INTRODUCTION TO NANOMAGNETISM

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22/03/2006

Outline

Introduction

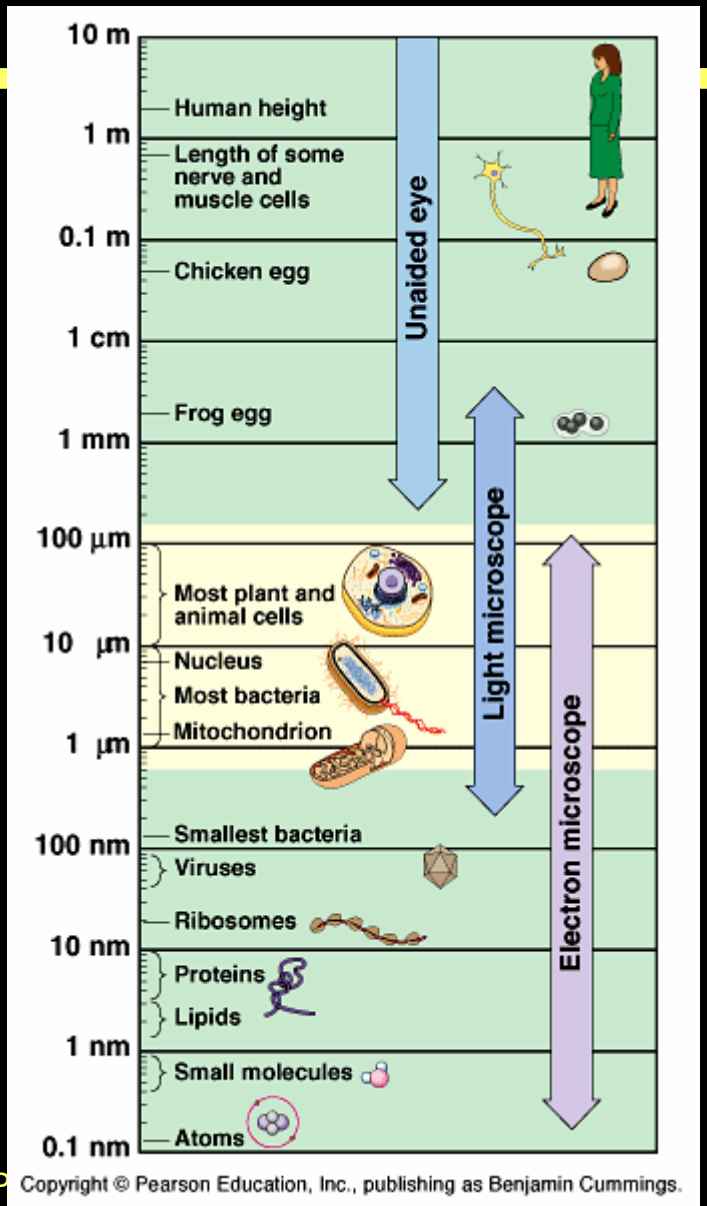
Why nanomagnetism is important?

Why nanomagnetism is different from bulk magnetism?

Types of low-dimensional solids?

New effects in nanomagnetic systems

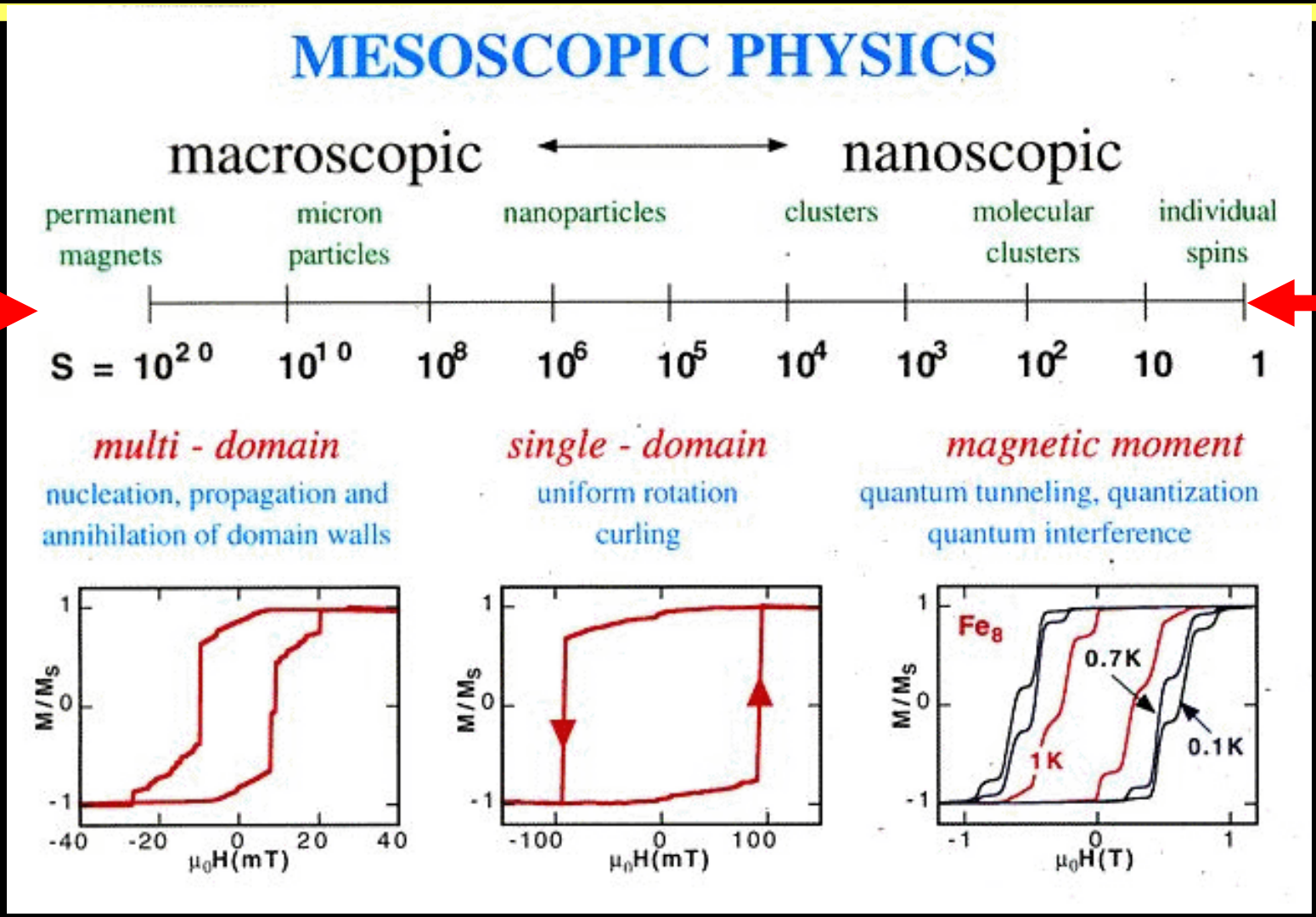
The nano scale



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Phenomena in objects with 1-100 nanometers

Nanomagnetism-mesomagnetism

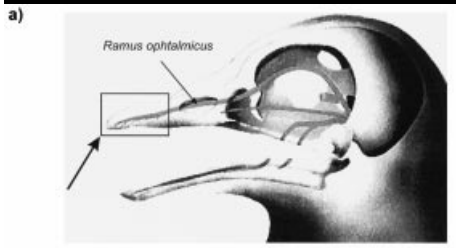


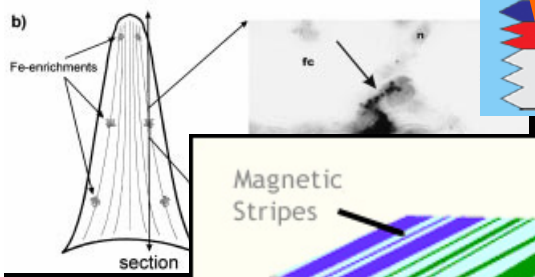
Wernsdorfer 1996

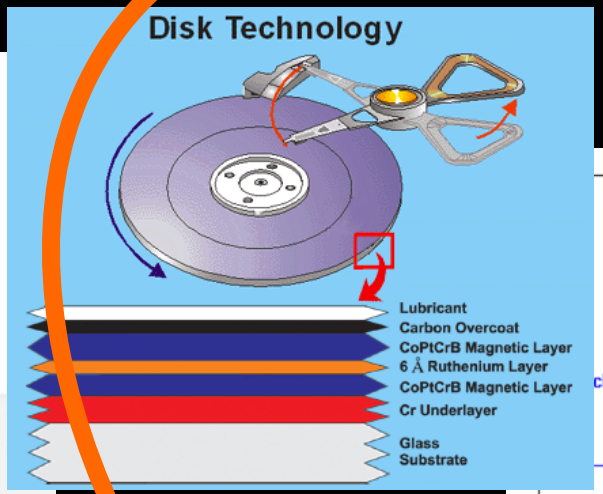
Nanoscopic systems

- Grains or particles (free-standing or embedded in a matrix) (0D)
- Wires (free-standing or in a matrix) (1D)
- Films or multilayers (2D)
- Rings, etc

