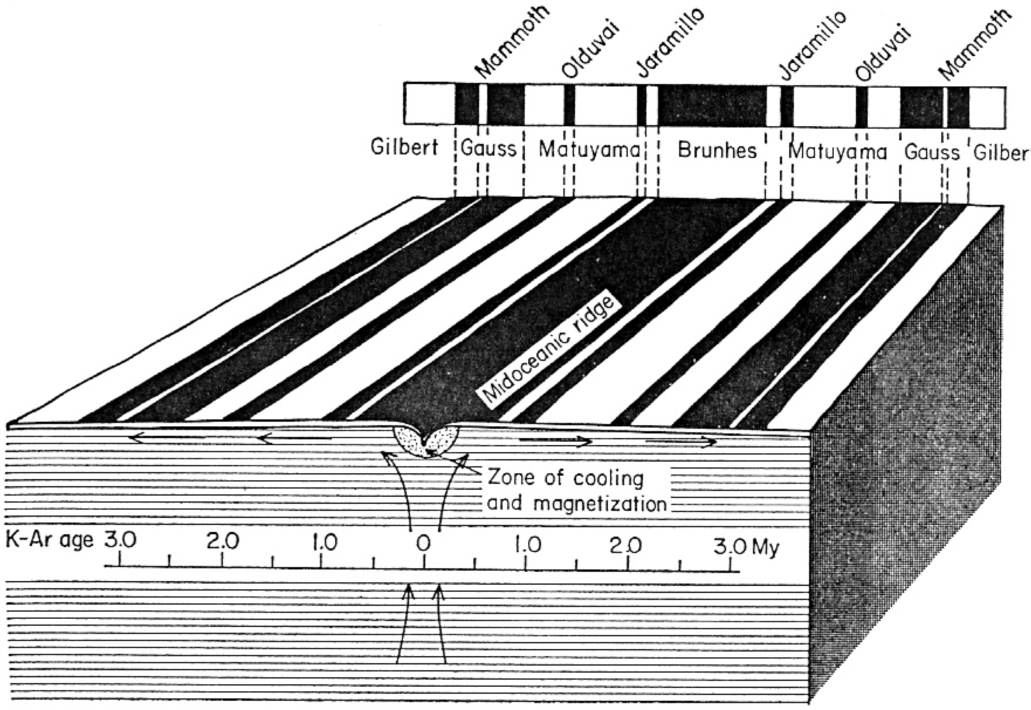


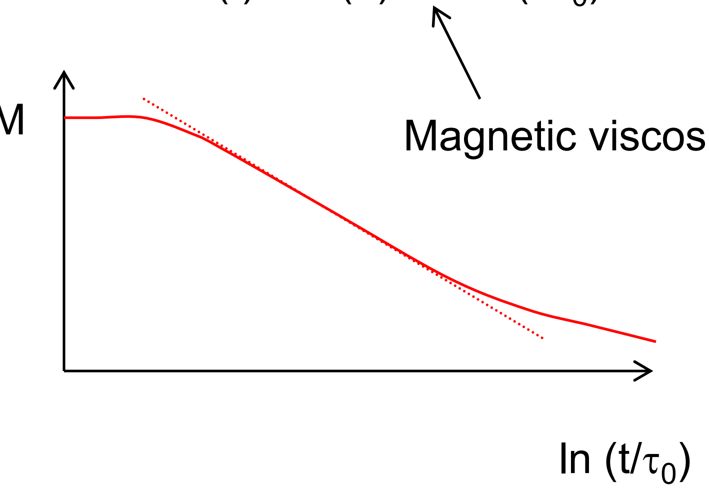
Fig 8.4. Schematic representation of plates separating at a mid-ocean ridge.

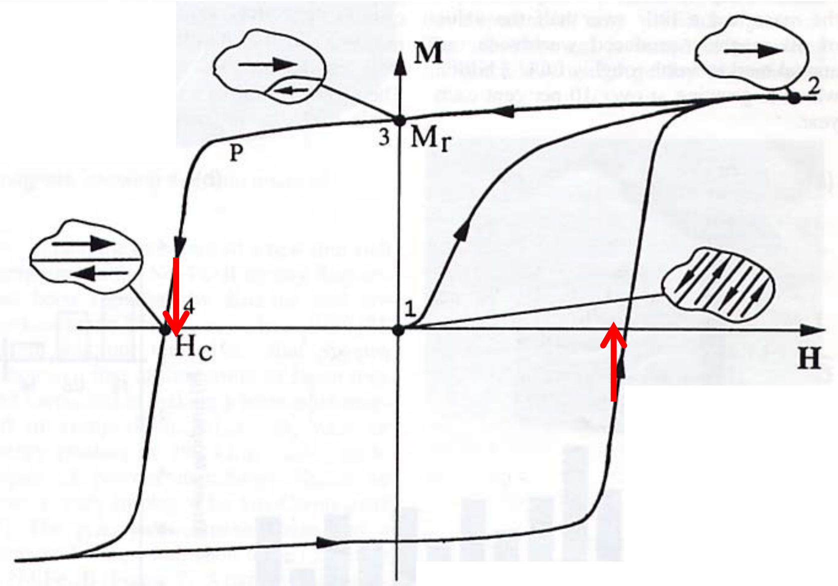
3.1 Magnetic viscosity

The stable state of a bulk ferromagnet is a multidomain state with no net magnetization. The magnetic states around the hysteresis

Metastability is most evident near the coercive field.

$M(t) \approx M(0) - S \ln (t/\tau_0)$

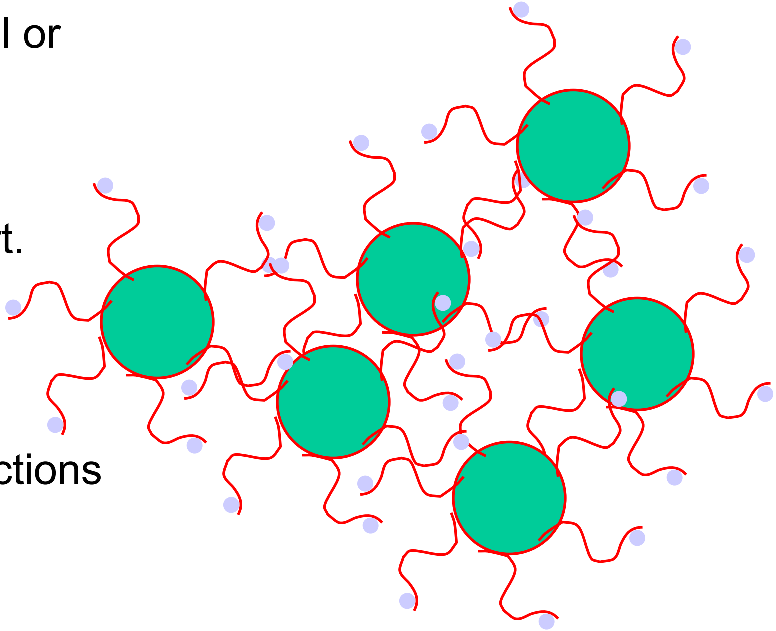




$M(t) = M(0)\int P(\tau)\exp(-t/\tau)\, d\tau$

3.2 Ferrofluids

Colloidal suspensions of superparamagnetic particles in oil or water. They behave like ferromagnetic liquids.



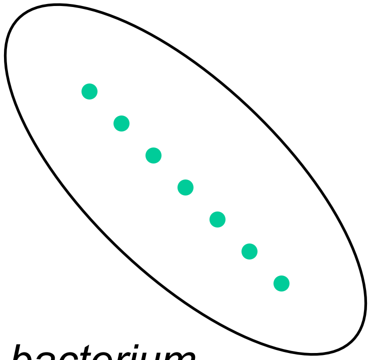
Particles are coated by surfactant, which keeps them apart.

A stable ferrofluid must be stable under the influence of

gravity, and under the influence of the dipole-dipole interactions (may supress the superparamagnetic fluctuations) .

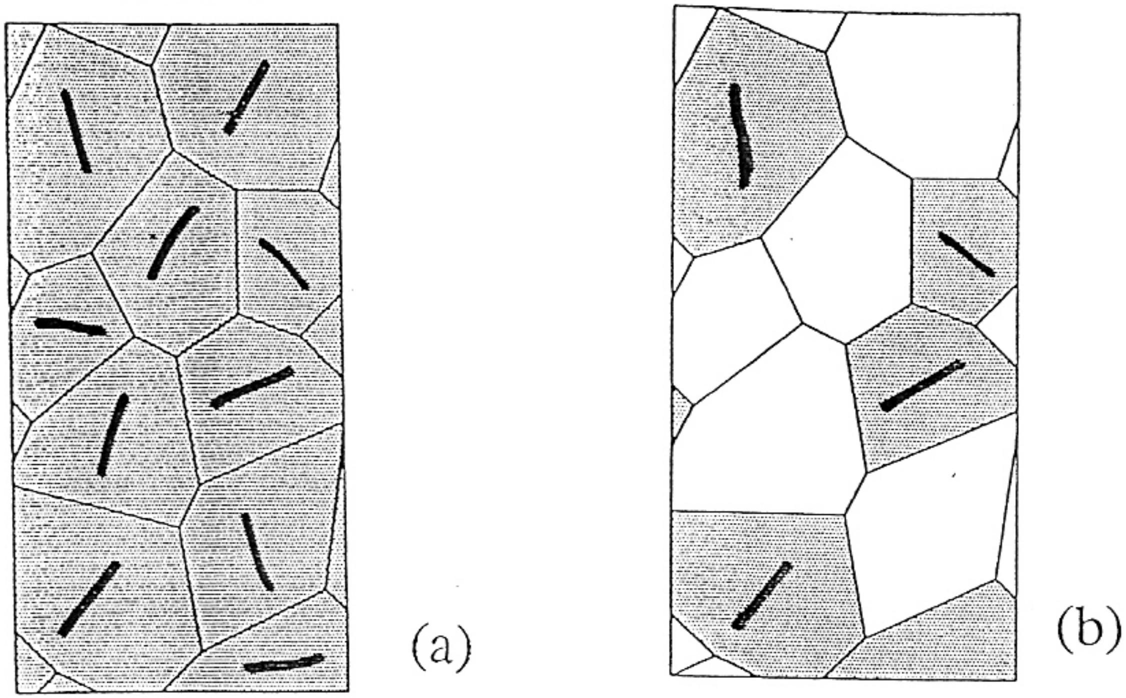
Uses: vacuum bearings, separation by floatation (effective density depends on applied magnetic field; external susceptibility ≈ 3).

