Magnetic thin films and multilayers

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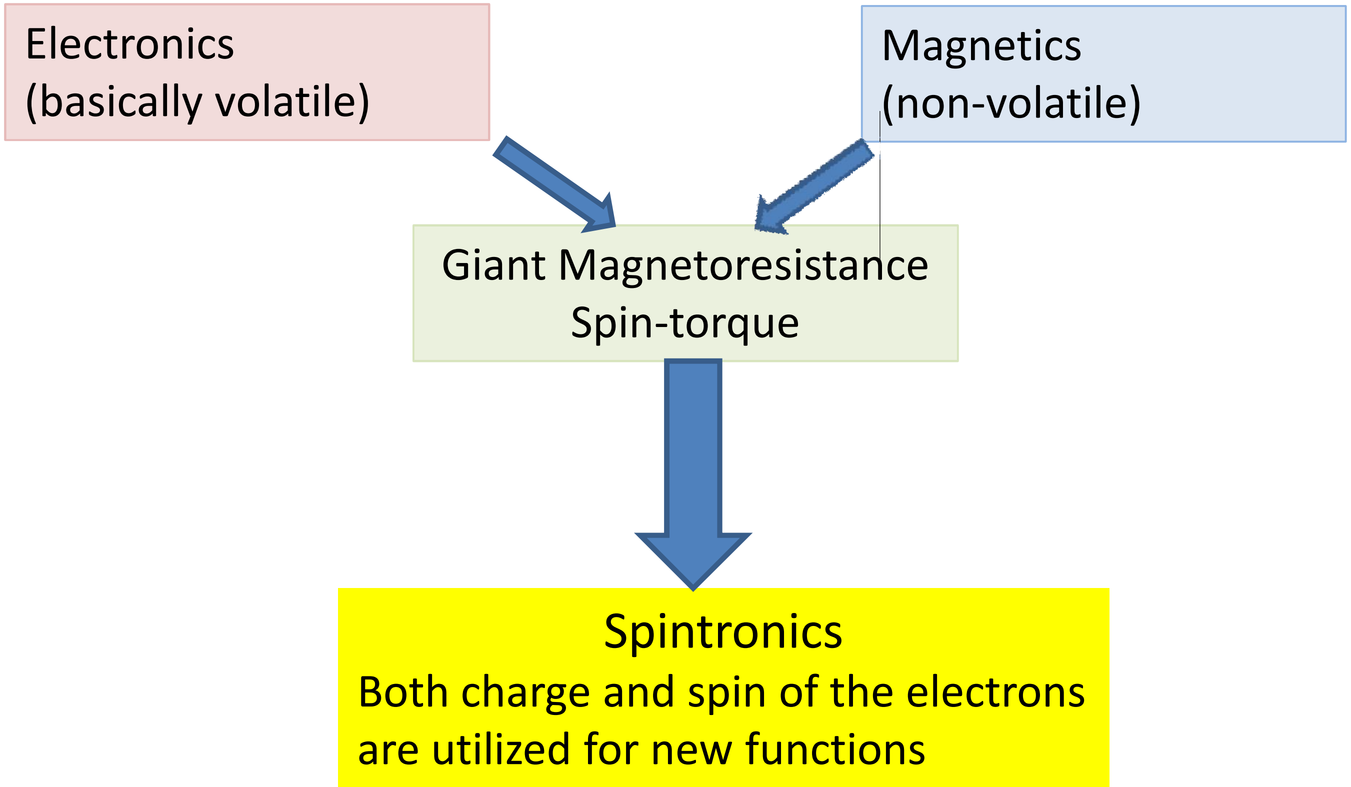
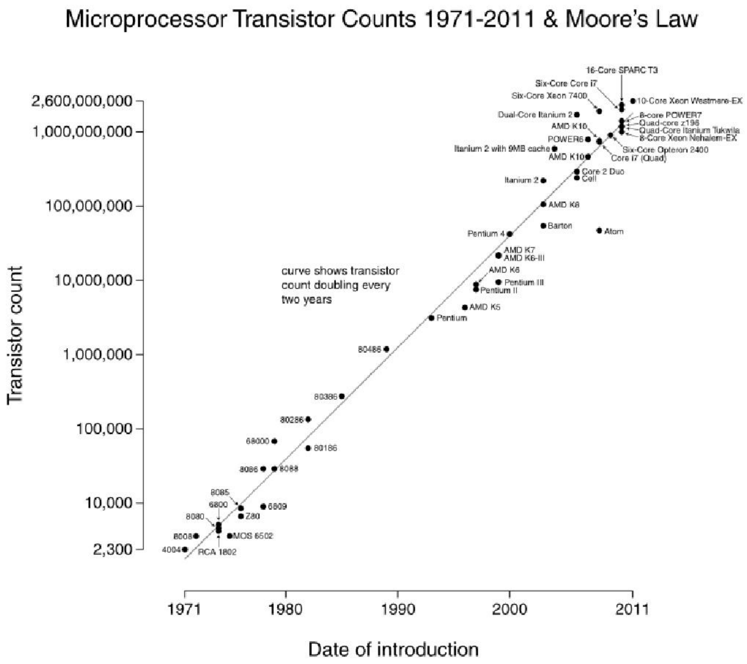
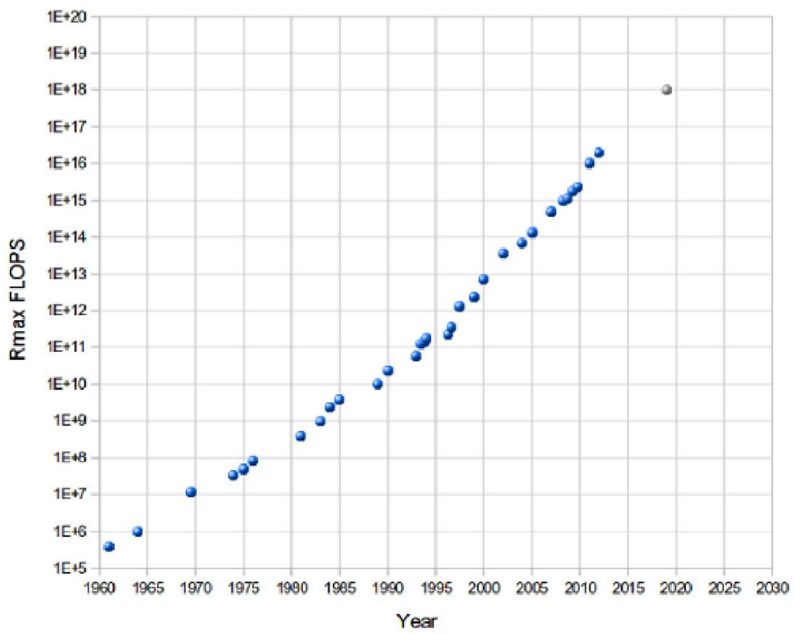