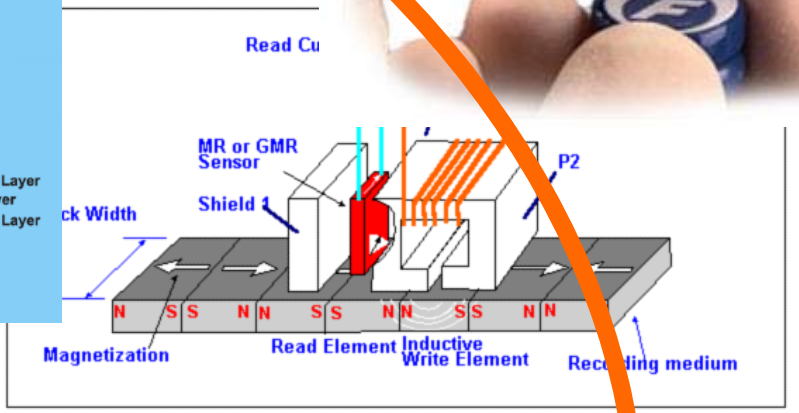
Relevance of nanomagnetism

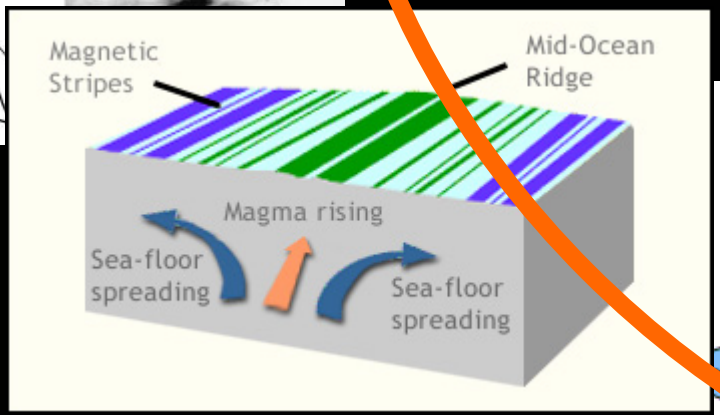


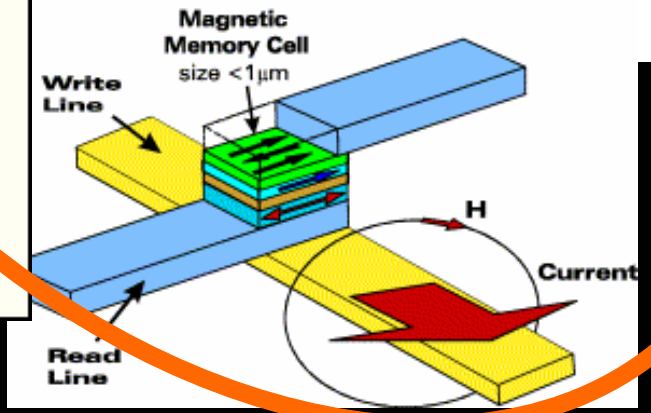


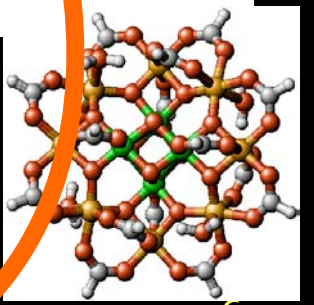




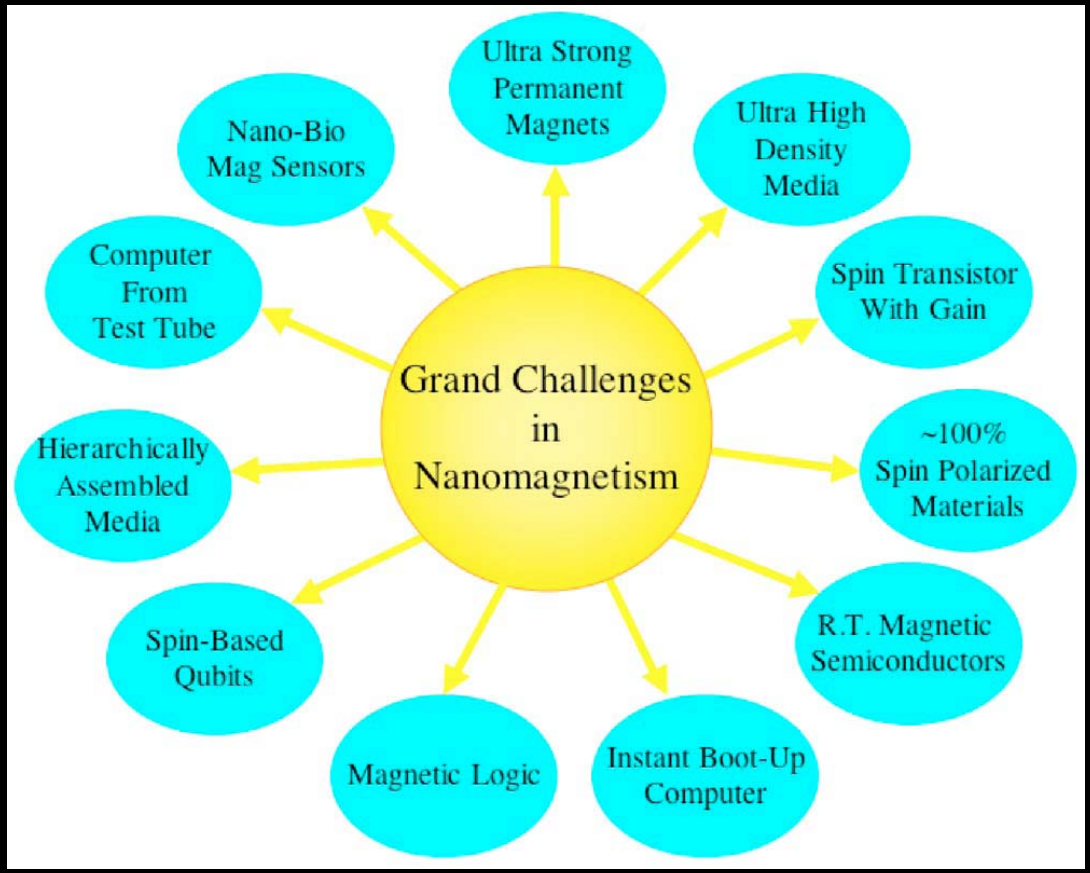






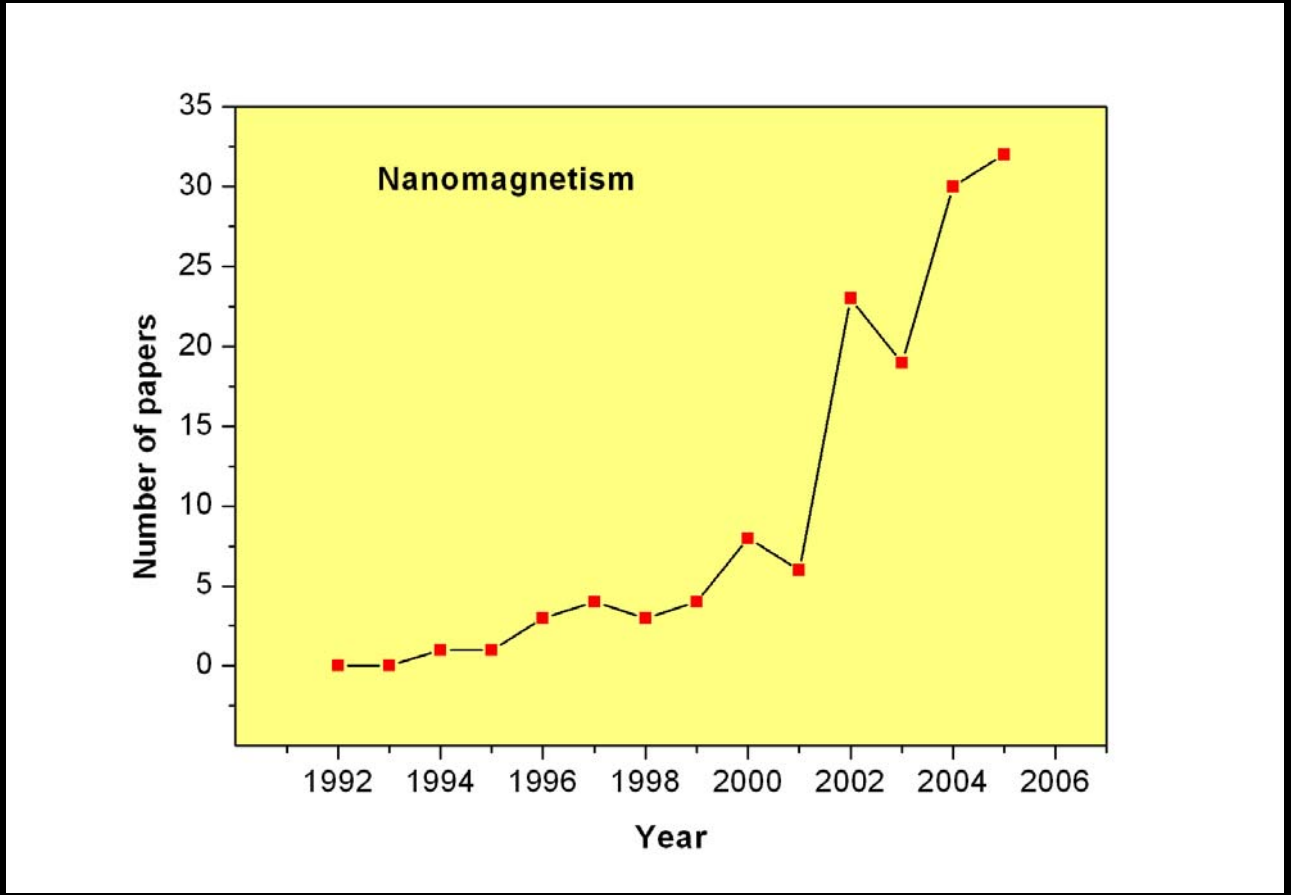


Areas of influence of nanomagnetism



Bader 2005

Nanomagnetism as a research topic ?



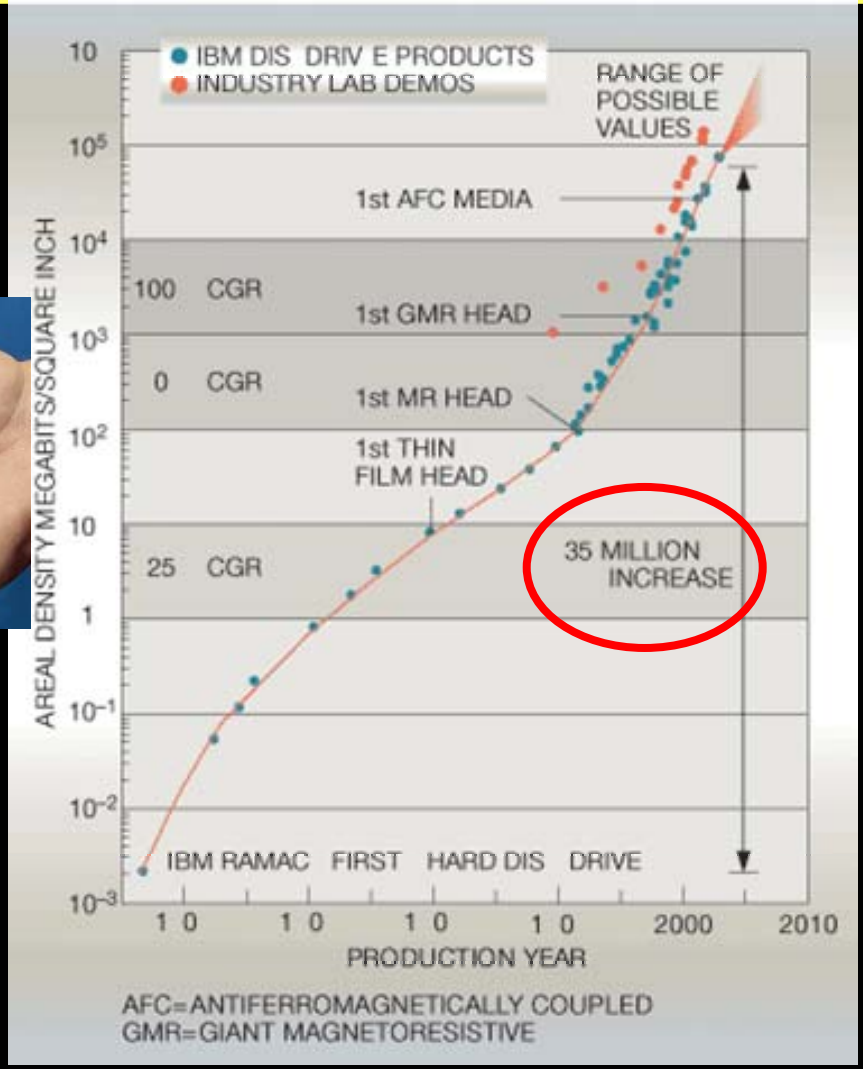
Web of Science (ISI)

Evolution of magnetic recording





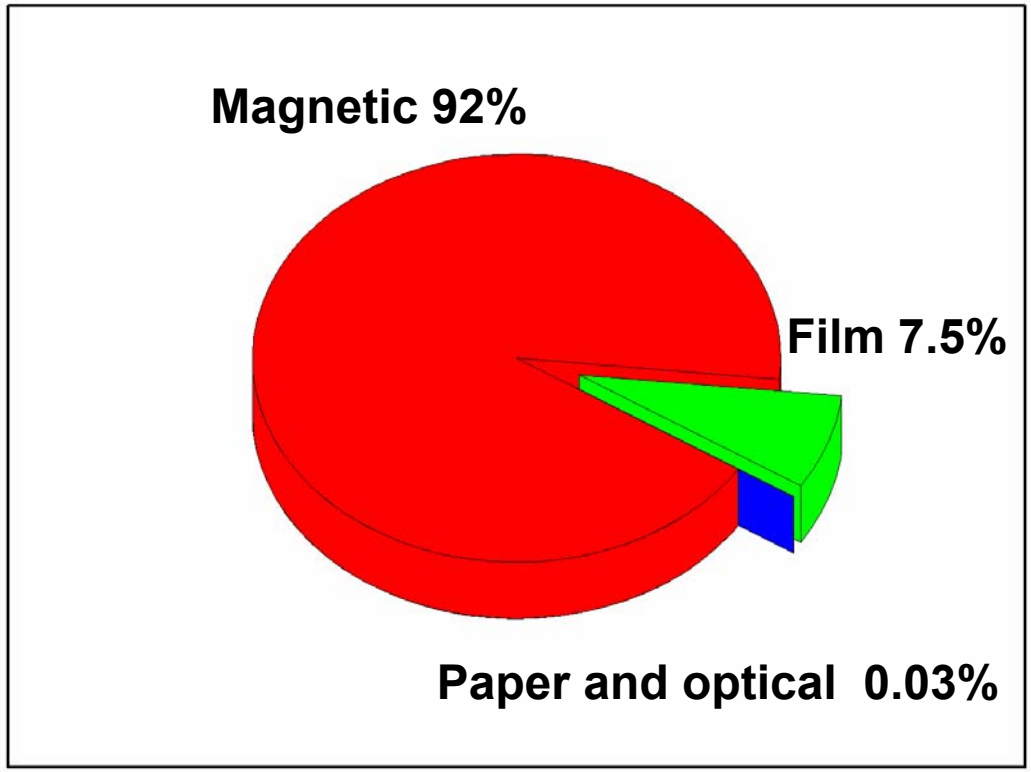
Three generations of magnetic hard disks



Areal density evolution

IBM

The importance of magnetic recording



About 10 exabytes=10^{19} bytes

Proportion of data stored under different forms in 2003 (UCBerkeley 2004)

Spin diffusion lengths: examples

	Co	$Ni_{80}Fe_{20}$	Cu
l_{ds}	5,5 nm	4,6 nm	22,6 nm
l^*_{ds}	0,6 nm	0,6 nm	22,6 nm

l_{ds} : majority spin lengths,

l^*_{ds} minority

Magnetic Particles



Galatea, Salvador Dali 1952

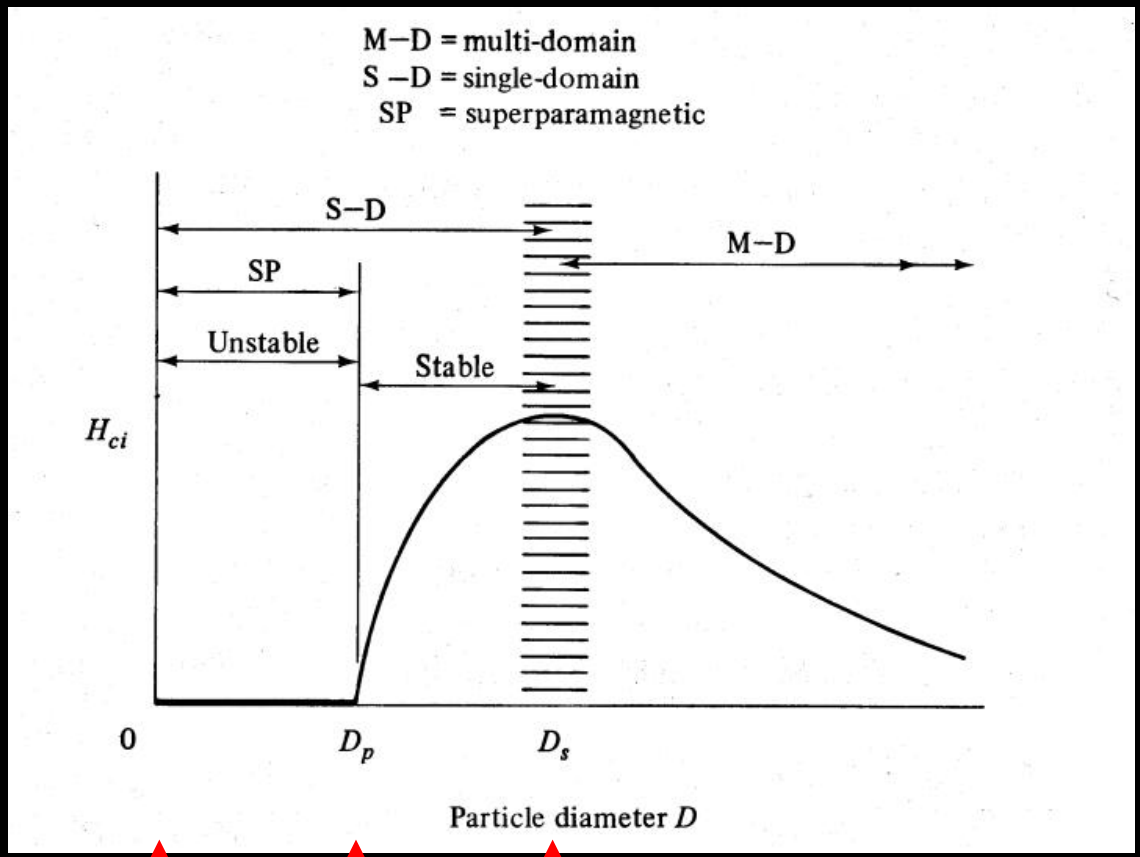
Magnetic behavior of magnetic particles

Three regimes:

a) Superparamagnetic

b) Monodomain FM

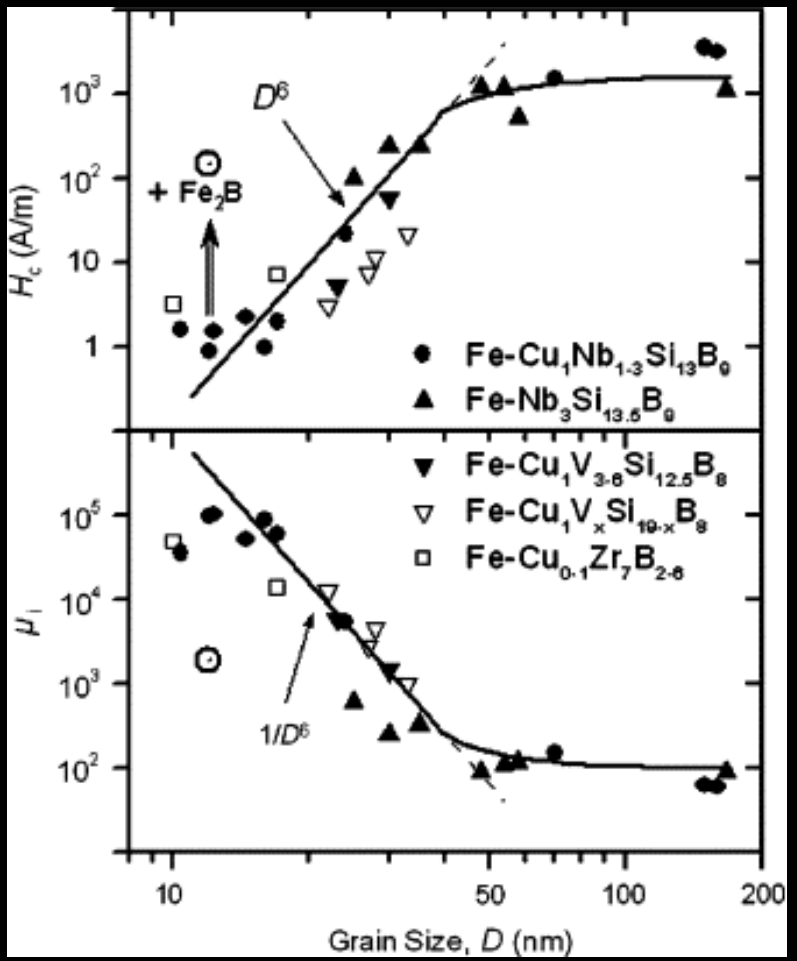
c) Multidomain



Cullity 1972

Example: coercivity and grain size in nanocrystalline Fe alloys

Coercivity and permeability versus grain size in nanocrystalline Fe alloys



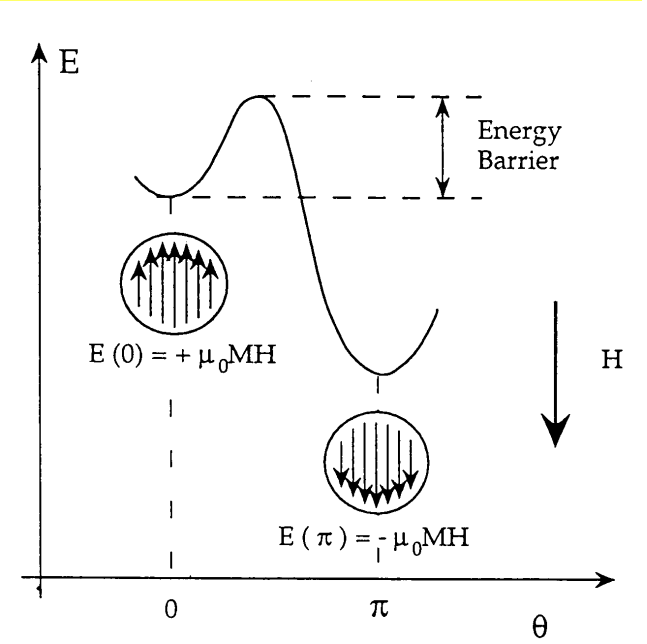
Herzer 2005

Superparamagnetism

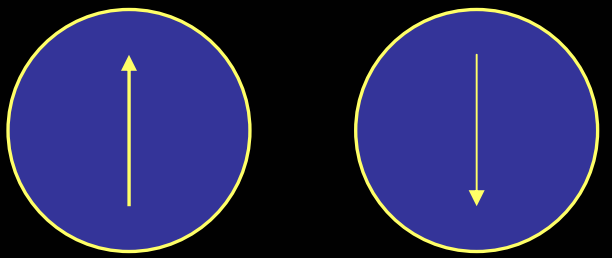
Monodomain particle: anisotropy energy KV $\cos^2\square$

Transition over barrier of height KV is thermally activated

The magnetization of an ensemble of magnetized particles, when field H is set to zero, varies as



$$\frac{dM}{dt} = \frac{1}{\tau_0} M e^{\left(-\frac{KV}{kT}\right)} = \frac{M}{\tau}$$



Cullity 1972

Superparamagnetism: relaxation time □

Relaxation time:

$$\tau = \tau_0 e^{\left(\frac{KV}{kT}\right)}$$

(□ depends exponentially on V and T)

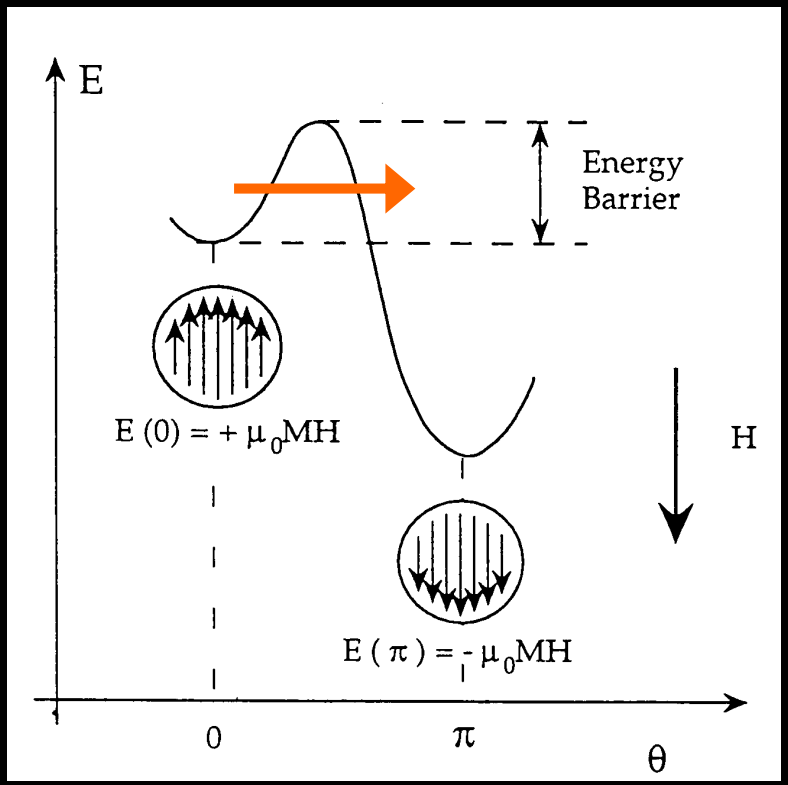
Diameter (nm)	□ (s)
6,8	10^{-1}
9,0	$3{,}2X10^{9}$= 100 years

(Values at room temperature)

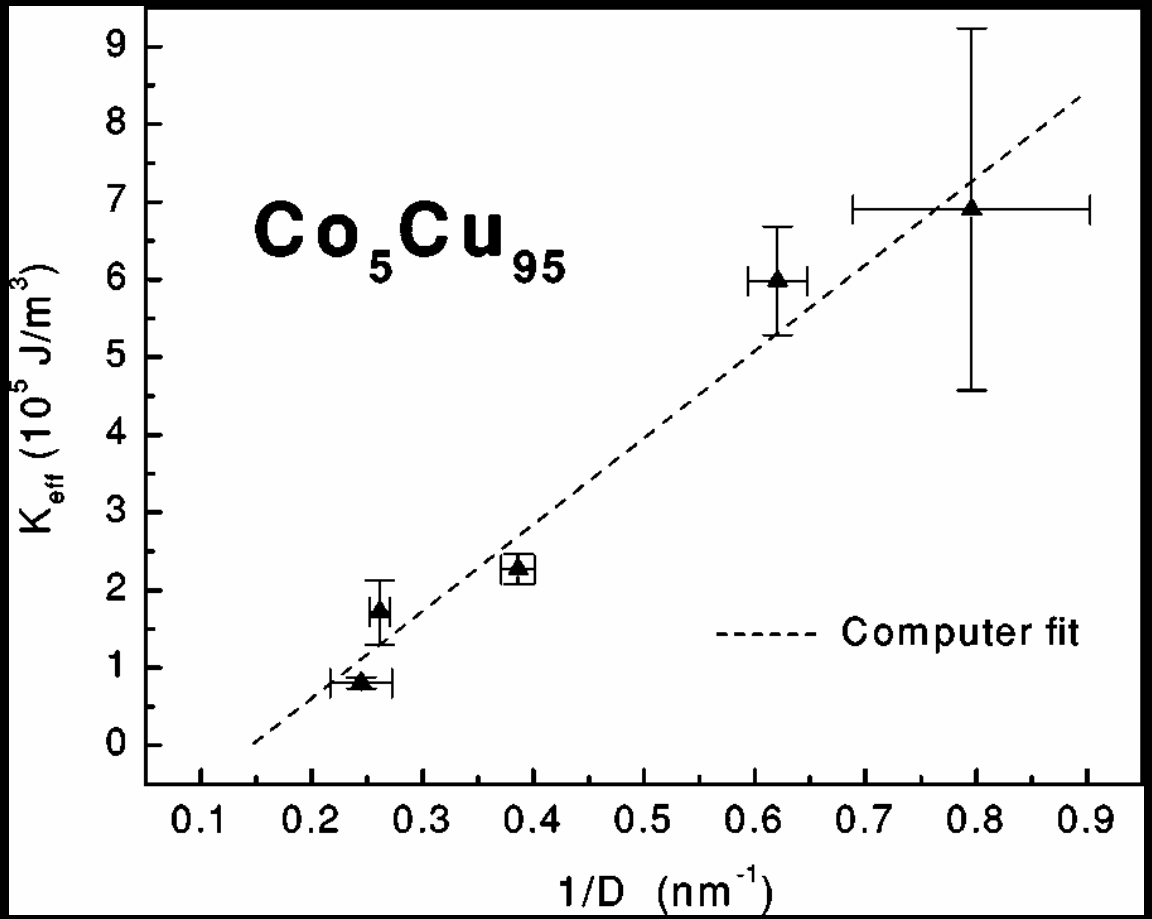
Cullity 1972

Macroscopic quantum tunneling (MQT)

At very low temperatures the particles may invert their magnetization by tunneling, i.e., without thermal assistance.