Magnetorheological fluids have no surfactant; dipole interactions and viscosity are controlled by an external magnetic field.



Magnetotactic bacterium

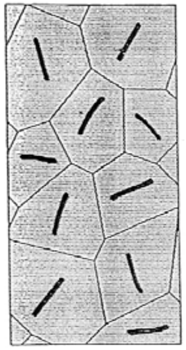
4 Bulk nanostructures



Single and two-phase magnetic nanostructures. The easy axis in the harder phase is marked.

The nanostructures may be exchange-coupled across the grain boundaries.

4.1 Single-phase nanostuctures


(a

Exchange-averaging of the anisotropy arises when

- Crystallites are single-domain, with a crystallite size *D* << domain wall width δ
- There is exchange coupling across the grain boundaries.

Exchange averaging is effective over the length scale δ_w

A volume δ_w^3 includes N = $(\delta_w/D)^3$ crystallites.

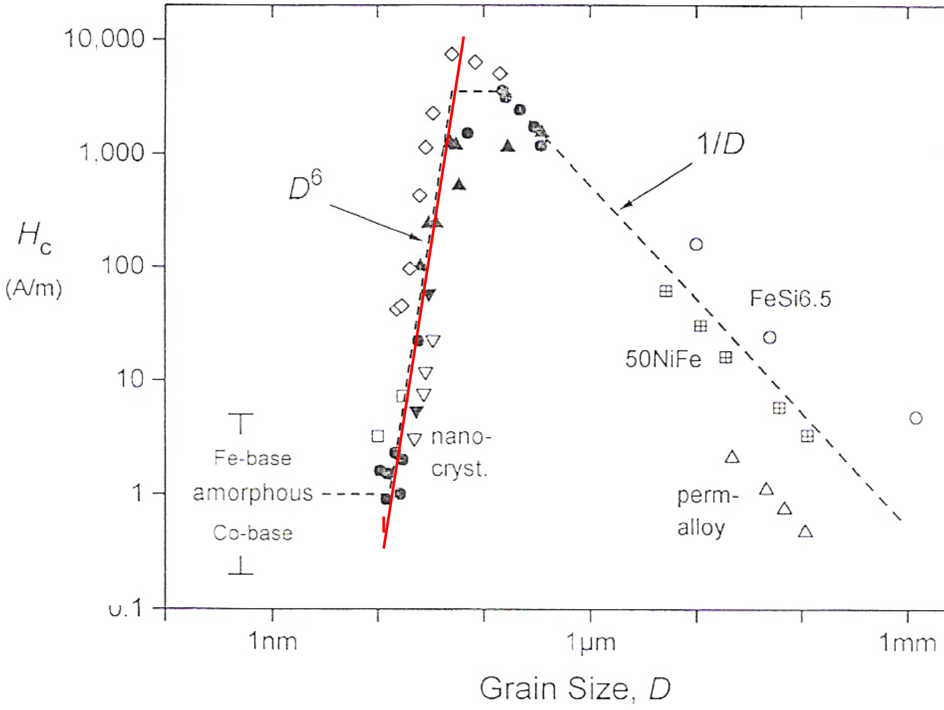
Total anisotropy of the volume obtained by adding

$$\langle K\rangle \approx K_1(D/\delta_w)^{3/2}$$

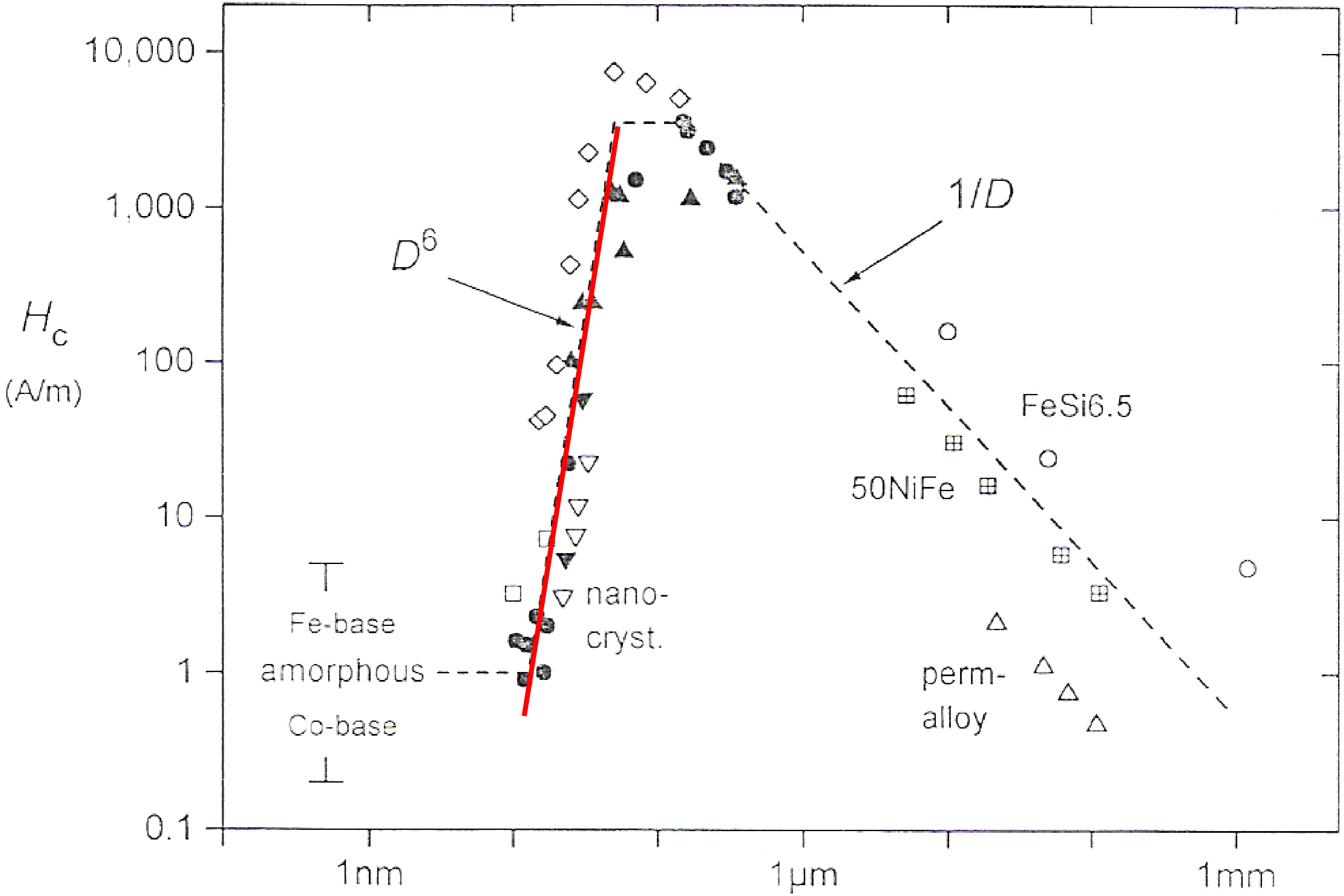
Use this consistently in the expression for the wall

$$\boxed{\delta_w = \pi\sqrt{(A/K)}\text{; hence}}$$

$$\langle K\rangle = K_1^4 D^6/\pi^3 A^3$$



Coercivity vs. grain size for a range of soft magnetic materials.



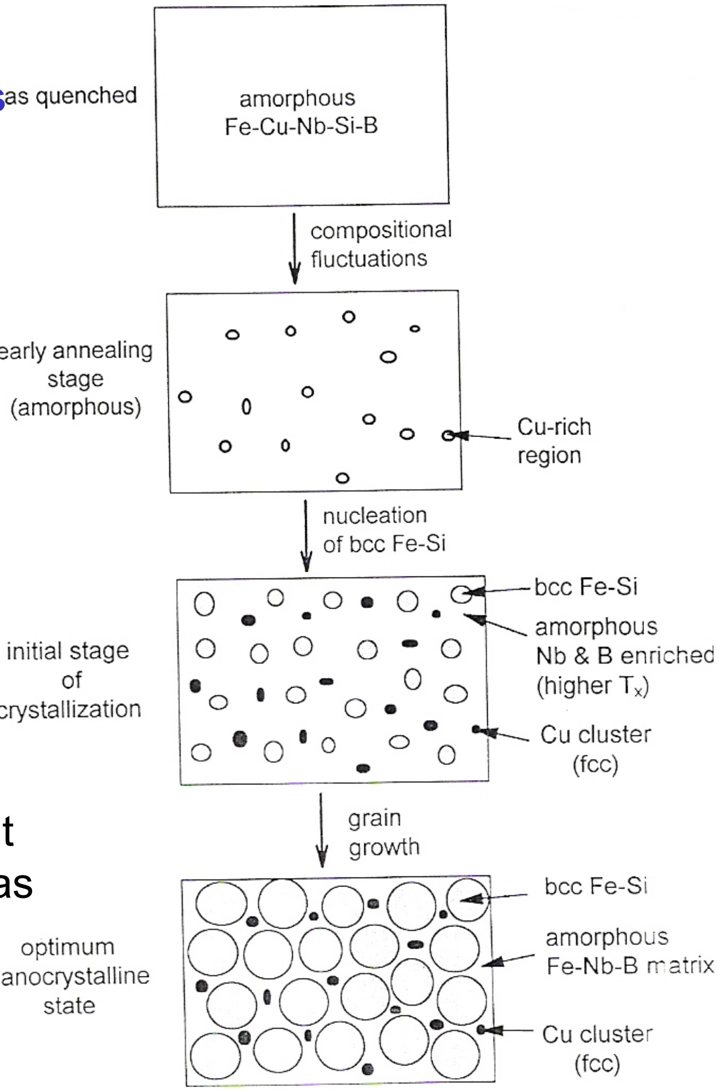
Coercivity vs. grain size for a range of soft magnetic materials.