Electronics
(basically volatile)
Magnetics
(non-volatile)
Giant Magnetoresistance
Spin-torque
Spintronics
Both charge and spin of the electrons
are utilized for new functions

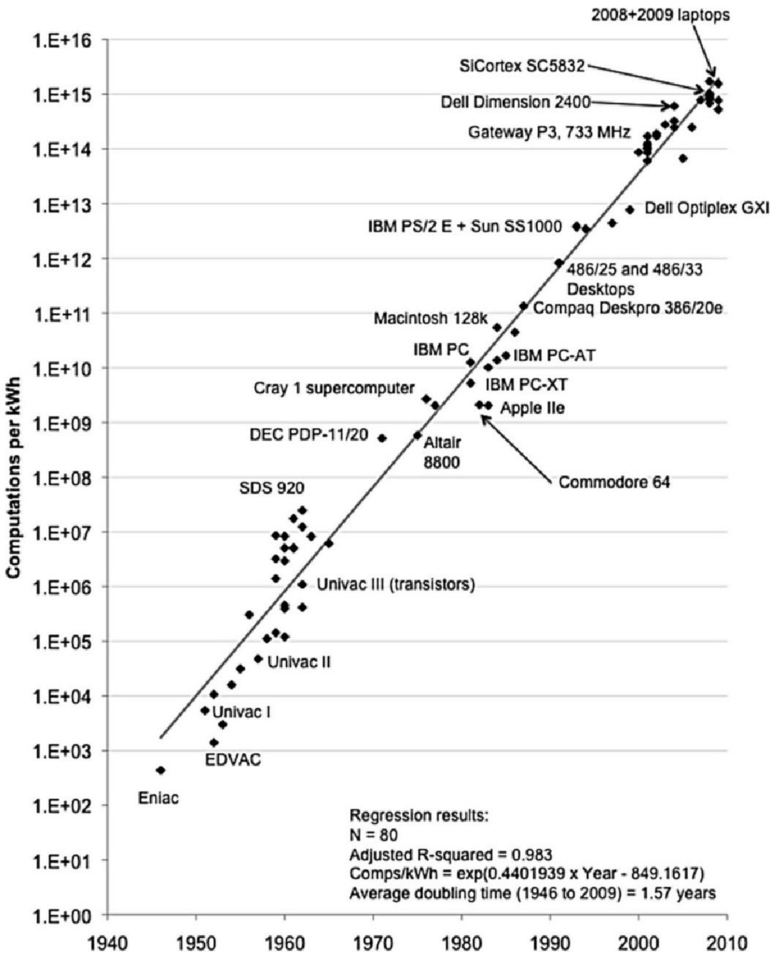
Moor’s Law:



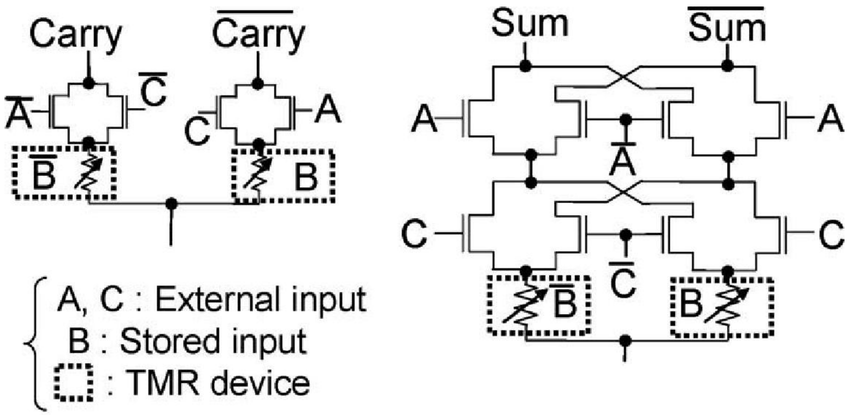


22nm technology

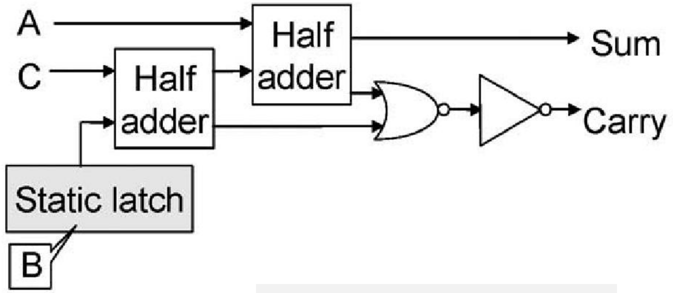
SRAM cell size is 0.092 μm^2


2008+2009 laptops
SiCortex SC5832
Dell Dimension 2400
Gateway P3, 733 MHz
Dell Optiplex GXI
IBM PS/2 E + Sun SS1000
486/25 and 486/33 Desktops
Compaq Deskpro 386/20e
Macintosh 128k
IBM PC
IBM PC-AT
IBM PC-XT
Cray 1 supercomputer
Apple IIe
DEC PDP-11/20
Altair 8800
Commodore 64
SDS 920
Univac III (transistors)
Univac II
Univac I
EDVAC
Eniac
Regression results:
N = 80
Adjusted R-squared = 0.983
Comps/kWh = exp(0.4401939 x Year - 849.1617)
Average doubling time (1946 to 2009) = 1.57 years
Computations per kWh
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
1.E+08
1.E+09
1.E+10
1.E+11
1.E+12
1.E+13
1.E+14
1.E+15
1.E+16
1940
1950
1960
1970
1980
1990
2000
2010