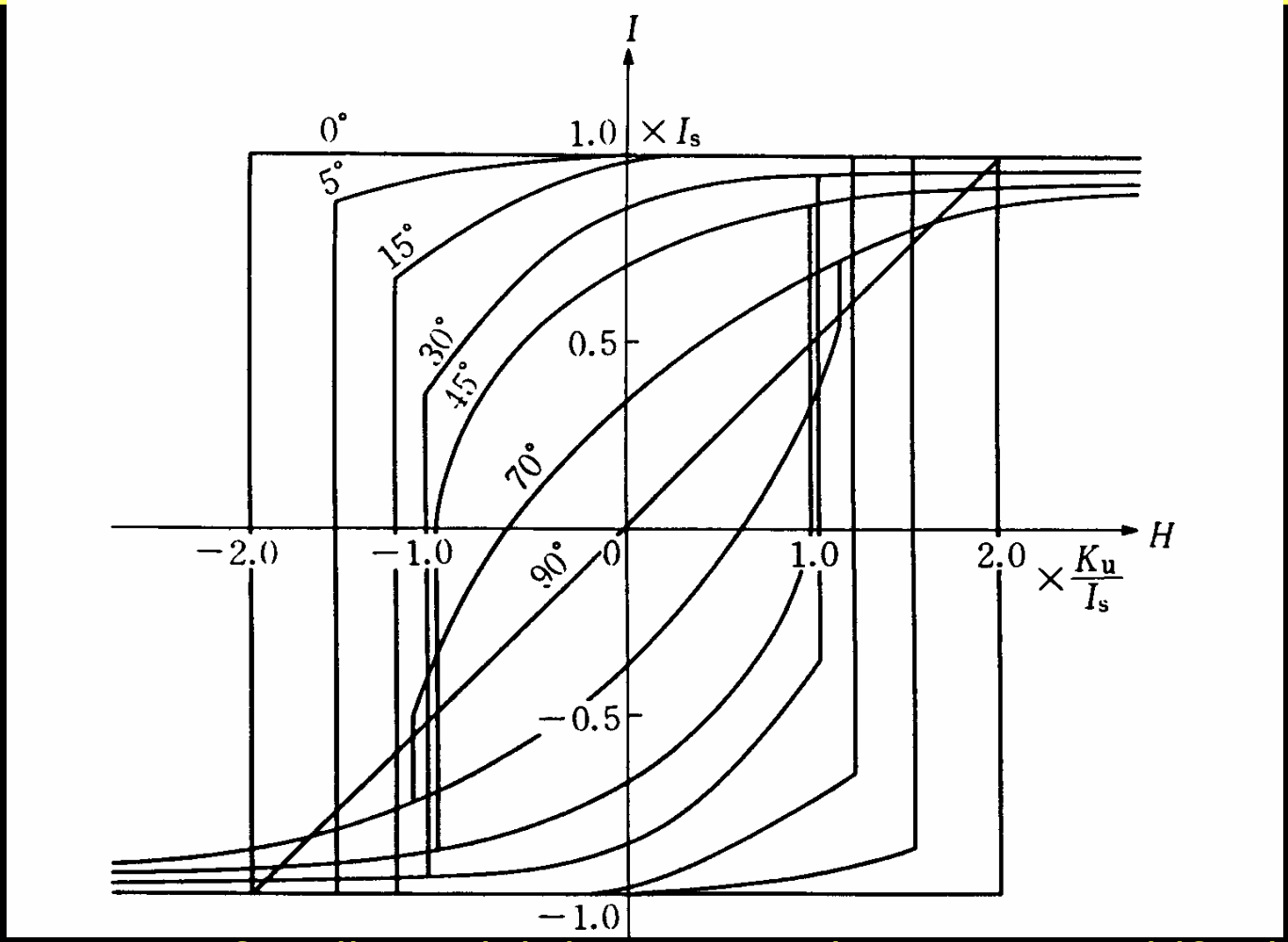
Particle size and anisotropy



A grain of Co of 1.6 nm has 60% of the atoms on the surface!

Pujada 2003

S-W Model: hysteresis

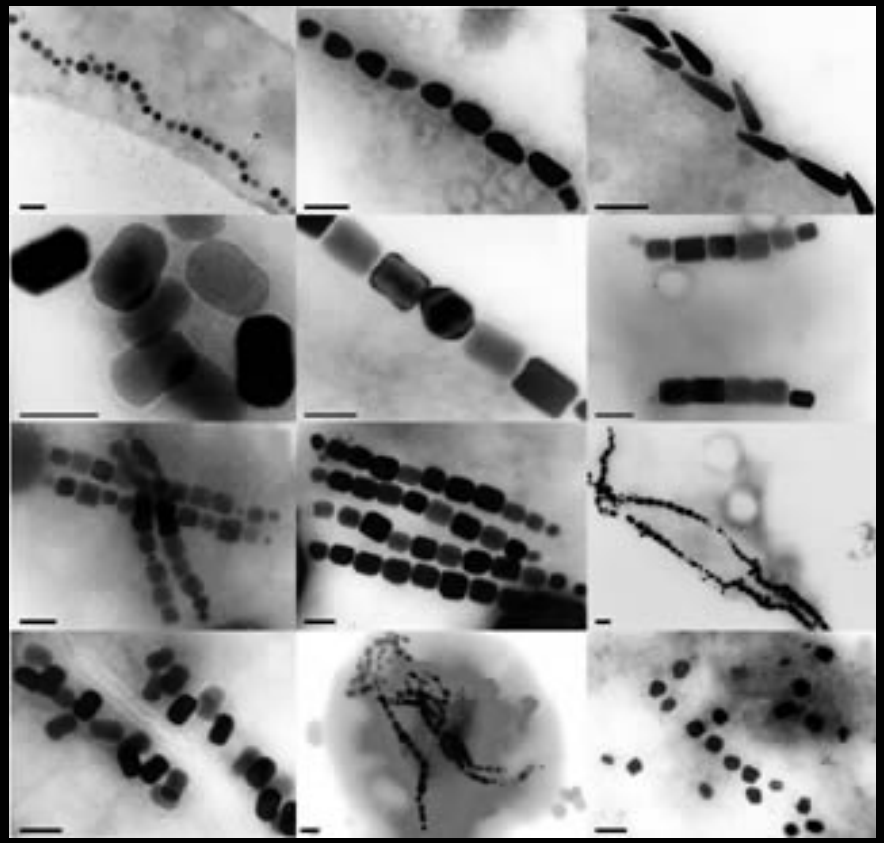


Hysteresis curves for ellipsoidal domains in the Stoner-Wohlfarth model for different directions of H

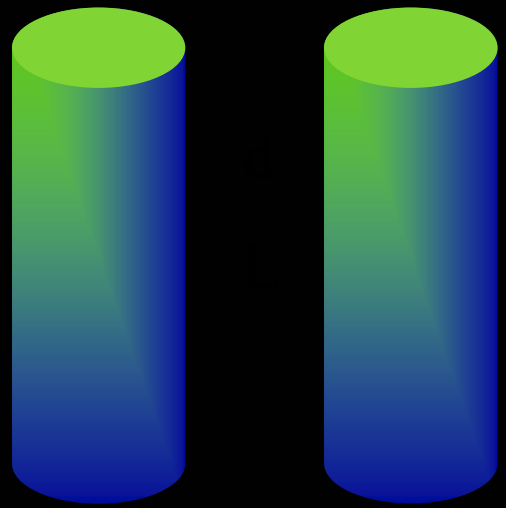
Cullity 1972

Nanomagnets in bacteria

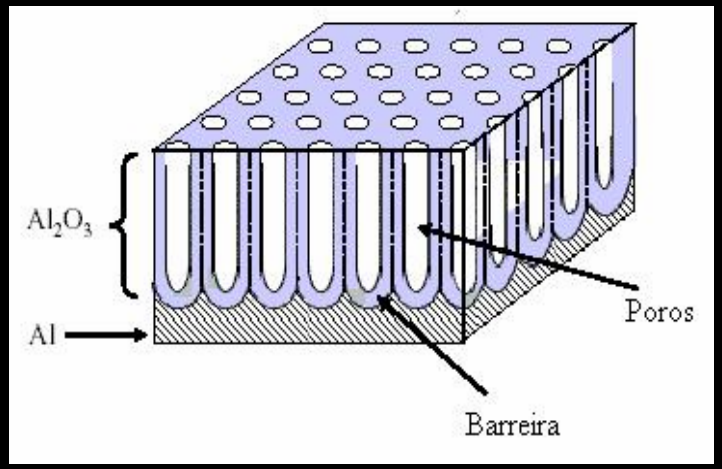
Nanocrystals of magnetic materials were found in many living beings



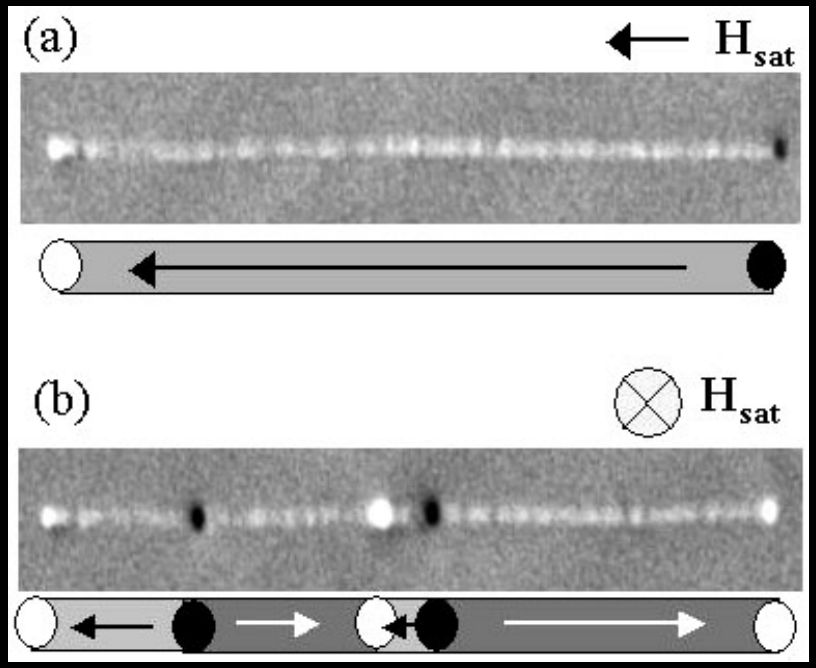
Nanowires, rings, etc



Nanowires I



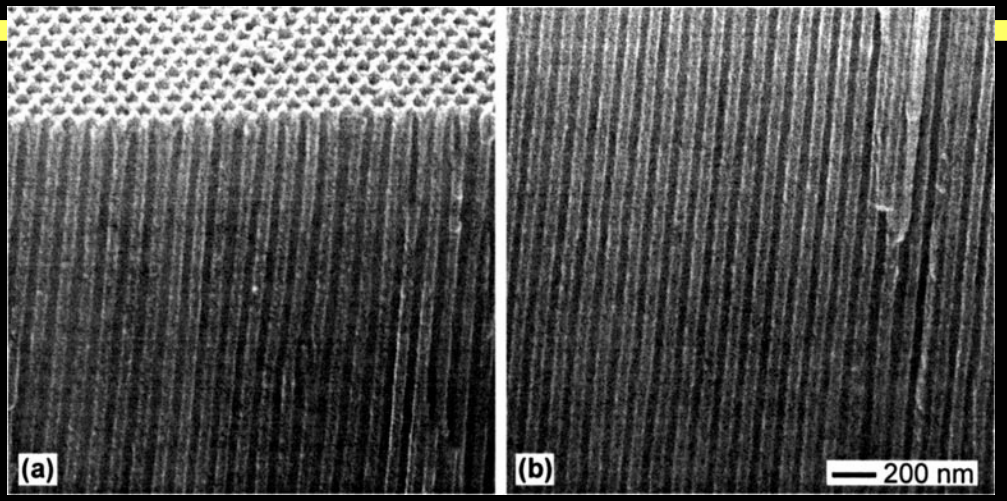
Al_2O_3 porous membrane used for deposition of nanowires.