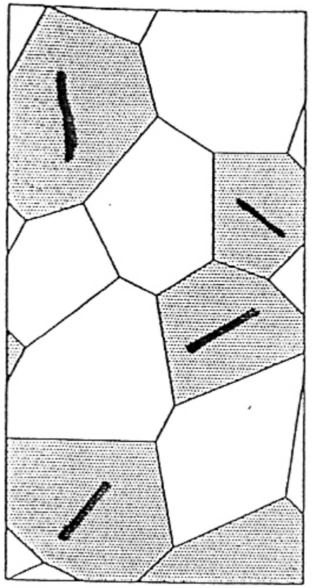
4.2 Two-phase nanostructures

- Preparation of *soft/soft* nanostructures
- Crystalline particles, in an amorphous matrix
- f the volume fraction of the crystalline phase is v, the anisotropy is given by:

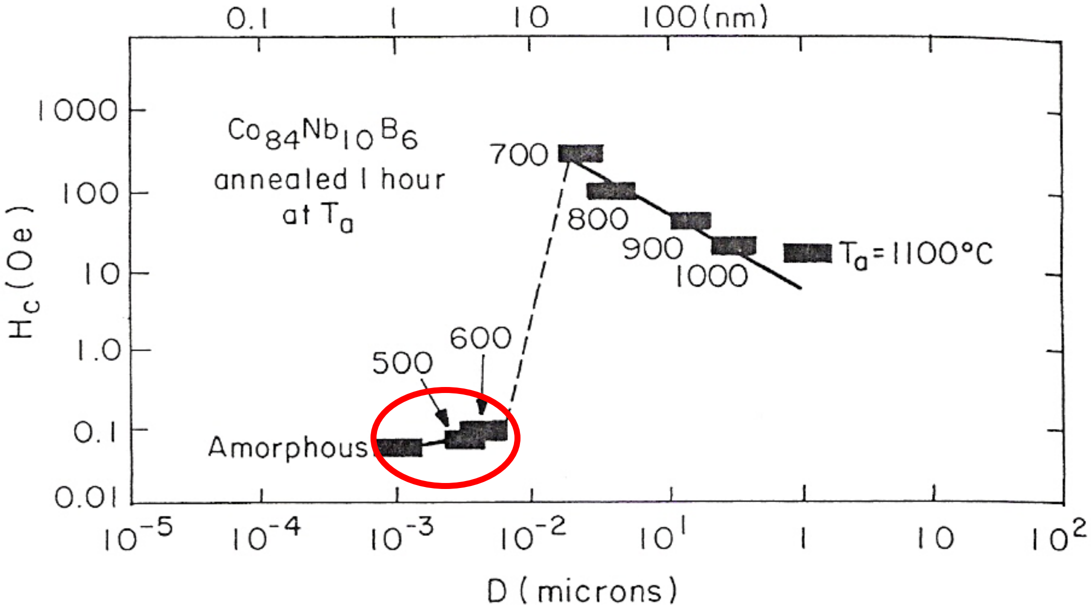
$<K> = v^2 K_1^4 D^6 / \pi^3 A^3$

- Method can be used to cancel out he magnetostriction if $\lambda_{crystalline}$ has opposite sign with respect to $\lambda_{amorphous}$





crystallization of amorphous Fe-Cu-Nb-Si-B to obtain a two-phase crystalline/amorphous soft nanocomposite 'Finemet'



Coercivity of a partially recrystallized amorphous Co-Nb-B alloy.

5 Needles and wires

Acicular particles with shape anisotropy are used for magnetic recording (tapes and floppy discs).

Shape anisotropy $K_d = [(1-3N)/4]\mu_0 M_s^2$

For a wire N = 0. Hence, $K_d = \mu_0 M_s^2/4$. The maximum limit of the coercivity is the anisotropy field $H_k = 2K_d/\mu_0 M_s = M_s/2$

For a true permanent magnet (one that can be made into any desired shape) $H_c > M_s/2$. Shape anisotropy is therefore not enough to make a truly permanent magnet.

Example CrO_2 tapes; particles are 30 x

Alnicos are two-phase CoFe/NiAl nanostructures where he permanent-magnet properties are due to the shape anisotropy of the CoFe acicular egions.

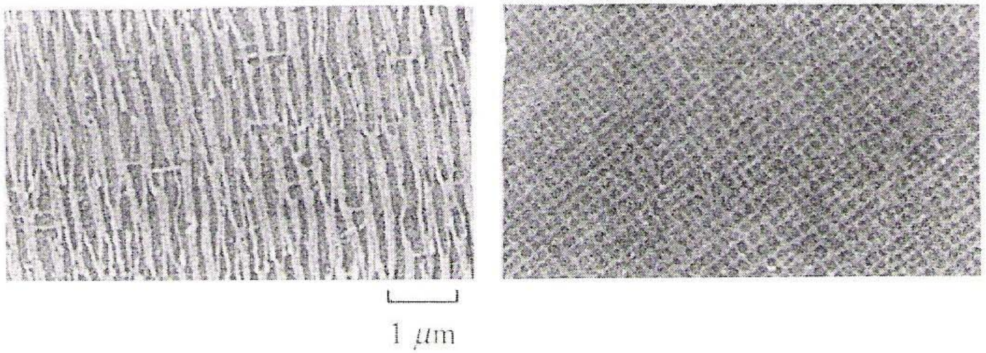


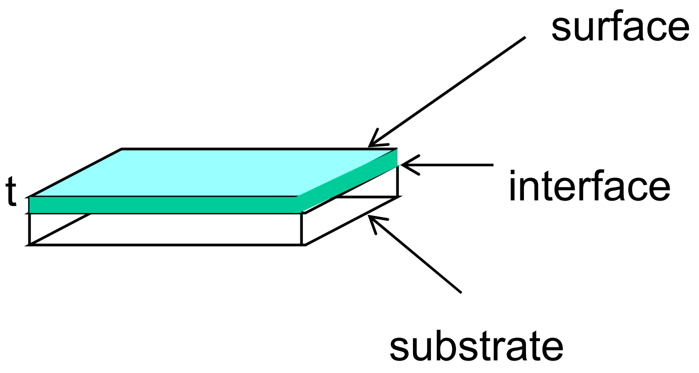
Fig 8.12 The microstructure of an aligned Alnico magnet, showing Fe-Co needles embedded in a nonmagnetic Ni-Al matrix.

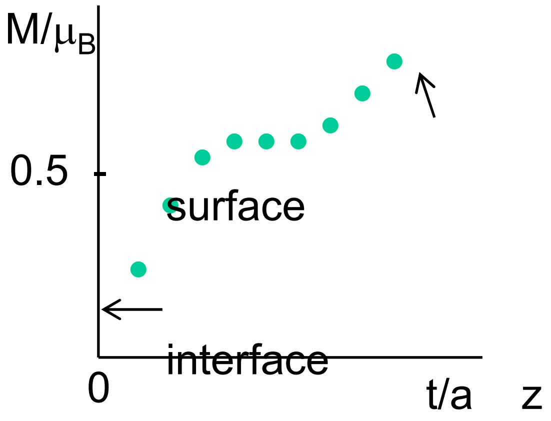
6 Thin films

Intrinsic magnetic properties may be different in thin films than in the bulk – Curie temperature, magnetization, anisotropy, magnetostriction.

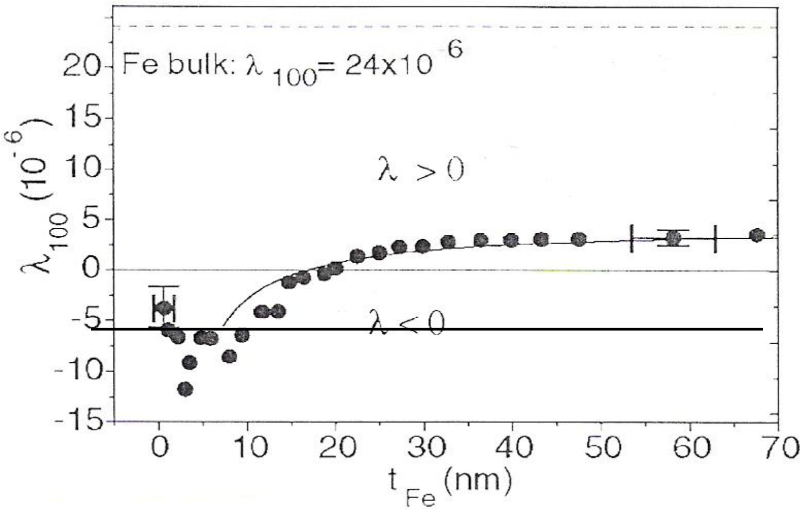
Reasons are:

- the numbers of surface ions t/a, and interface ions t/a
- difference in lattice parameters in *epitaxial* films; ≈ few %





Moment in an 8-monolayer film of Ni on Cu



Magnetostriction of iron thin films

6.1 Magnetization and Curie point

Dramatic changes in magnetic properties may be found in very thin films.

- Band narrowing at the surface may cause ferromagnetism in some d-elements, e.g. V, Pd (Stoner criterion)
- Films grown epitaxially on their substrate can have different lattice parameters or crystal structure to the bulk, hence potentially very different magnetic properties. E.g. Fe grown on Cu (fcc) may be nonmagnetic or antiferromagnetic, according to the substrate temperature.
- Films with different orientations may have different moments. e.g Surface layer of 100 iron has atomic moment of 3.0 μ_B, 110 has 2.6 μ_B
- Hybridization with the substrate usually reduces the moment, and may even change sign of *J*'

Curie point may decrease in thin films due to weakened exchange of surface / interface layers, or it may increase in some cases because of band narrowing.