Koomey's Law



TMR-based full adder

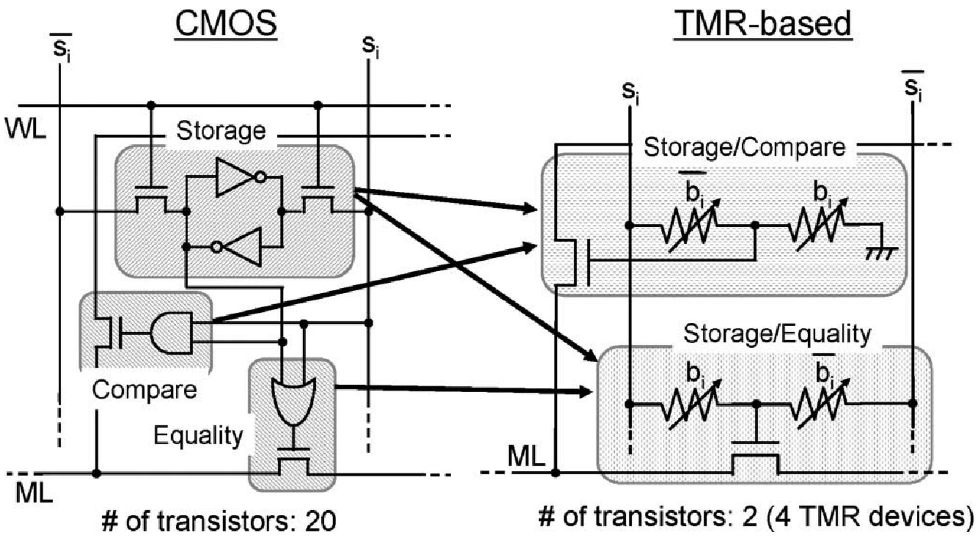


CMOS full adder

COMPARISON OF FULL ADDERS

	CMOS	TMR-based
Delay	310ps	310ps
Device counts	40Tr.	24Tr.+2C
Dynamic power	51μW	16μW
Static power	55nW	0.084nW

(0.18μm TMR/CMOS, V_{DD}=1.8V)



COMPARISON OF 16-b-WORD CAMS

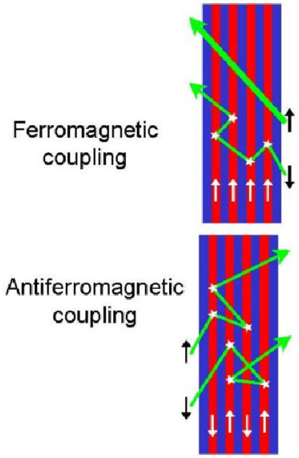
		CMOS	TMR-based
Delay (ns)		0.69	0.61
Power (μW)	Dynamic	275	193
	Static	16.2	0
# of transistors		5	1

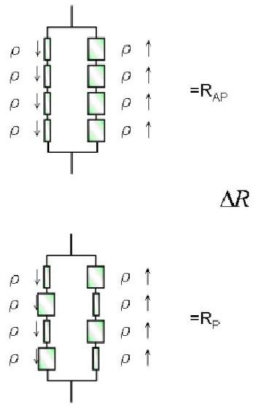
(MR ratio: 1000%)

IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 54, NO. 5, MAY 2007

New Physical Phenomena in magnetic multilayers:

Giant magnetoresistance

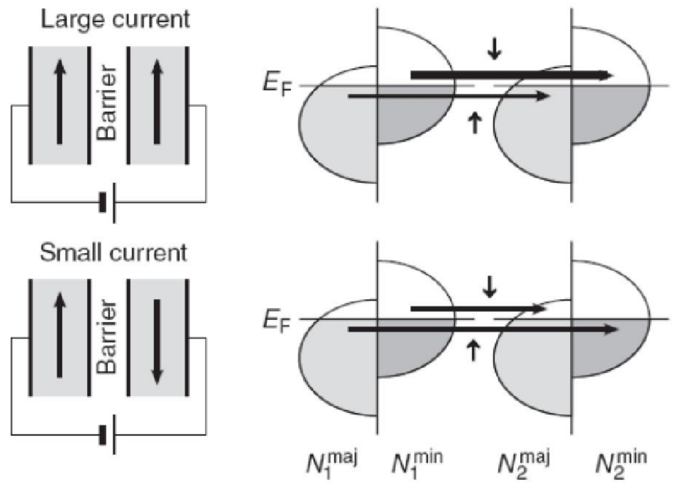




$$\Delta R = \frac{R_{AP} - R_P}{R_P}$$

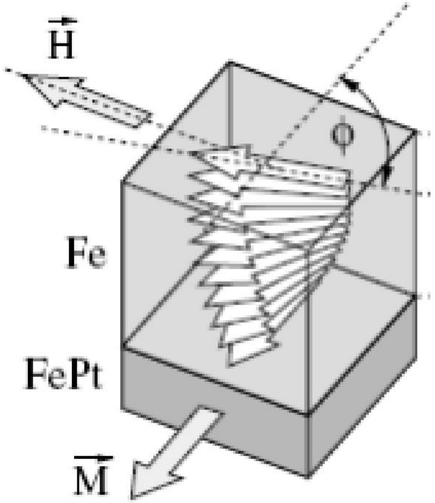
Fe/Cr; Co/Cu; Fe/Si

Tunnel magnetoresistance

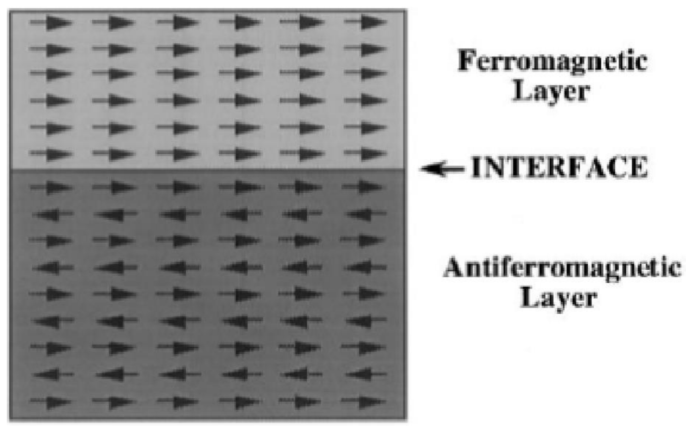


Fe/MgO/Fe

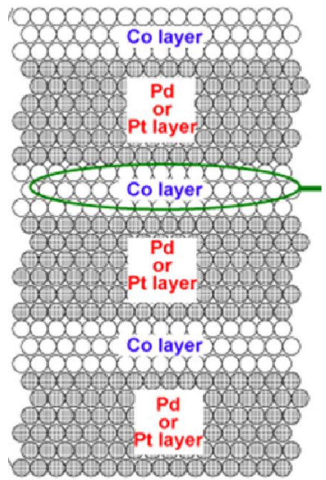
Exchange spring magnets:



Exchange bias:

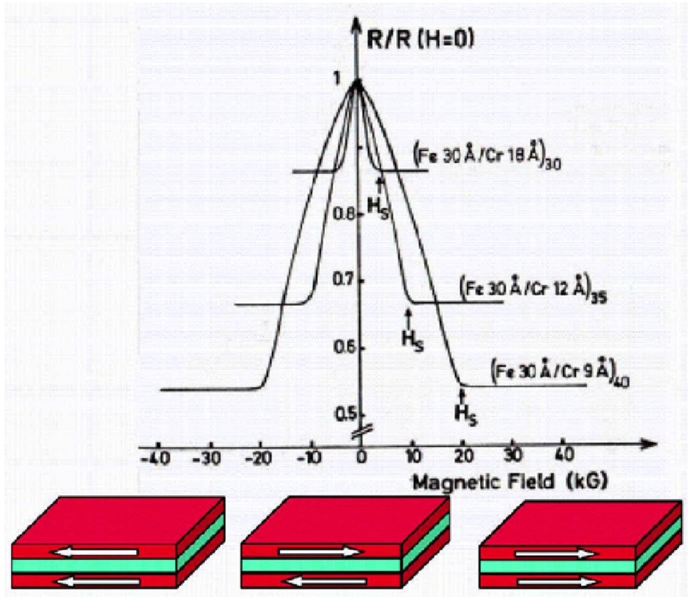


Perpendicular magnetic anisotropy



Giant magnetoresistance:

Oscillatory inter-layer coupling
+
Spin dependent scattering



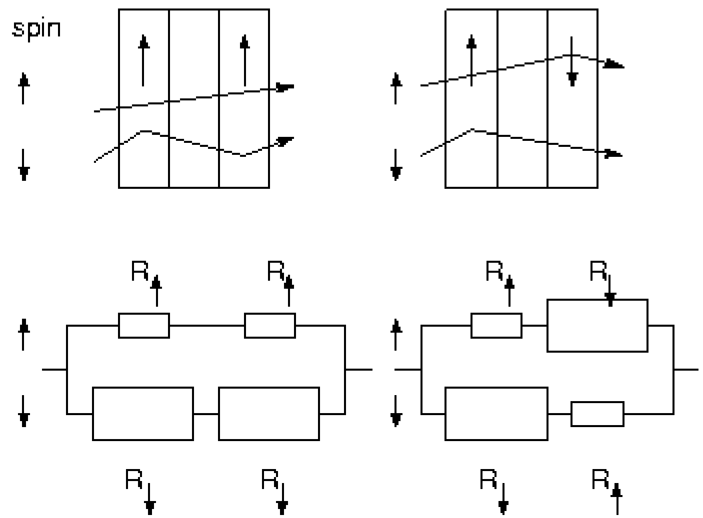
Fe/Cr/Fe

$$H_{\mathrm{ex}} = -J_{ij} \cdot S_i \cdot S_j$$

Ruderman, Kittel, Kasuga, and Yoshida interaction:

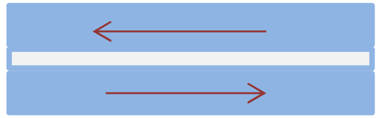
spin polarization of the s and p electrons of the surrounding Medium by exchange interaction with d electrons of magnetic atoms

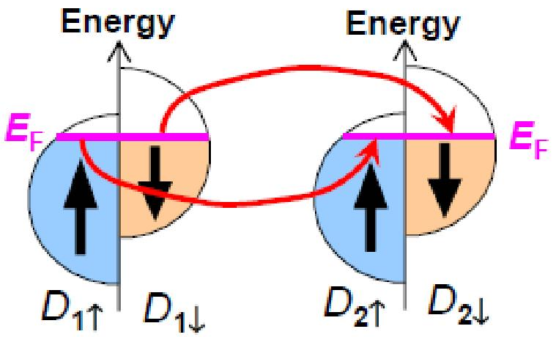
$$J_{ij(\mathrm{RKKY})}(R) \sim \frac{\cos(2k_{\mathrm{F}} \cdot R)}{(2k_{\mathrm{F}} \cdot R)^3} \sim \frac{1}{R^3}$$



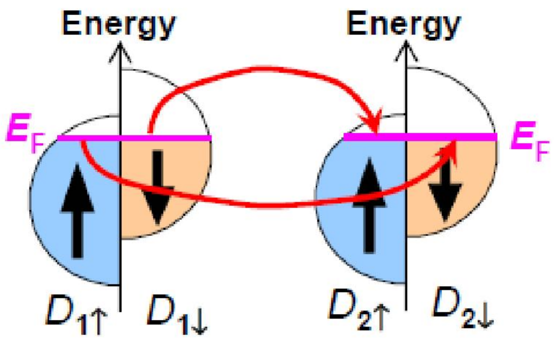
MR ratio ≡ $(R_{AP} - R_P) / R_P$

Tunnel magnetoresistance:





Parallel (P) state
Tunnel resistnce: R_P



Antiparallel (AP) state
Tunnel resistnce: R_{AP}

MR ratio $\equiv (R_{AP} - R_P) / R_P$

<u>Parallel state</u>

$$J^{parallel} \propto D_1^{\uparrow} D_2^{\uparrow} + D_1^{\downarrow} D_2^{\downarrow}$$

<u>Antiparallel state</u>

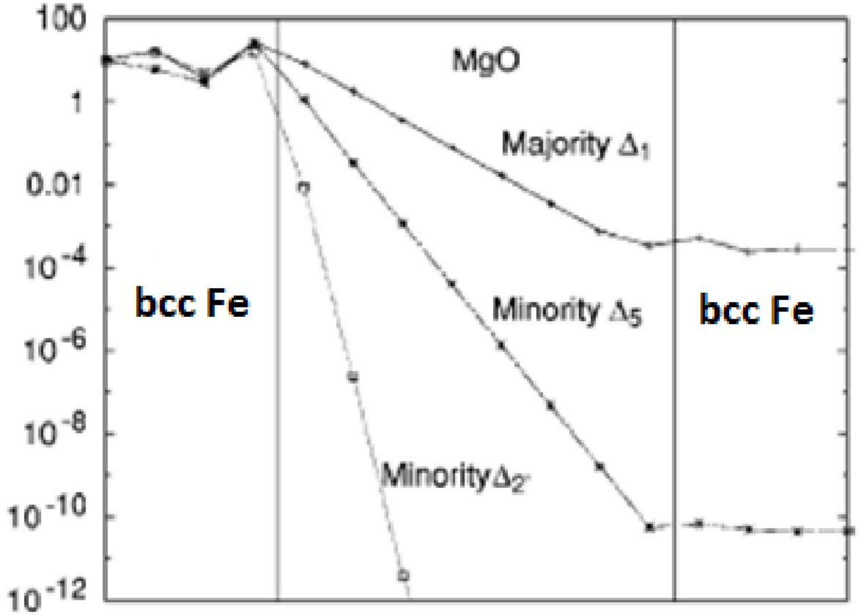
$$J^{antiparallel} \propto D_1^{\uparrow} D_2^{\downarrow} + D_1^{\downarrow} D_2^{\uparrow}$$