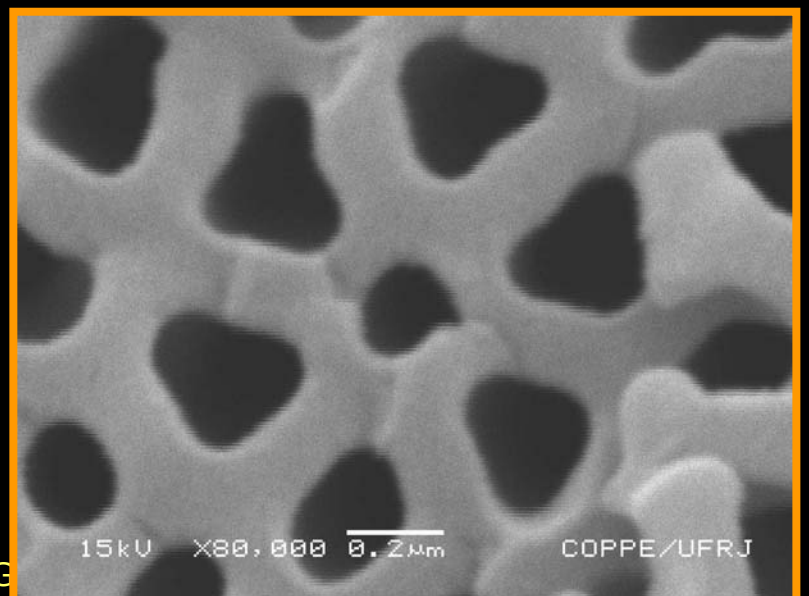


MFM image of a 35 nm diameter Co wire with H a) parallel and b) perpendicular

Dennis 2004

Nanowires II



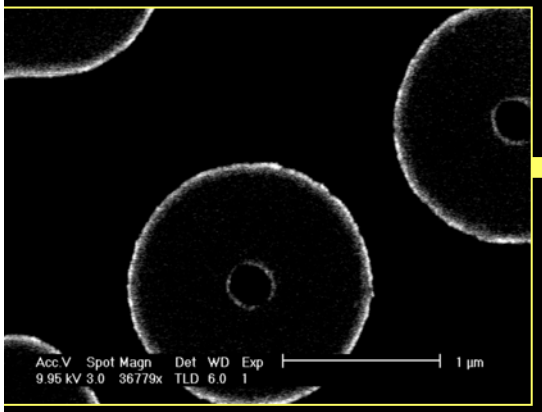


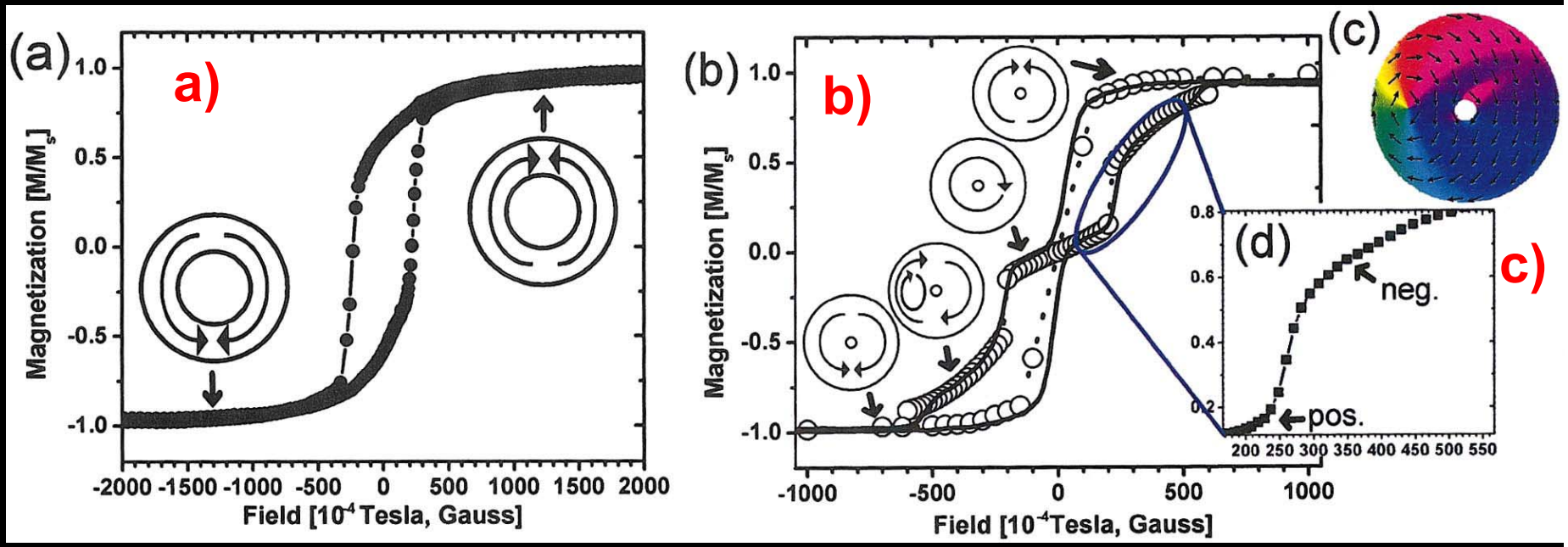
Scanning electron microscope image of an ordered lattice of nanopores

Sellmyer 2001

Caffarena 2005

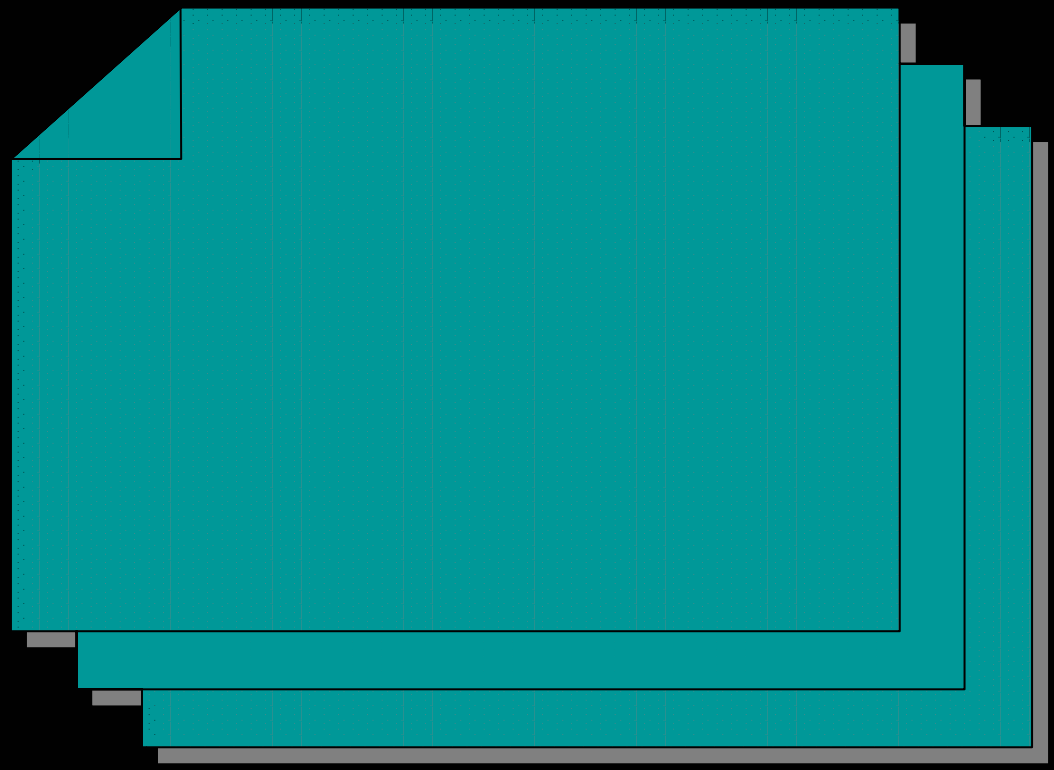
Co rings



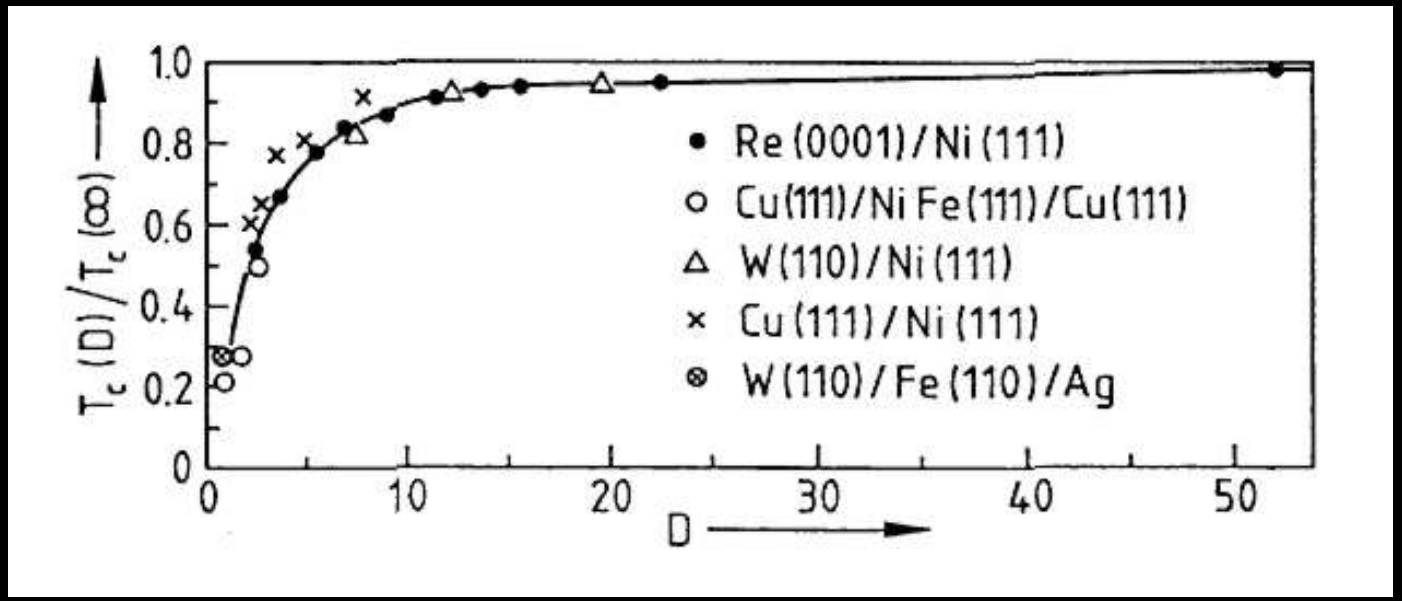


Hysteresis of sub-micron Co rings showing a) two 'onion' states; b) same states and a vortex, and c) computed local magnetizations

Thin Films



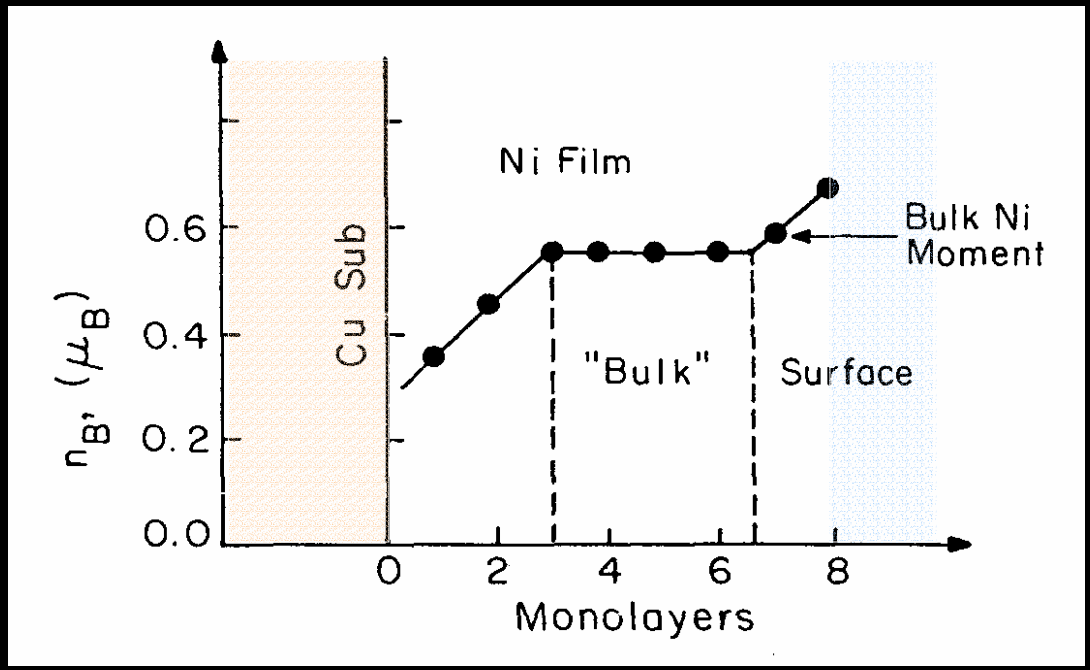
T_C of ultra-fine films



Ratio T_C of ultra-fine films to T_C of the corresponding bulk materials, as a function of thickness (in atomic layers).

Gradmann 1993

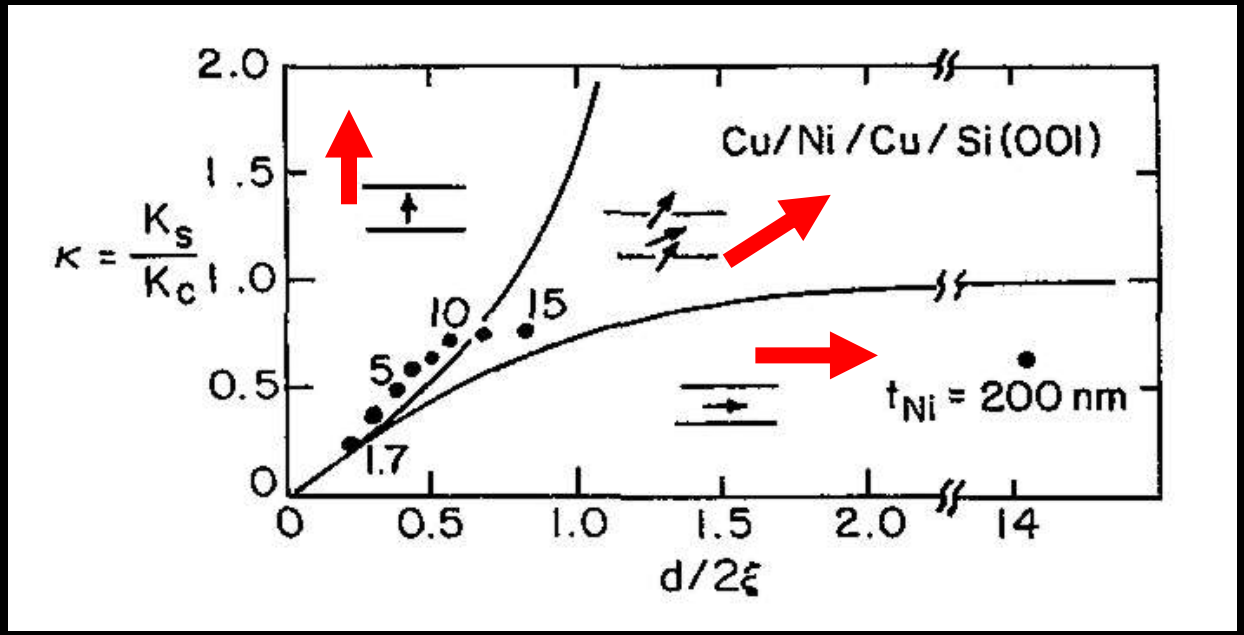
Magnetic moment of ultra-fine films



Computed magnetic moment of Ni atoms in 8 multilayers of metal deposited on Cu

Tersoff and Falicov 1982

Direction of magnetization as a function of thickness



Phase diagram of a film in the graph of surface anisotropy versus thickness (in units of exchange length ξ)