Note that a *unifromly magnetizedí thin film produces no stray field*

$$B_\perp = 0; \quad H_{||} = 0$$

6.2 Anisotropy and domain structure

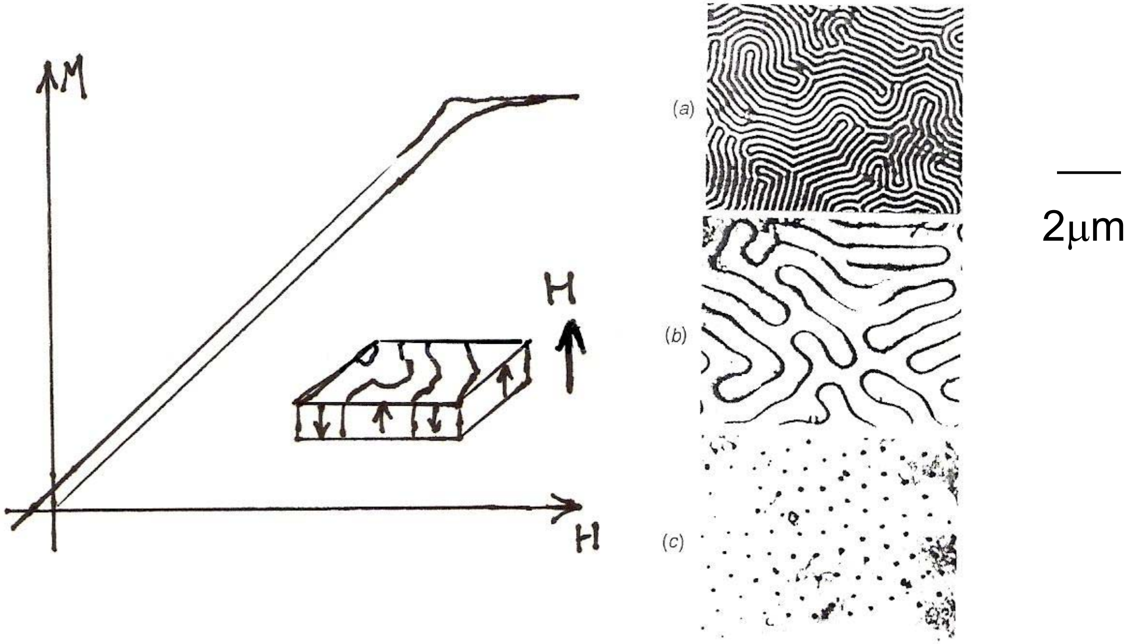


Fig 8.15. Magnetization and domain structure of a thin film with perpendicular anisotropy

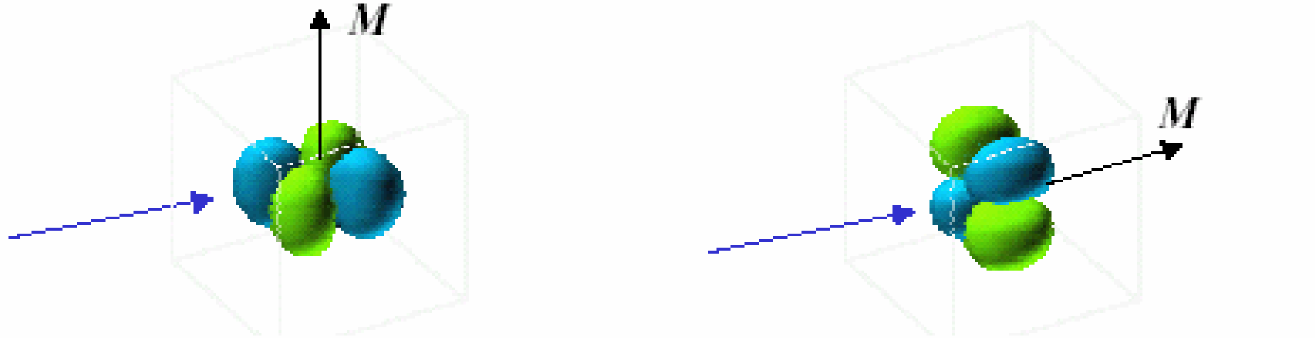
.3 Anisotropic magnetoresistance

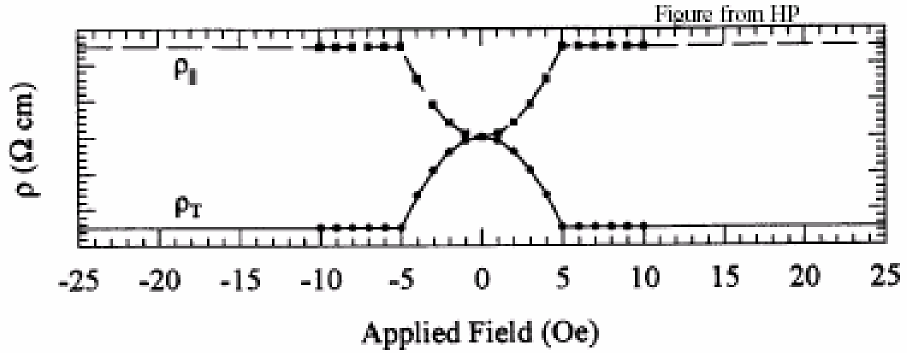
Feature of magnetic materials

AMR originates from spin-orbit coupling.

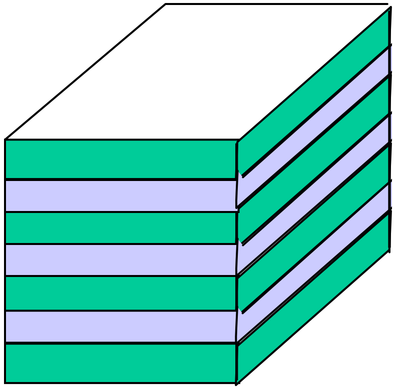
It can be positive and negative and its magnitude depends on the scattering cross-section that is presented to conduction electrons by the anisotropic charge distribution of the atoms.

Order of magnitude 1 %.



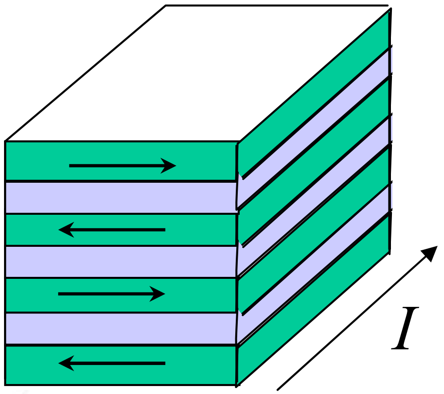


7 Thin film heterostructures



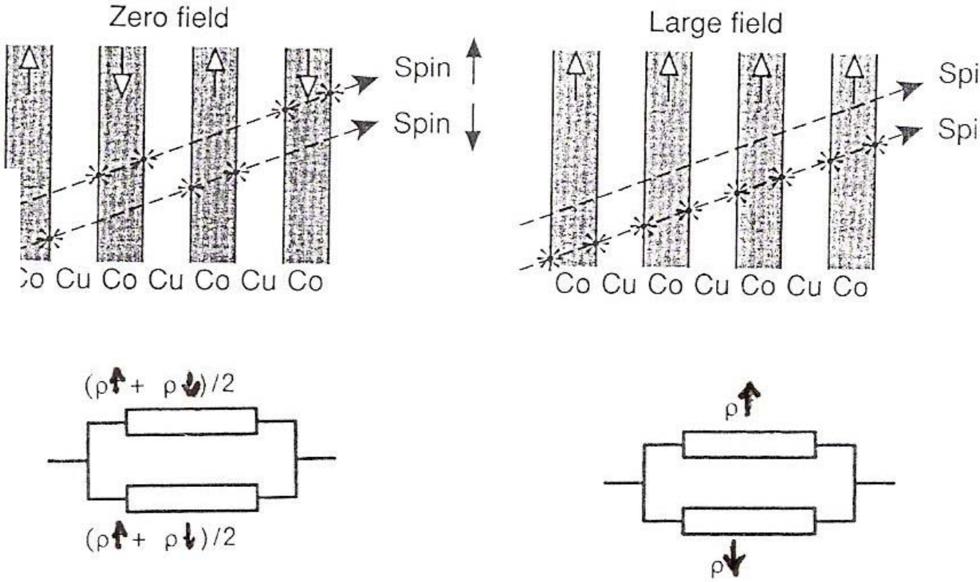
Practical devices are compose of > 10 layers made of six different metals; Some are very thin e.g. Ru, Co-Fe, AlO_x 1 - 2 nm.

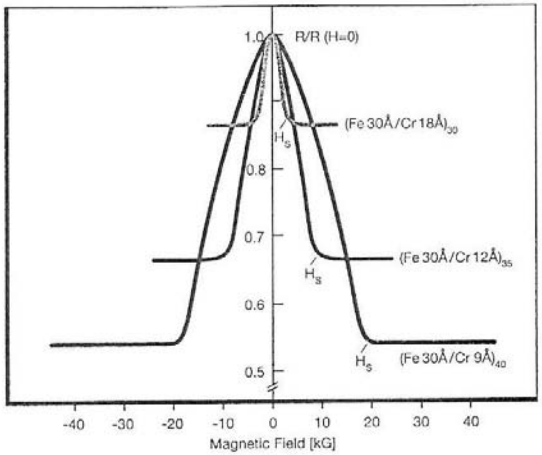
7.1 Giant magnetoresistance



Requires multilayer structures of alternating magnetic and nonmagnetic materials

Origin in spin-dependent electron transmission at interfaces and spin-dependent conductance in ferromagnetic layers





ig 8.25. Giant magnetoresistance in Fe/Cr multilayers.

Illustration of the derivation of Eq 8.8. 9.9.

7.2 Indirect exchange coupling

The sign of indirect exchange coupling (RKKY interaction) in multilayers with alternating ferromagnetic and nonmagnetic layers oscillates with the thickness of the nonmagnetic layers.

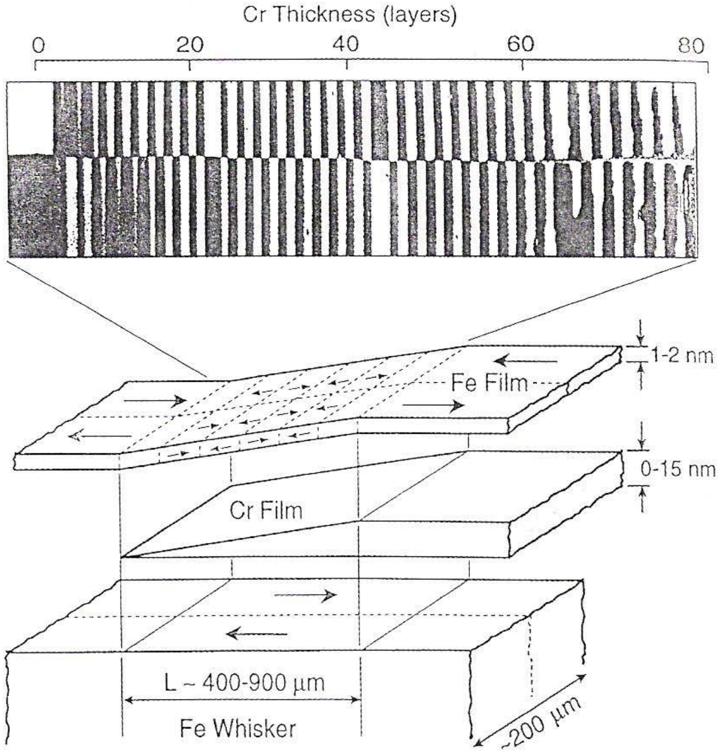


Fig 8.18 An experiment which demonstrates the oscillating spin polarization as a function of spacer thickness.