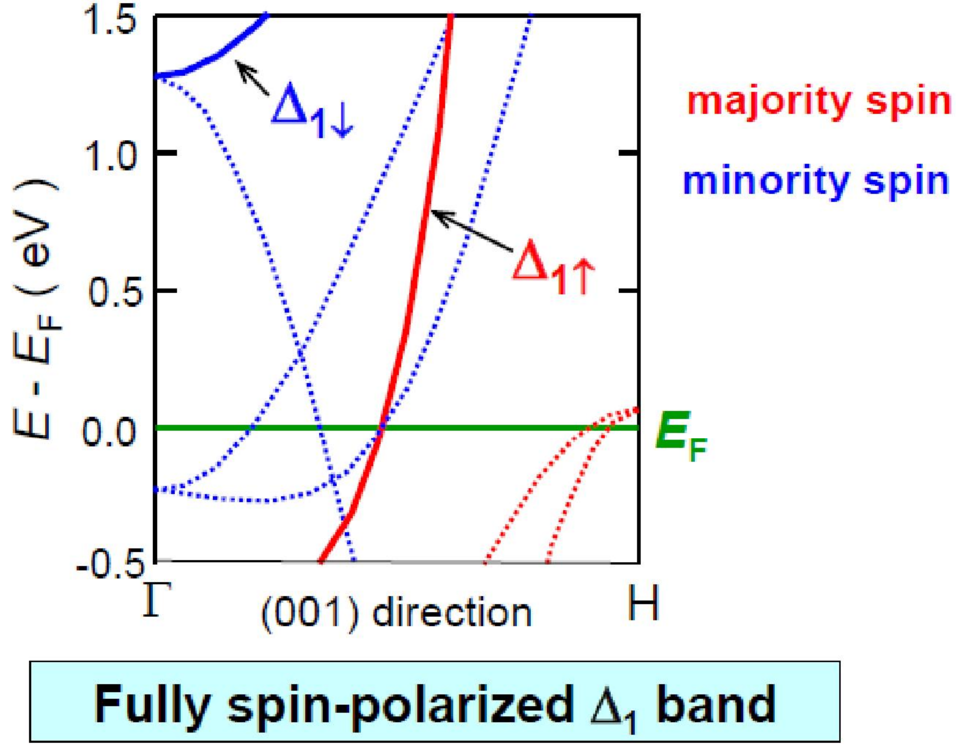
$$P = \frac{D^{\uparrow}(E_F) - D^{\downarrow}(E_F)}{D^{\uparrow}(E_F) + D^{\downarrow}(E_F)}$$

$$TMR = \frac{\Delta R}{R_{AP}} = \frac{2 P_1 P_2}{1 + P_1 P_2}$$

Jullière, Phys. Lett. A54 225 (1975)