O'Handley 2000

Properties of the surfaces I

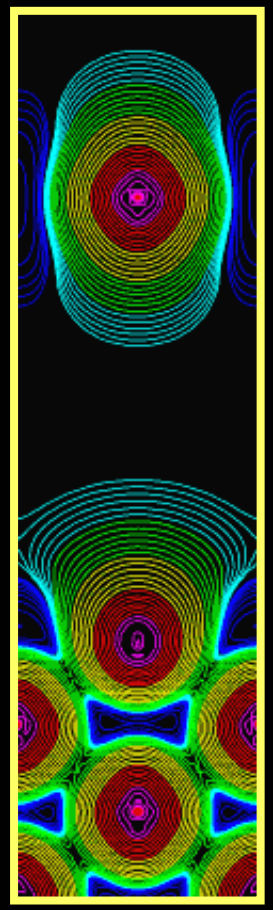
Changes in the neighborhood of the atom:

- Symmetry
- Coordination
- Distances

Consequences

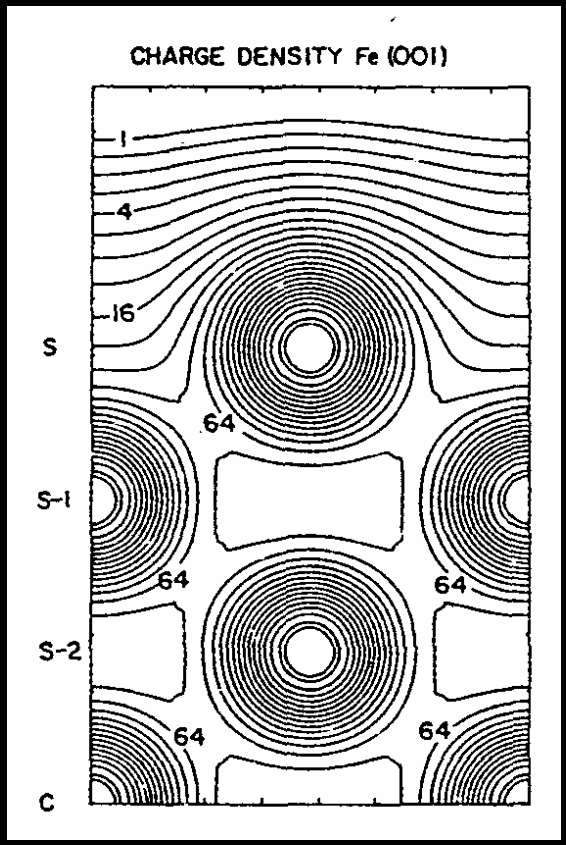
- Change in electronic structure
- Change in T_C
- Change in magnetic moment
- Change in anisotropy, etc.

Properties of the surfaces II



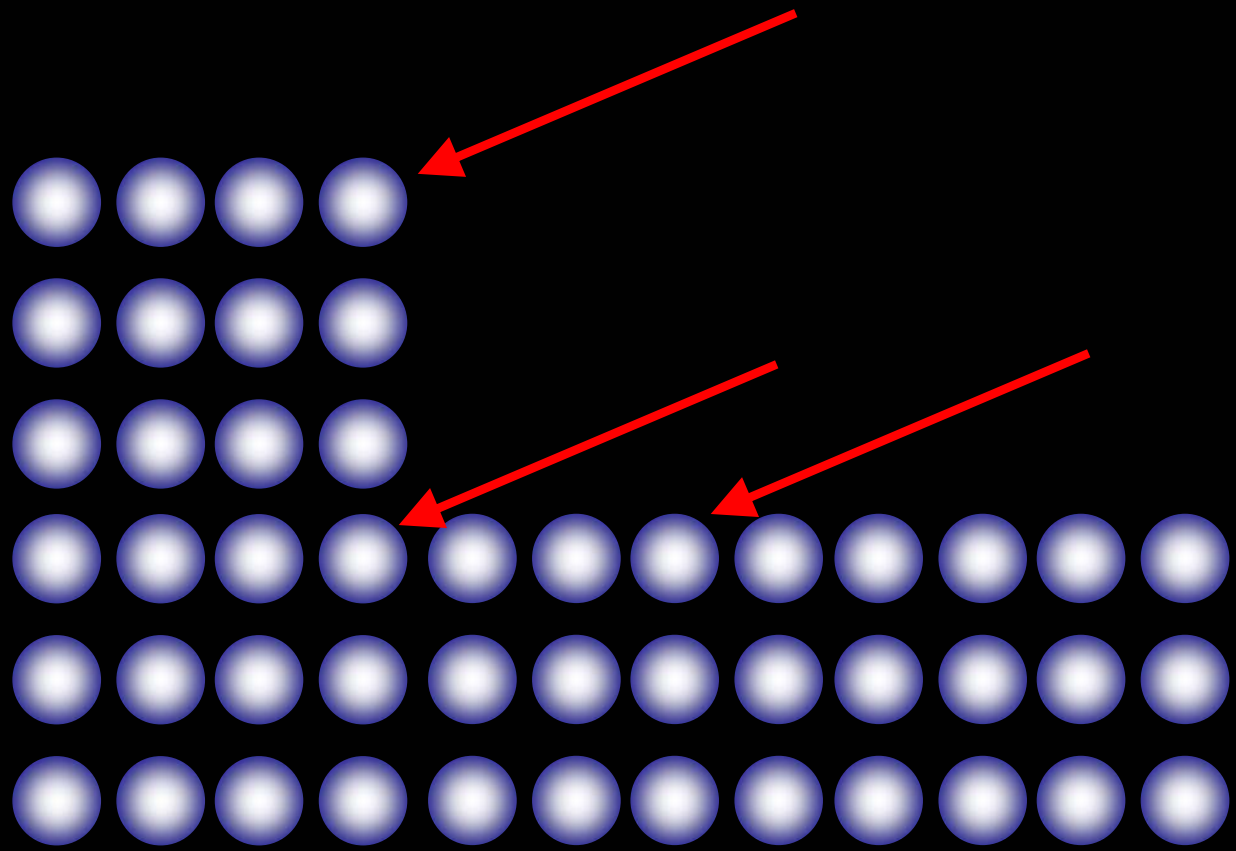
Spin density at Fe monolayer

Spin density at Fe surface (Blue indicates negative spin density) (Freeman)

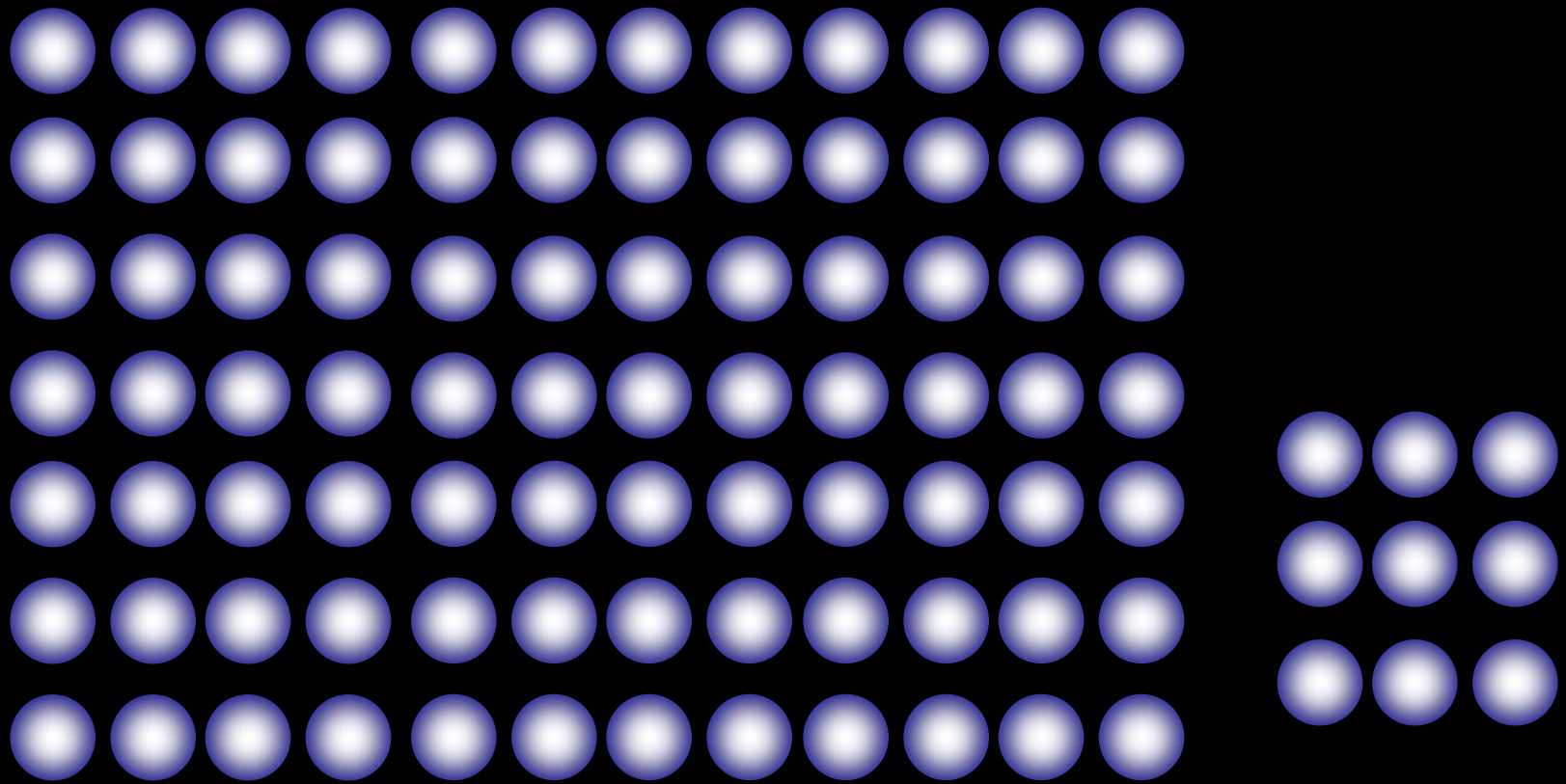


Computed charge density at Fe(001) surface (Ornishi et al. 1983)

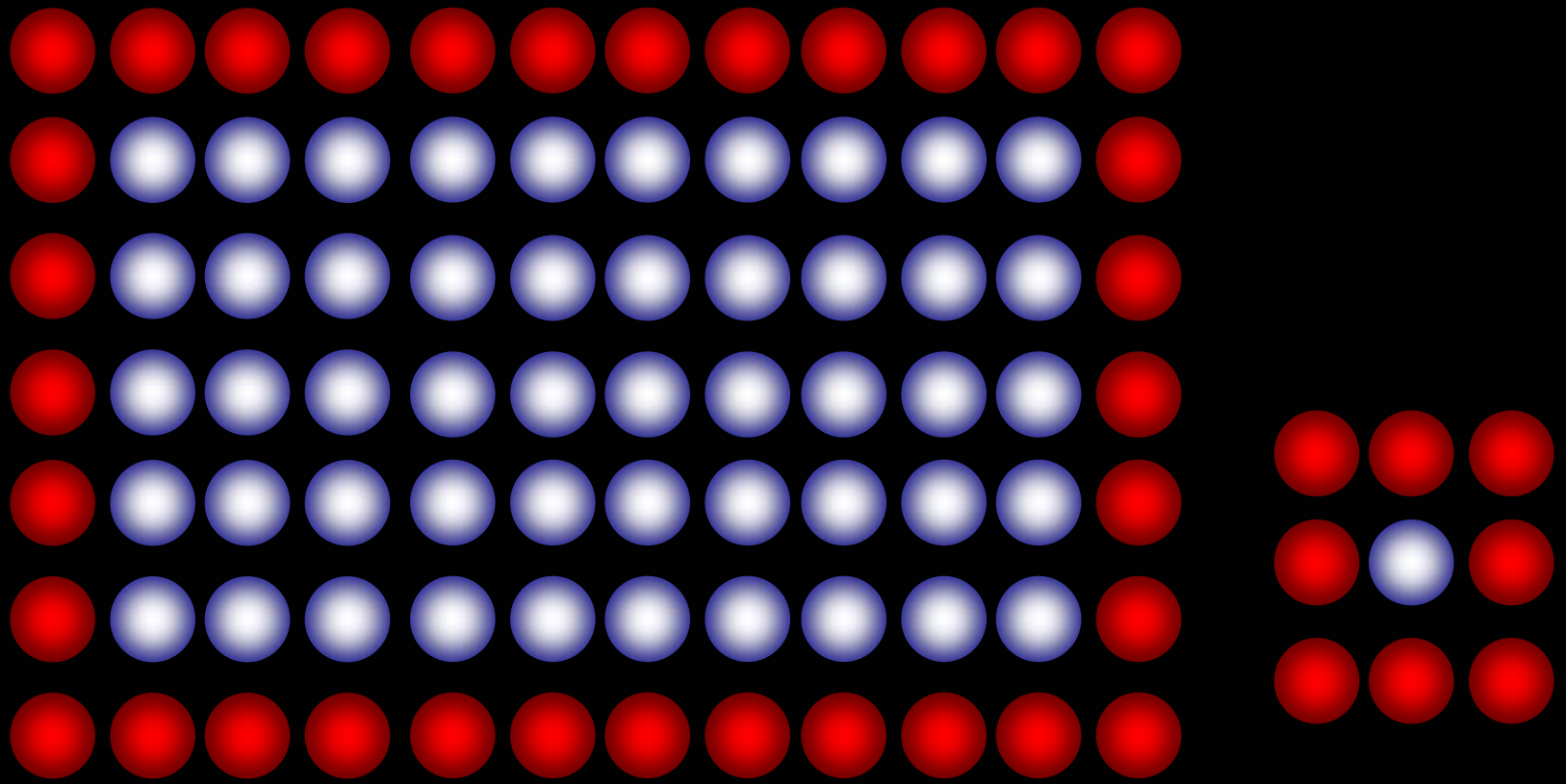
Differences in coordination (2D)