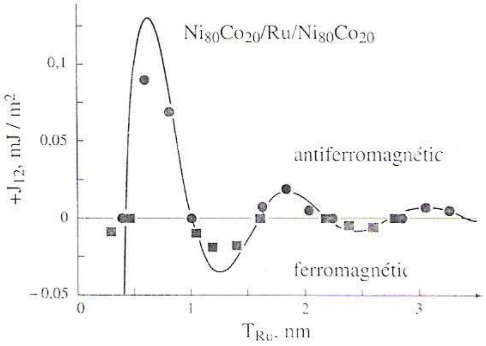


Fig 8.19. Oscillating exchange coupling in Co/Ru/Co trilayer

7.3 Dipolar coupling

There is no dipolar coupling between perfectly-smooth uniformly-magnetized ferromagnetic layers (no stray field).

However, in an actual multilayer the interface are rough and this creates a dipolar coupling field.

If the roughness is correlated the dipolar coupling (orange-peel coupling) is ferromagnetic.

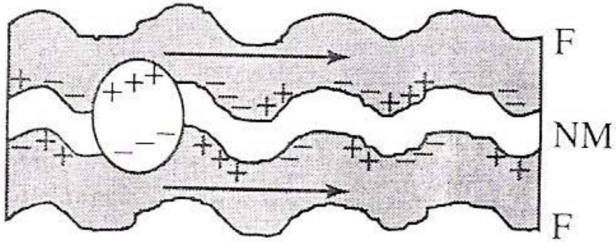


Fig 8.21. The orange-peel effect

7.4 Exchange bias

Needed to *fix* the direction of one of layers.

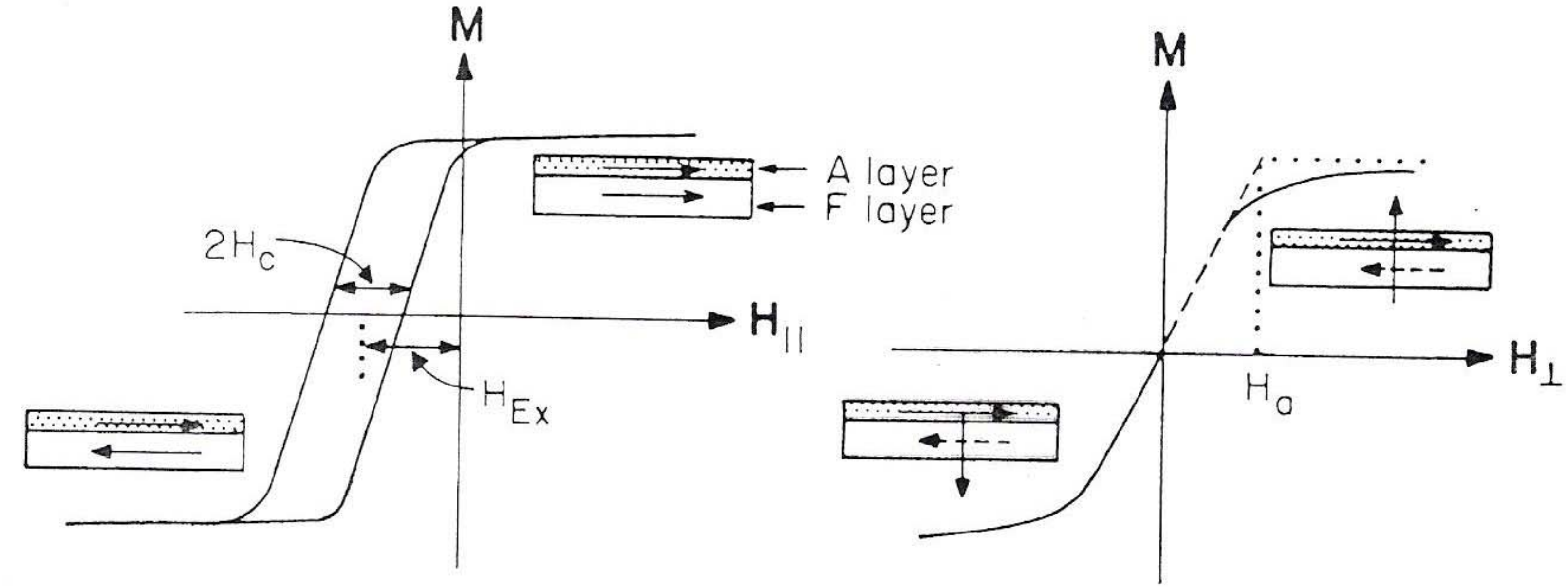


Fig. 8.31 The effect of exchange anisotroppy on the hysteresis loop of a ferromagnetic layer coupled to an antiferromagnetic layer. The arrow in the A-layer shows the direction of the exchange field, wgich is not necessarily the antiferromagnetic axis. The loop on the left is measured with the applied field in this direction; the one on the right with the applied field in the perpendicular direction.

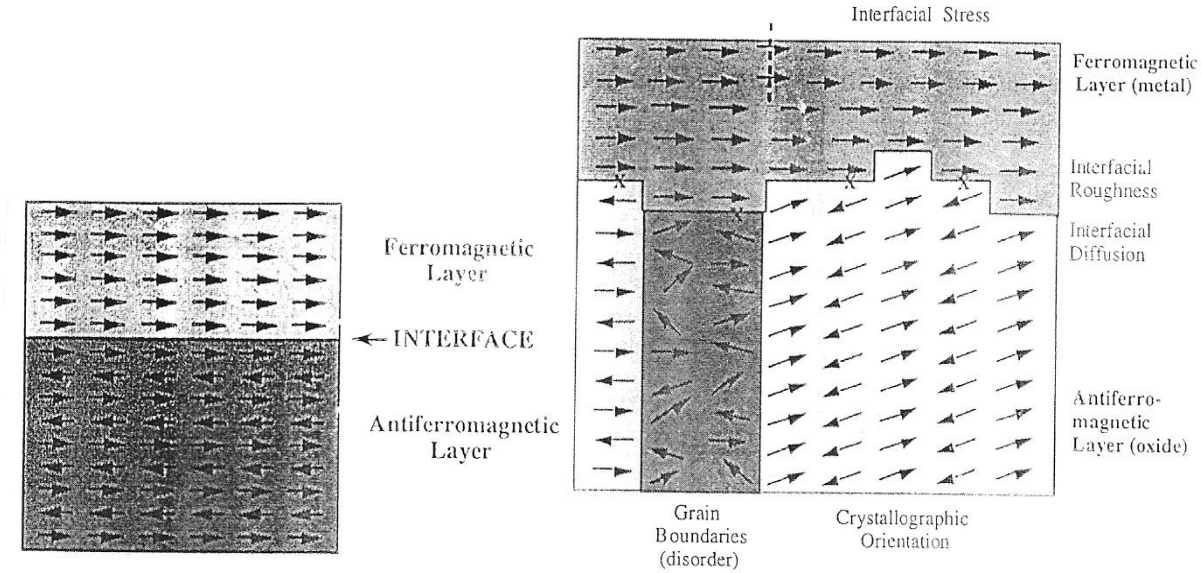


Fig. 8.35 An ideal interface and a real interface.

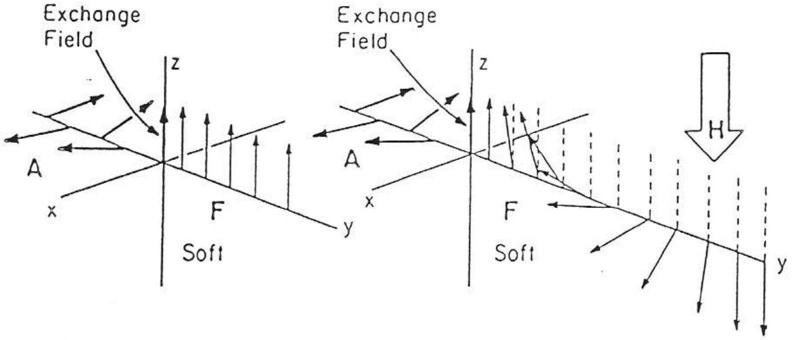
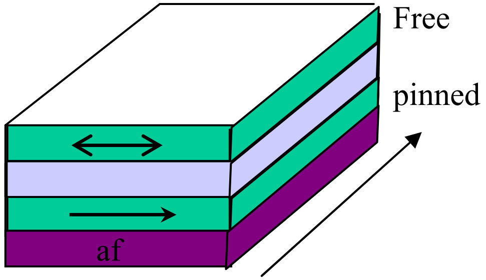
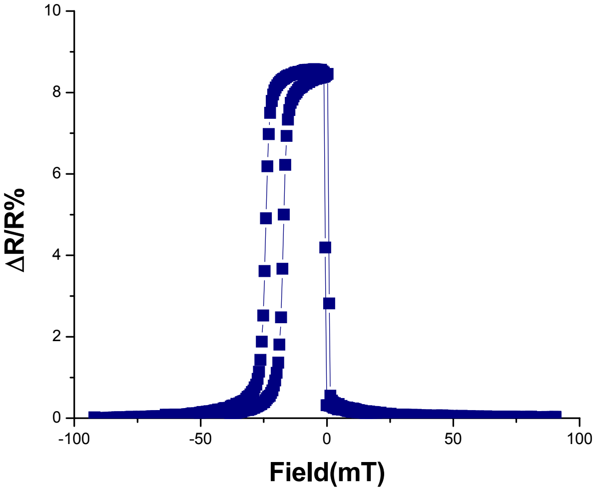


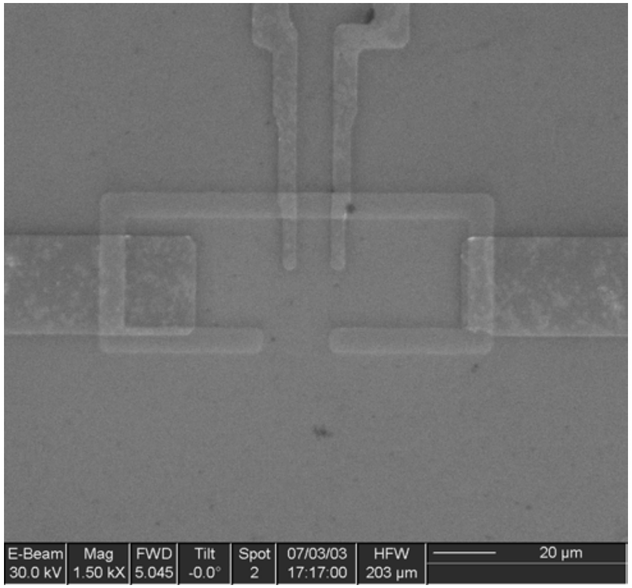
Fig. 8.36. Formation of a domain wall at an interface of a soft ferromagnetic layer exchange-coupled to an antiferromagnet.

7.4 Spin valves



GMR are effect in magnetic spin valves is typically 5 – 20%





Ta(5nm)/NiFe(3.5nm)/CoFe(1.2nm)/Cu(2.9nm)/CoFe(2.5nm)/IrMn(10nm)/Ta(5nm)

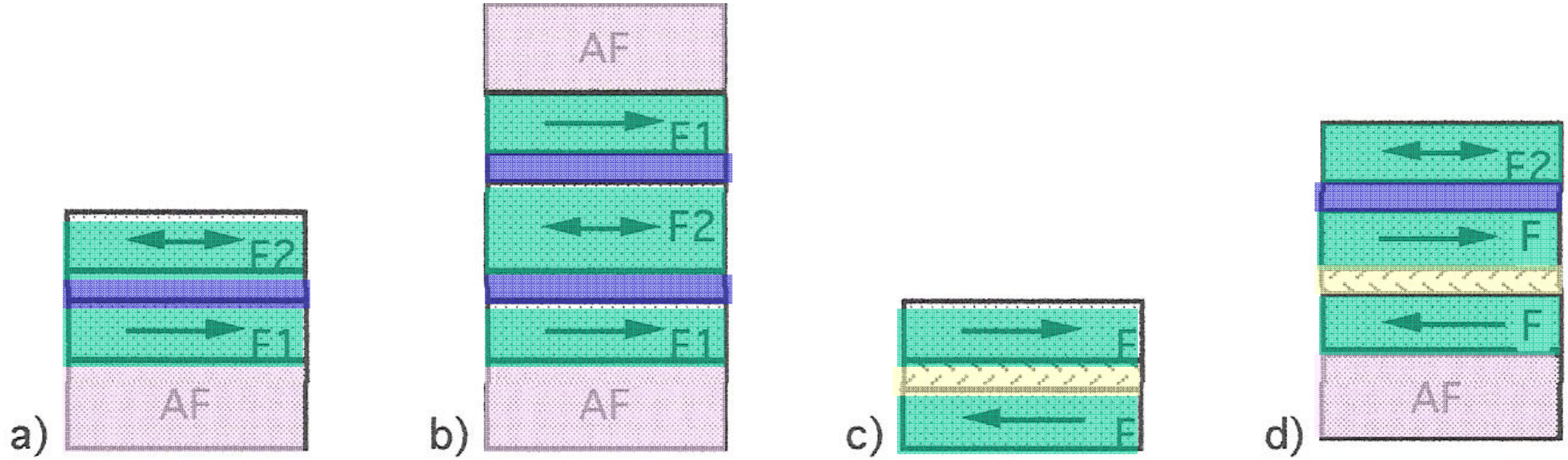
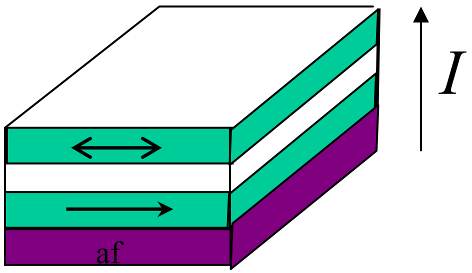
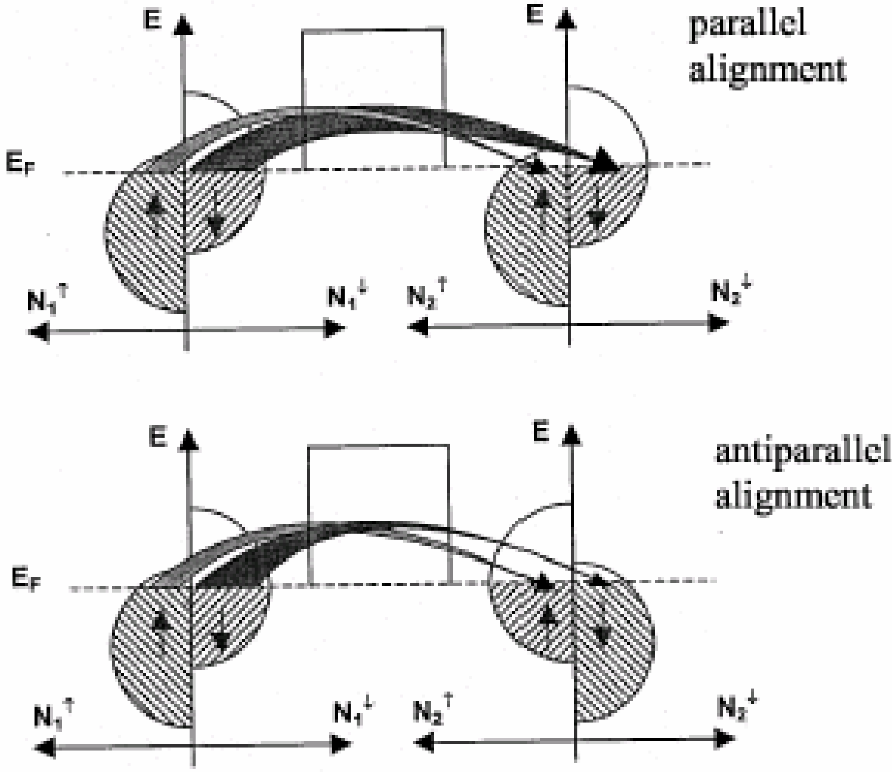


Fig. 8.26. Spin valve structures.: a) simple spin valve with an antiferromagnetic pinning layer, b) double spin valve c) an artificial antiferromagnet, d) a spin valve based on an artificial antiferromagnet. The interfaces between the magnetic layers (F1, F2) and the spacer layer (unshaded) are often decorated with an ultrathin cobalt layer to improve $\Delta\rho/\rho$ for the devices.

7.5 Metal/insulator/metal tunnel junctions





Define spin polarization

$$P = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}}$$

P is about 40% for 3d transition metals

TMR effect typically 50% for AlO_2 tunnel barriers.

Recently (late 2004) MTJs with MgO tunnel barriers exhibit TMR effects up to about 300%.

$$\frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\downarrow}} = \frac{(1/R_{\uparrow\uparrow}) - (1/R_{\uparrow\downarrow})}{(1/R_{\uparrow\downarrow})} = \frac{\Delta R}{R_{\uparrow\uparrow}} = \frac{2P}{1-}$$

$$\frac{\Delta R}{R_{\uparrow\downarrow}} = \frac{2P^2}{1+P^2}$$

7.6 Magnetic single-electron devices

Ion-beam or e-beam lithography

- Quantum dots
- Magnetic Coulomb blocade
- Kondo effect

8 Applications

8.1 Magnetic recording

Analog wire recording was invented in 1898 by Valdemar Poulson.

Analog tape recording using iron oxide particle tape was developed in Germany in the mid-1930s

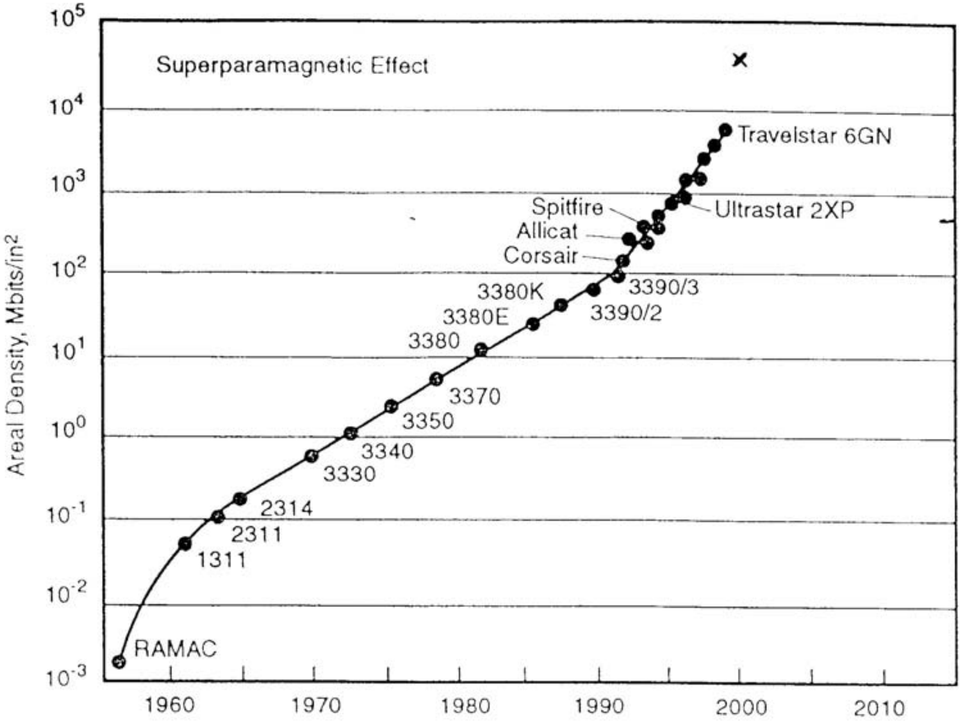
Digital disc recording was introduced by IBM in in the mid 1950s

t has been relentlessly perfected over 50 years. Densities have increased by a factor 10^8 to 100 Gb s
nch. (155 bits μm^{-2}) Data rates are ~ 1Ghz, Fly heights of the head over the disc surface are ~ 10 nm.