Proportion of surface atoms



Proportion of surface atoms



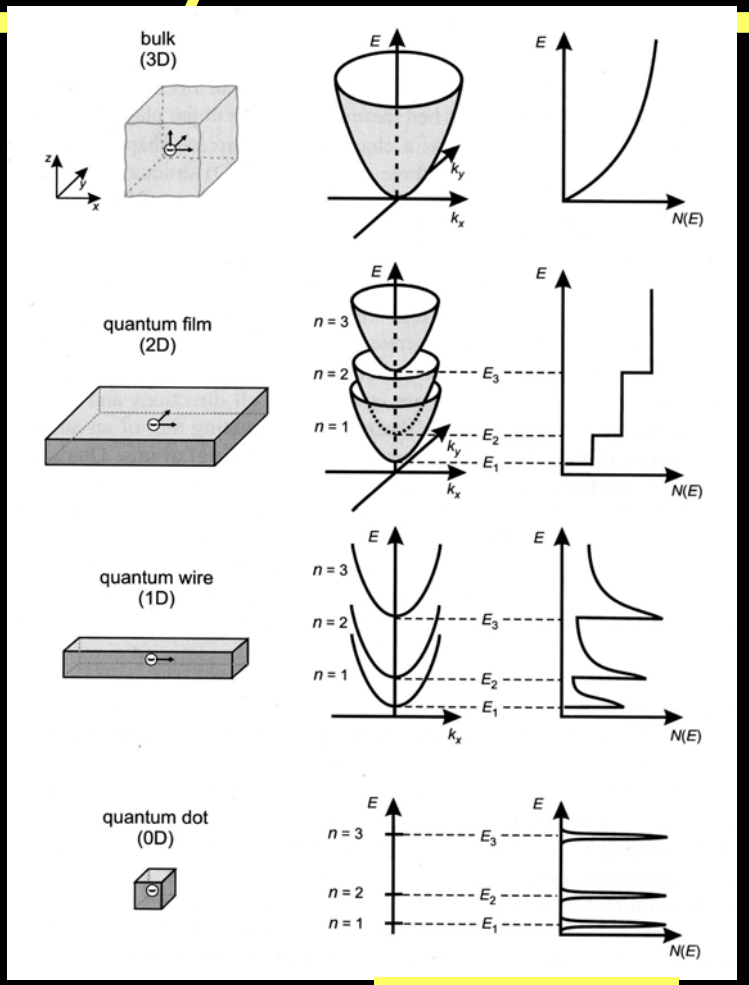
A grain of Co of 1.6 nm has 60% of the atoms on the surface.

Density of states and dimensionality

a. Dispersion relation E(k)

b. Density of electronic states (DOS) as a function of energy N(E) in 1, 2, and 3 dimensions

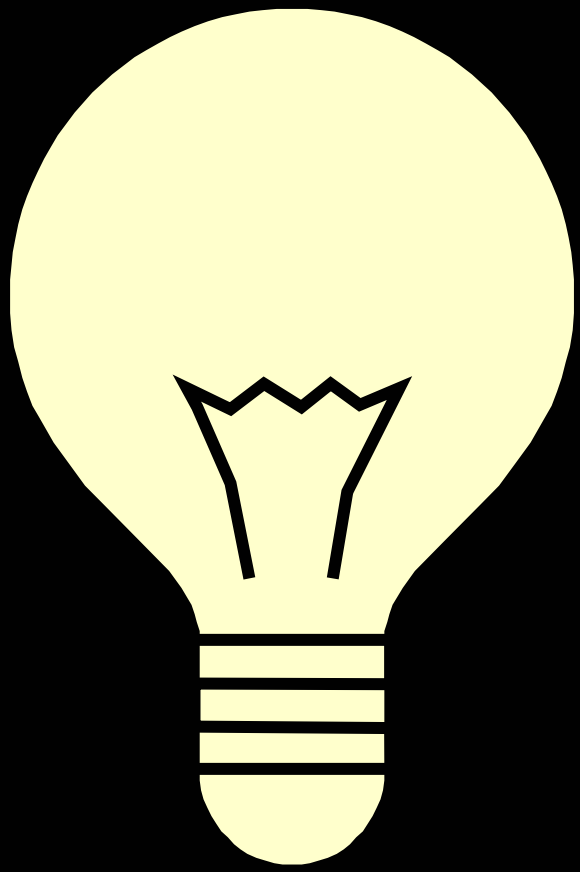
Relevance of DOS: Pauli susceptibility, electronic specific heat, etc.



a. b.

Borisenko and Ossicini 2004

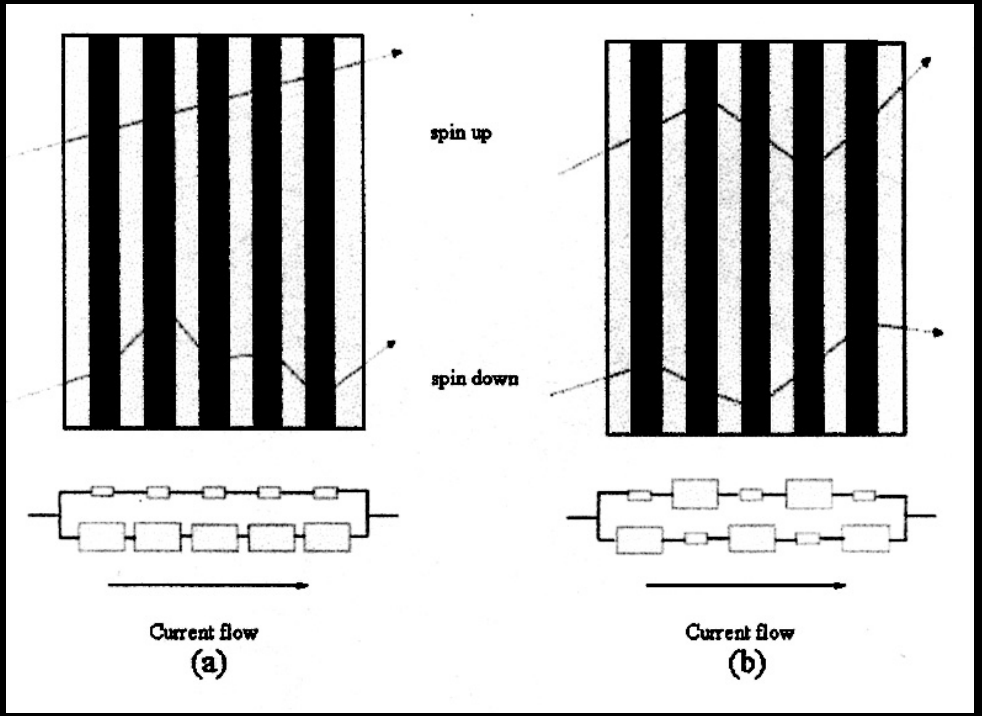
New phenomena



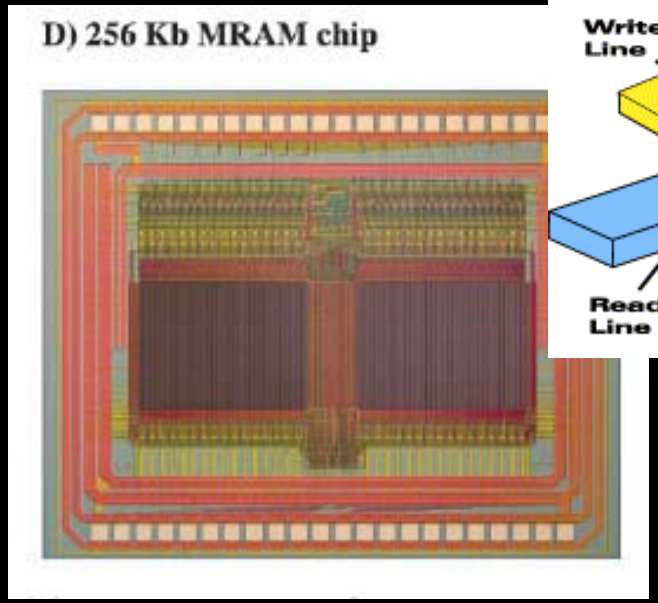
Spin dependent resistance and giant magnetoresistance (GMR)

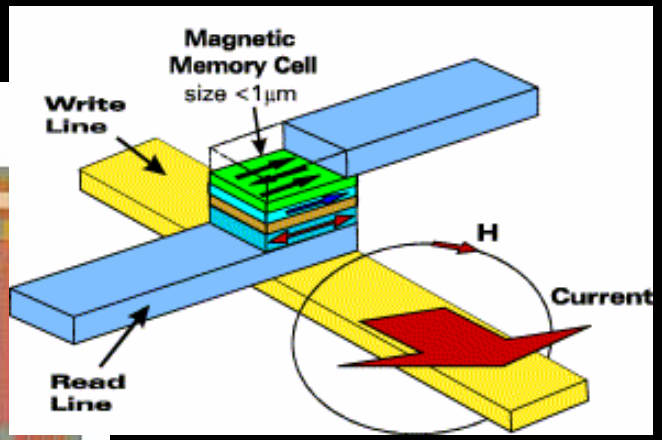
The electrical resistance depends on the relative orientation of electron spin and magnetization of the layer

Applying a field to change from antiparallel to parallel magnetization changes the resistance

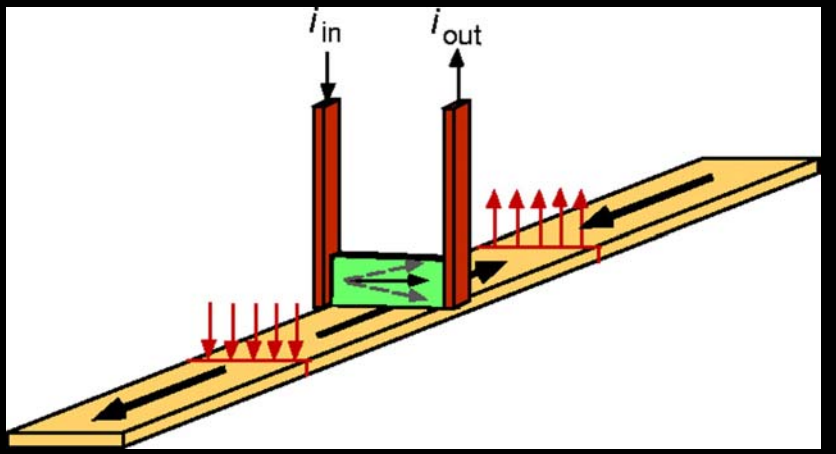


Applications of GMR





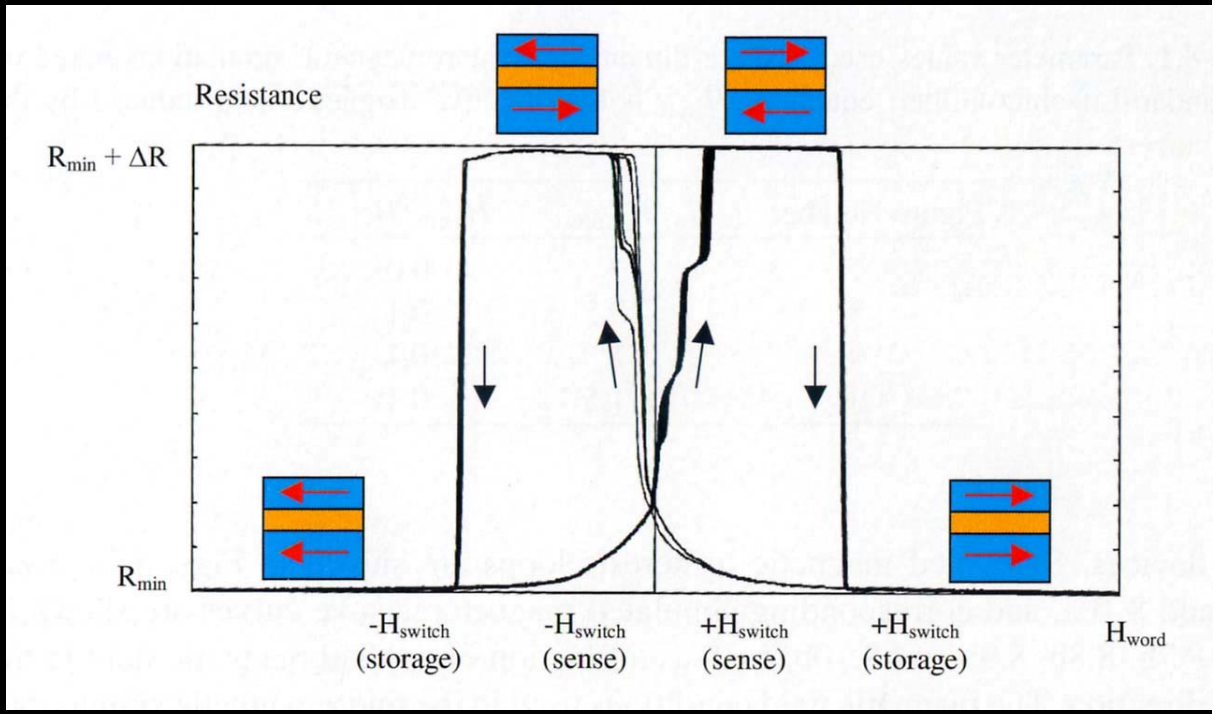
Magnetic random access memory (MRAM) using a tunnel junction (Wolf 2001)

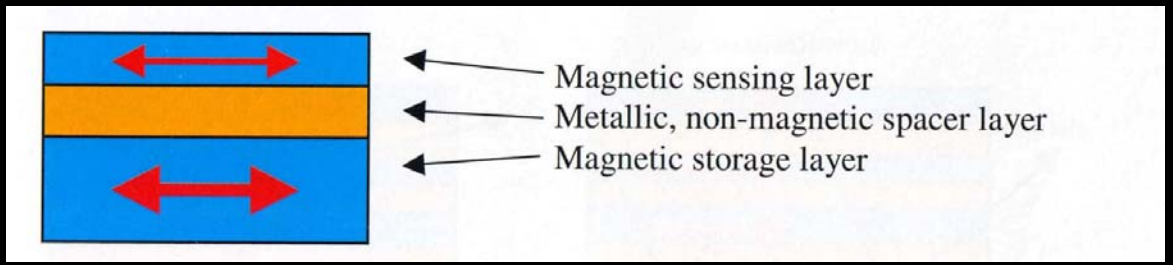


Reading head using GMR (Prinz 1998)

Application of GMR: Pseudo Spin Valve

Resistance vs. magnetic field

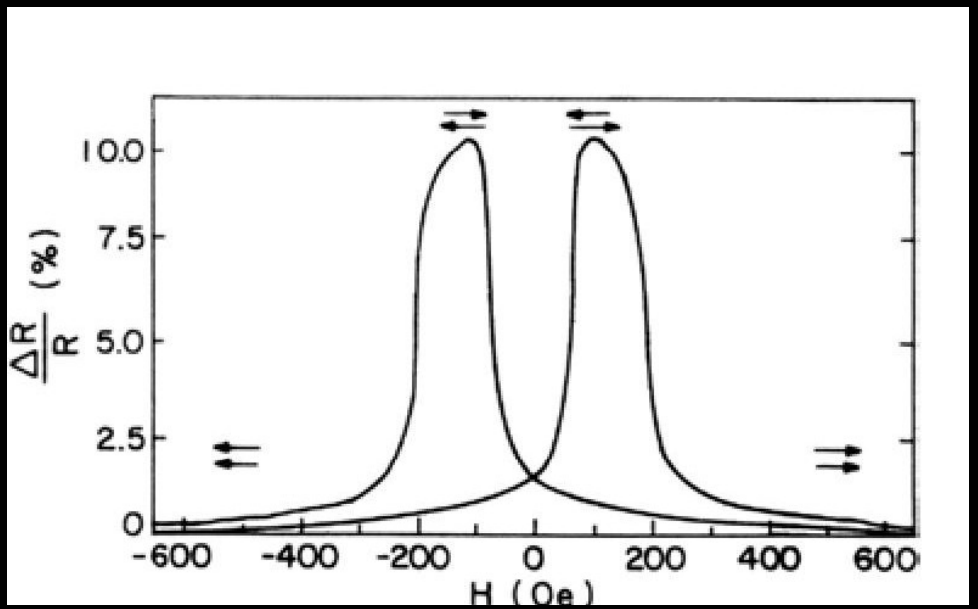




Scheme of a Pseudo Spin Valve

Katti 2005

Tunnel magnetoresistance (TMR)



Magnetoresistance of a tunnel junction (FM-insulator-FM)

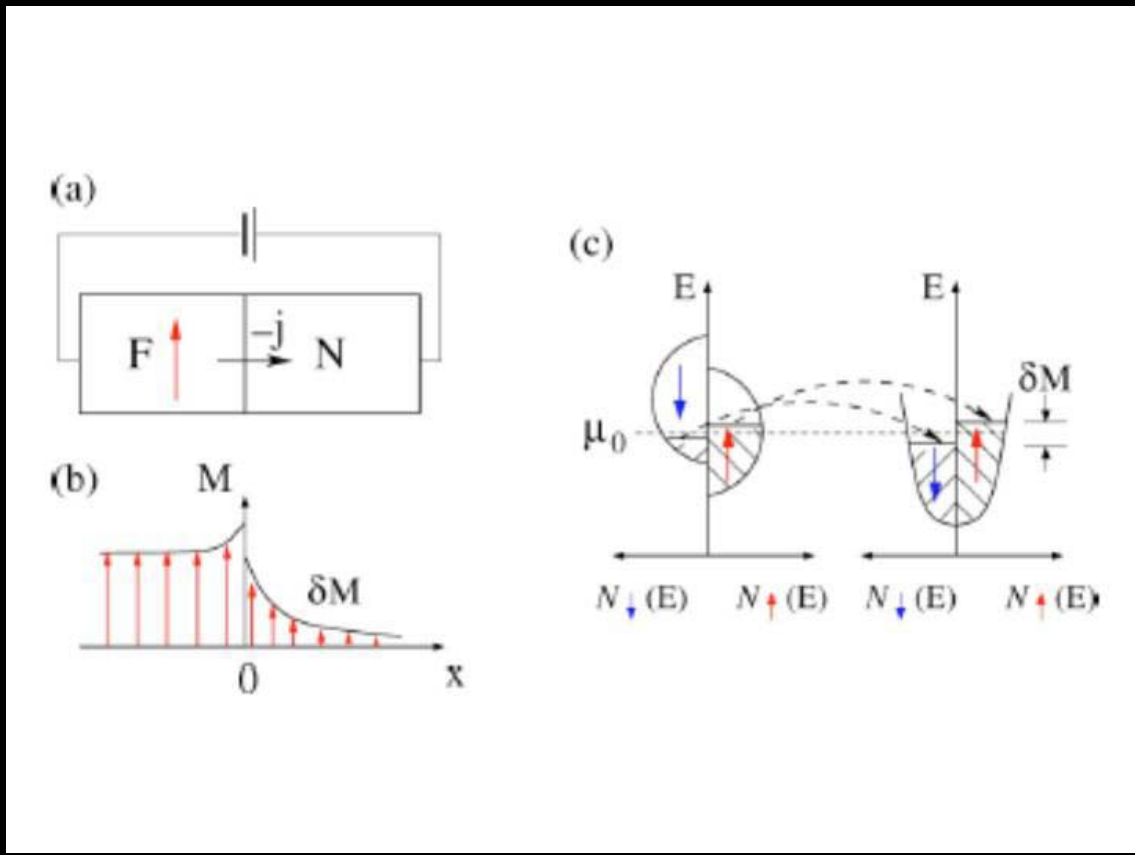
Spin injection

Spin injection from a ferromagnetic metal (FM) into a nonmagnetic metal (N).

a) Geometry of the device

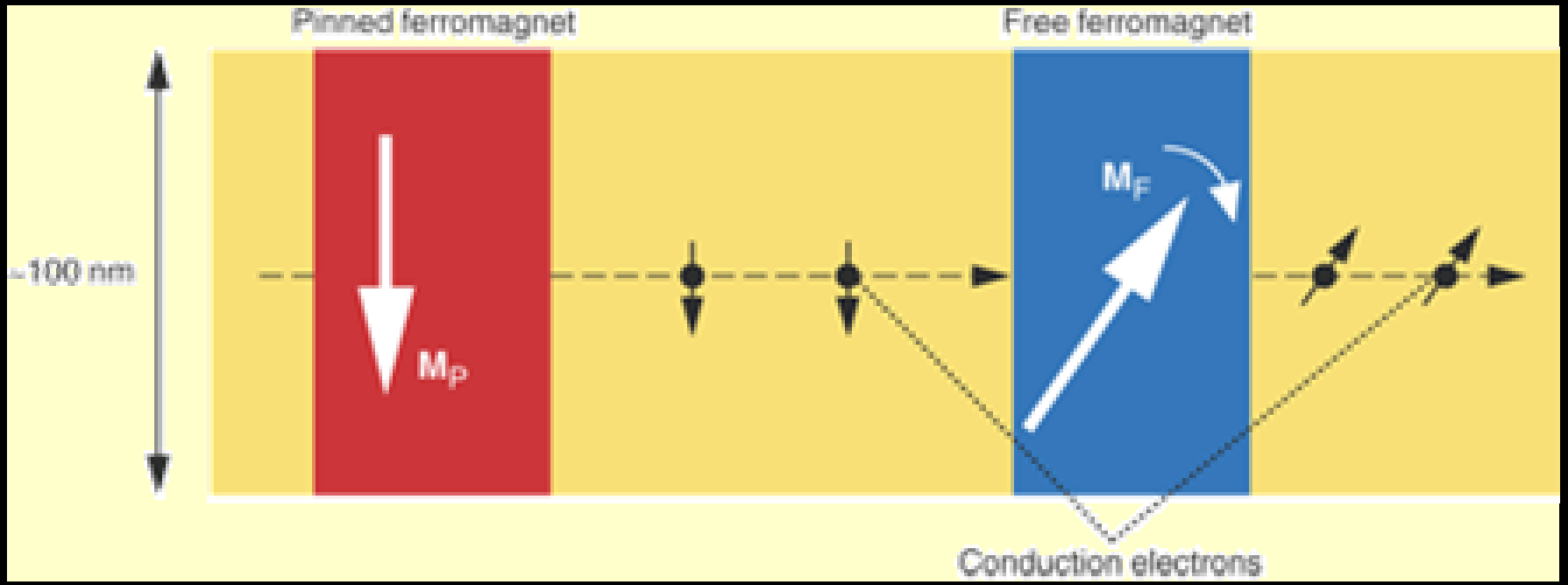
b) Distribution of magnetization

c) Conduction band scheme



Zutic (2004)

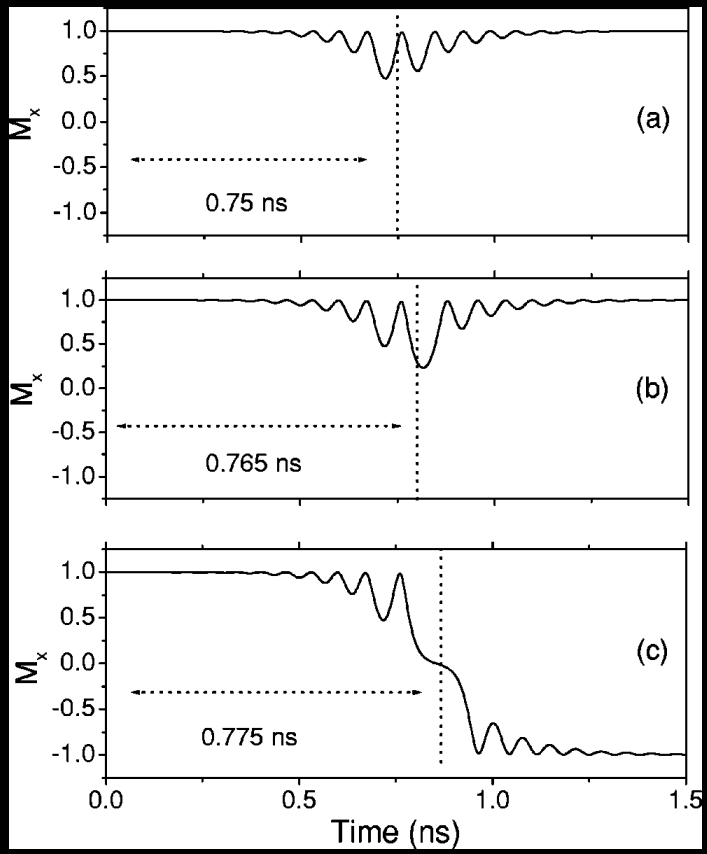
Spin torque I



Spin polarized current turns the magnetization of a layer; above a certain critical current (or duration) the magnetization is inverted

Krivorotov in Sciencemag 14/01/2005

Spin torque II



Transverse magnetization M_x versus pulse duration, showing the magnetization reversal.

In conclusion…

Origin of nanomagnetic behavior

Dimensions comparable to characteristic lengths

Break in translation symmetry

Reduced coordination number

Higher proportion of surface atoms

Change in electronic density of states

Anisotropy energy ~ kT

Some consequences

Increase in overall anisotropy

In metals, narrower band

Lower T_C

Higher magnetic moment

Other (higher reactivity, etc)

New phenomena

Giant magnetoresistance

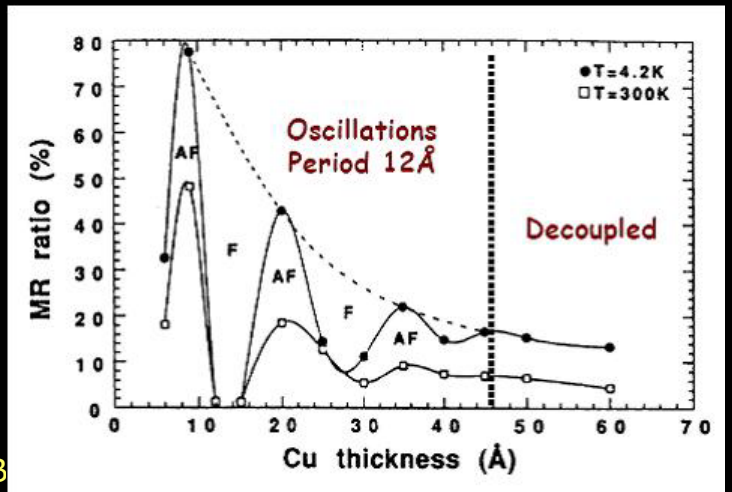
Tunnel magnetoresistance

Spin injection

Spin torque

Exchange bias, Spin Hall effect, etc

Obrigado!


MR ratio (%)
Cu thickness (Å)
●T=4.2K
□T=300K
Oscillations
Period 12Å
Decoupled
AF
F
AF
F
AF

Exchange bias