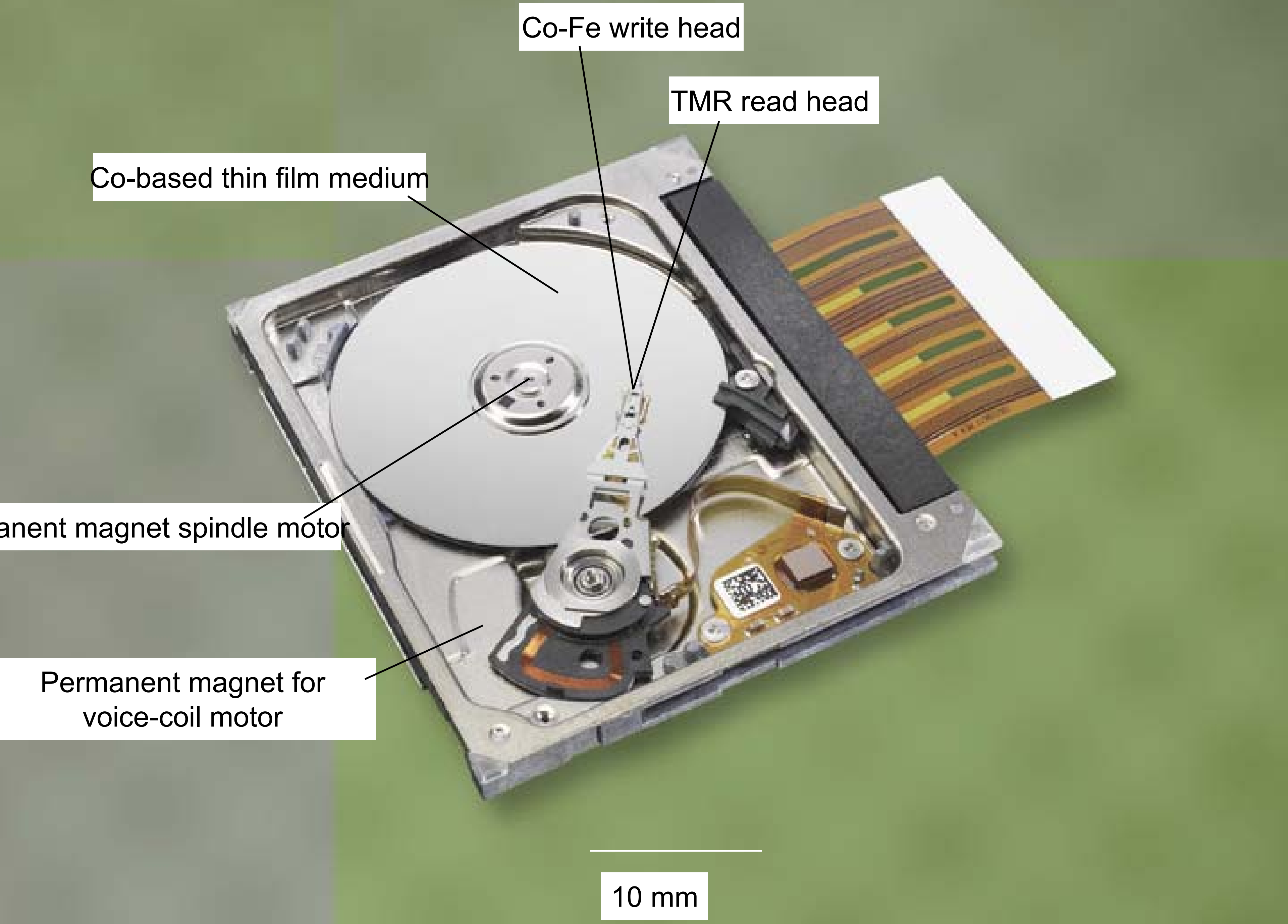
Digital and analog recording is a €20 B business, consuming large quantities of ferrite and other semi-hard magnetic materials for ecording media, and using sophisticated miniature magnetic circuits in the read and write heads.

The magnetic record is generally in the plane of the medium. Only magneto-optic recording uses perpendicularly-magnetized media at present.

The data are recorded on tracks on the media whose width is determined by the width of the write head.

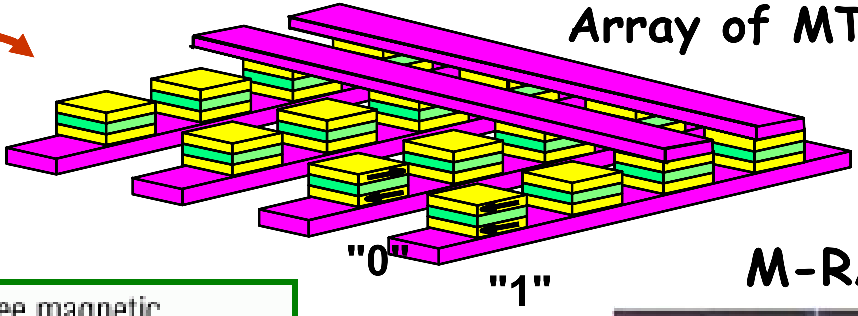


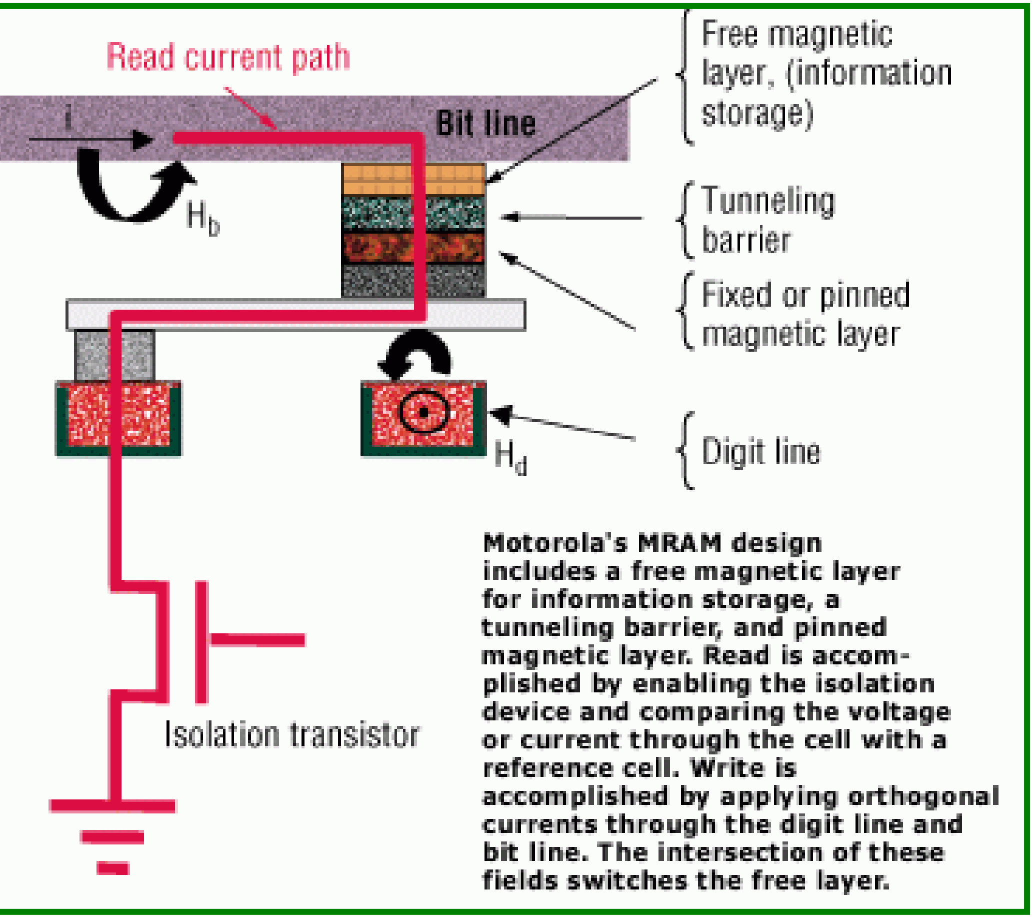
Data densities have been increasing at 60


Co-Fe write head
TMR read head
Co-based thin film medium
anent magnet spindle motor
Permanent magnet for voice-coil motor
10 mm

8.2 Magnetic Random - Access Memory (MRAM)

Array of MTJ





Motorola's MRAM design includes a free magnetic layer for information storage, a tunneling barrier, and pinned magnetic layer. Read is accomplished by enabling the isolation device and comparing the voltage or current through the cell with a reference cell. Write is accomplished by applying orthogonal currents through the digit line and bit line. The intersection of these fields switches the free layer.

M-RAM

Notebook, PC, etc

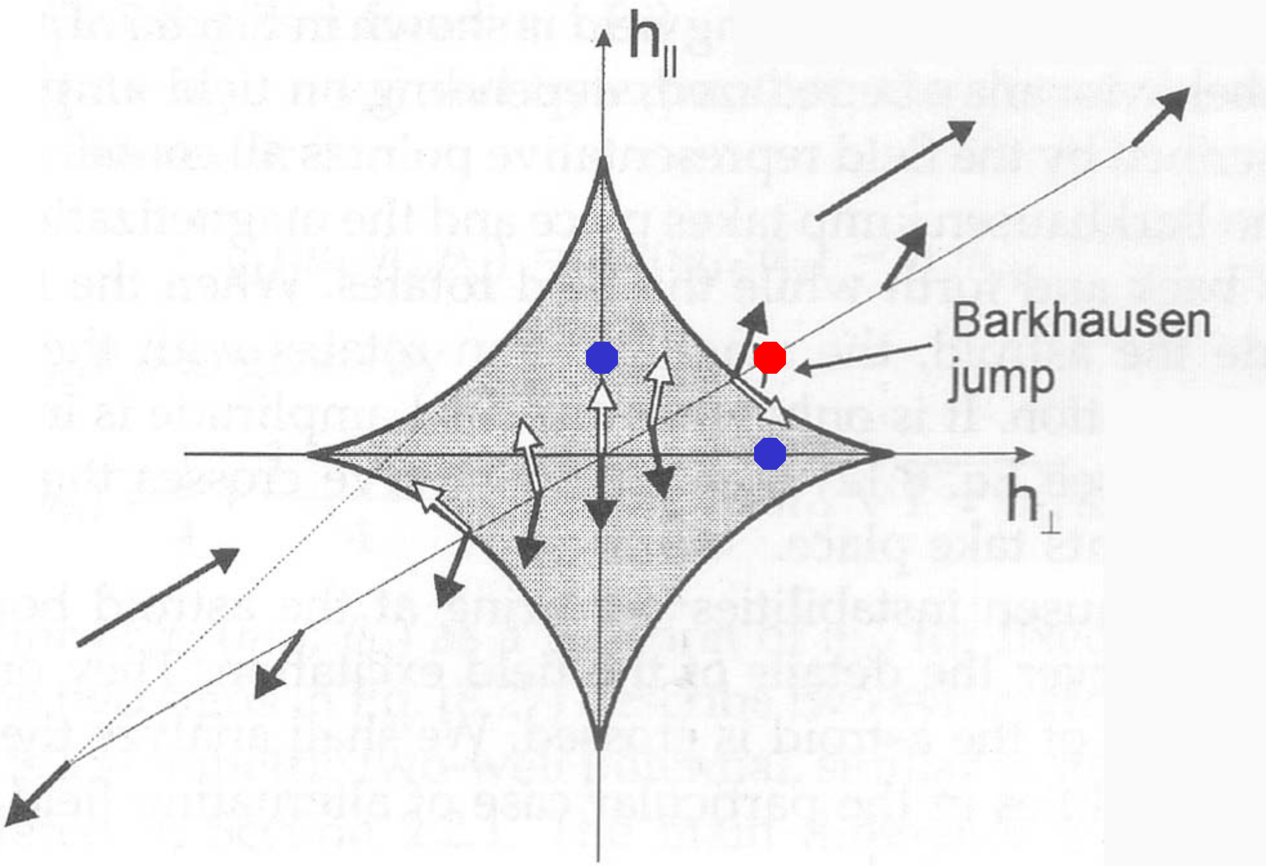
Palm Top

Mobile Phone

Thermally-assisted switching.

Current-induced switching

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.



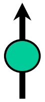
Half-select concept.

A pulse in the bit line or the word line is not enough to switch the element. *Both* must be present simu

8.3 Spin Electronics

Conventional electronics has ignored the spin in the electron:

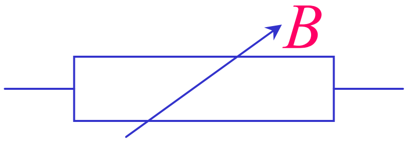
- Code information into the ↑ and ↓ channels
- Manipulate the ↑ and ↓ electrons independently
- Exploit magnetic and electric fields



$e = 1.6\ 10^{-19}\ \mathrm{C}$

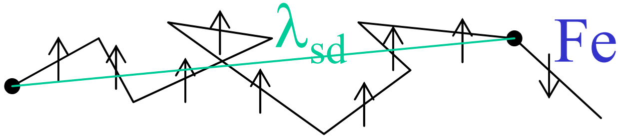
$m = e\hbar/2m = 1\mu$

TWO-TERMINAL DEVICES; Magnetoresistors



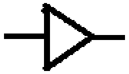
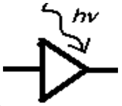
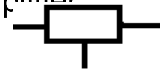
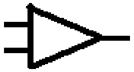
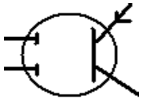
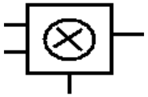
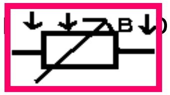
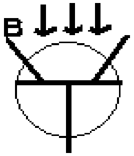
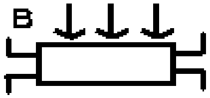
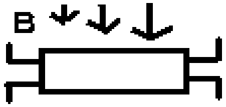
Source of spin-polarized electrons → Medium with long spin-diffusion length → spin-sensitive detector

Ferromagnetic metal; NiFe, CoFe



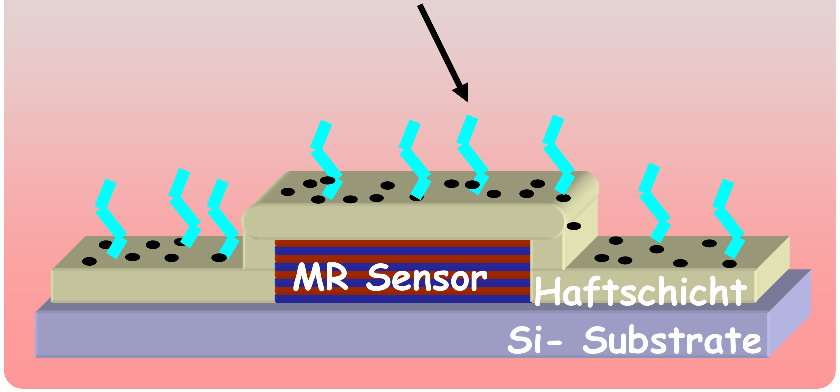
Ferromagnetic metal NiFe, CoFe

Normal metal; Cu

Number of Terminals	2	2+	3 / 3+	4 / 4+
Classical Devices	Switch  Resistor  Diode 	Photodiode  Varistor 	Transistor Filter  Amplifier  	Wheatsone Bridge 2-gate MOSFET  Tetrode Multiplier  
Spin Electronic Devices	Spin Switch 	Magnetic switch (MTJ) Mag  or Magnetic Photodiode 	Spin transistors 	Hall Probe  Magnetic Gradiometer (bridge) 

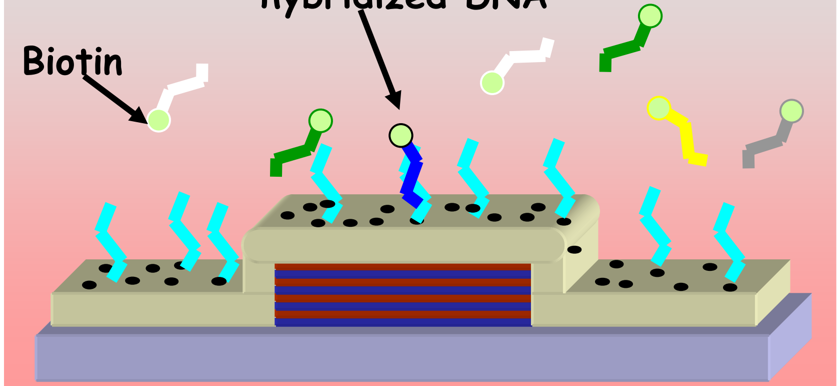
8.4 Biochips

1) Immobilisation of target molecules



Fixed DNA single strand

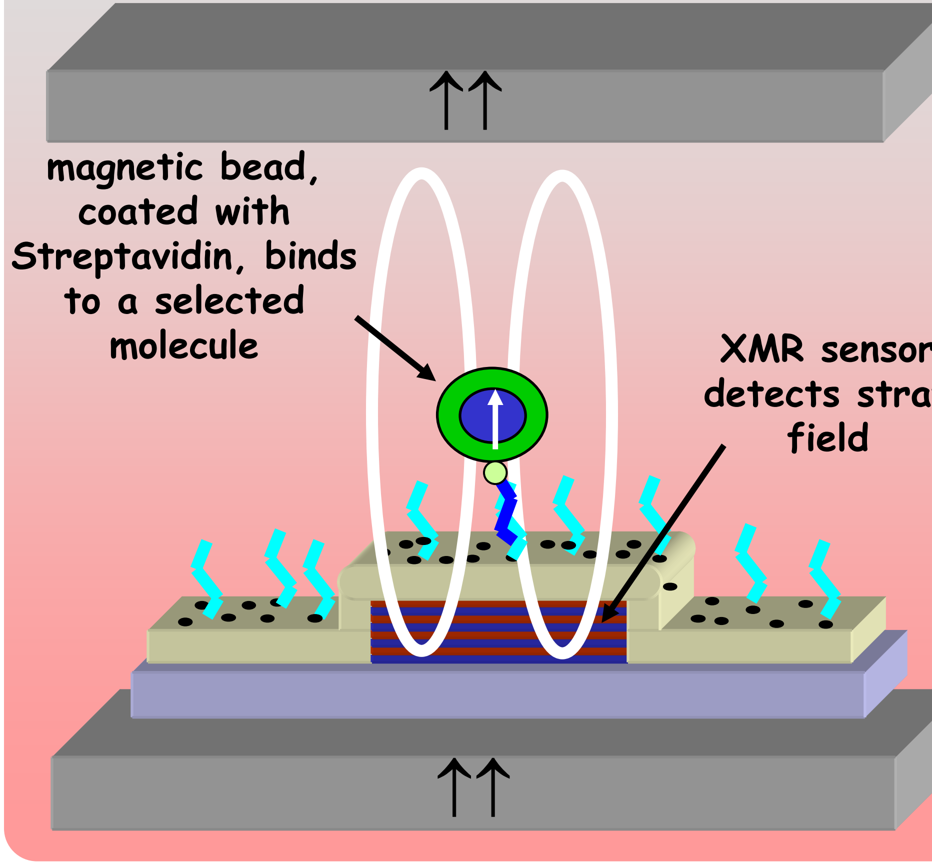
) Hybridisation of the probe molecules



hybridized DNA

Biotin

3) Hybridisation with beads and detection with MR sensor



magnetic bead,
coated with
Streptavidin, binds
to a selected
molecule

XMR sensor
detects stra
field

Magnetism Conferences

ICM International Conference on Magnetism (IUPAP Support)

- Every three years (IUPAP Support) Recife 2000, Rome 2003, Kyoto 2006, Karlsruhe 2009

APS meeting on Magnetism and Magnetic Materials MMM - Annual

INTERMAG Conference - Annual

Gordon Conference on Nanoscale Magnetism etc.

Suggestion:

IUPAP Meetings: 'Frontiers of Nanoscience' Every two years.

Cross-disciplinary; each supported by two or three commissions.

Nanoscience:	Small size 1 - 100 nm;
	Complexity
	Correlations.

Nanoscience: Science of condensed matter on a scale of 1 - 100 nm where interatomic or interelectronic interactions which impart a complexity which is absent in the bulk.