Fe/MgO(001)/Fe

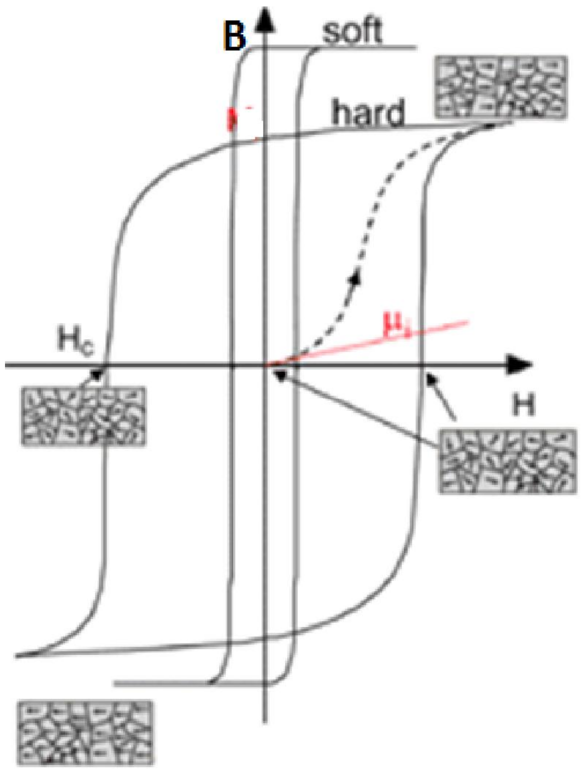


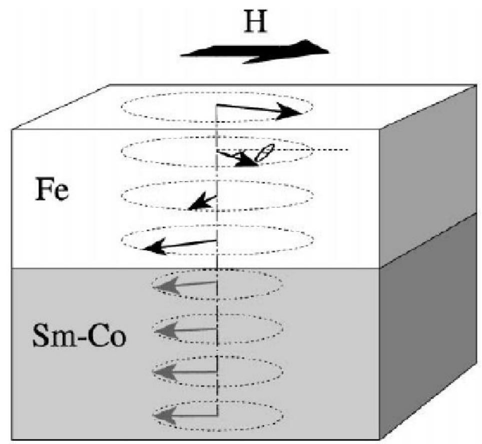


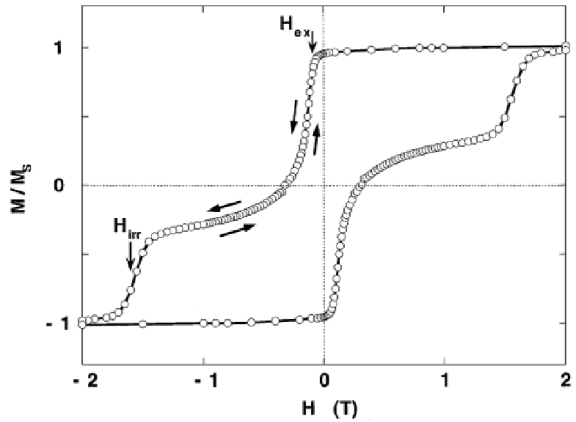
- Theoretically predicted TMR ~1000
- Maximum experimentally observed value ~500

Imperfections at the interfaces are responsible for deterioration in TMR

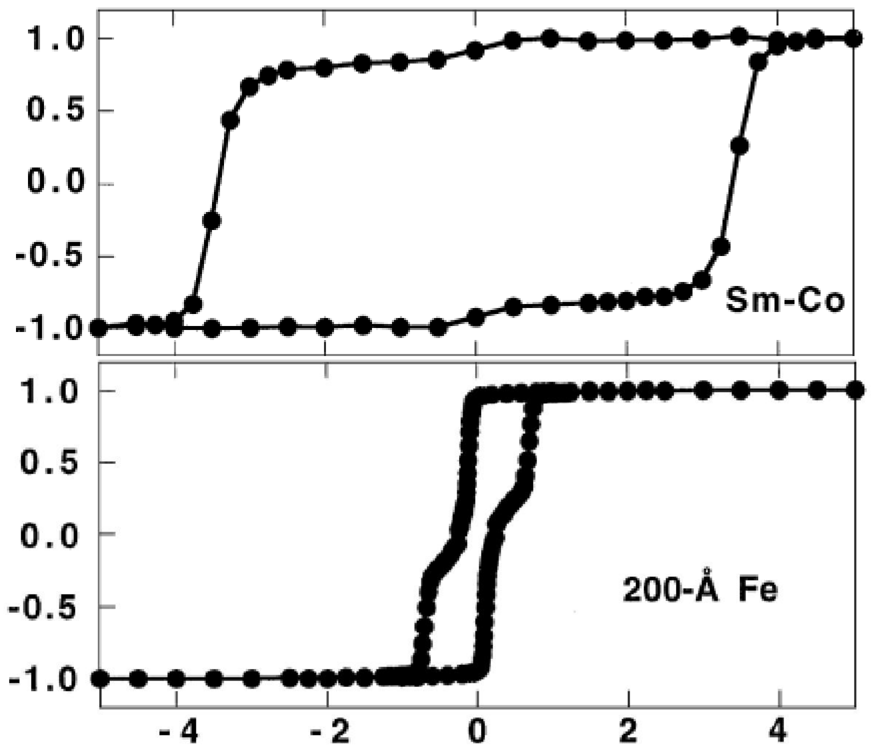
Exchange spring magnets:







$SmCo_5$, Sm_2Co_{17}, $Nd_2Fe_{14}B$,

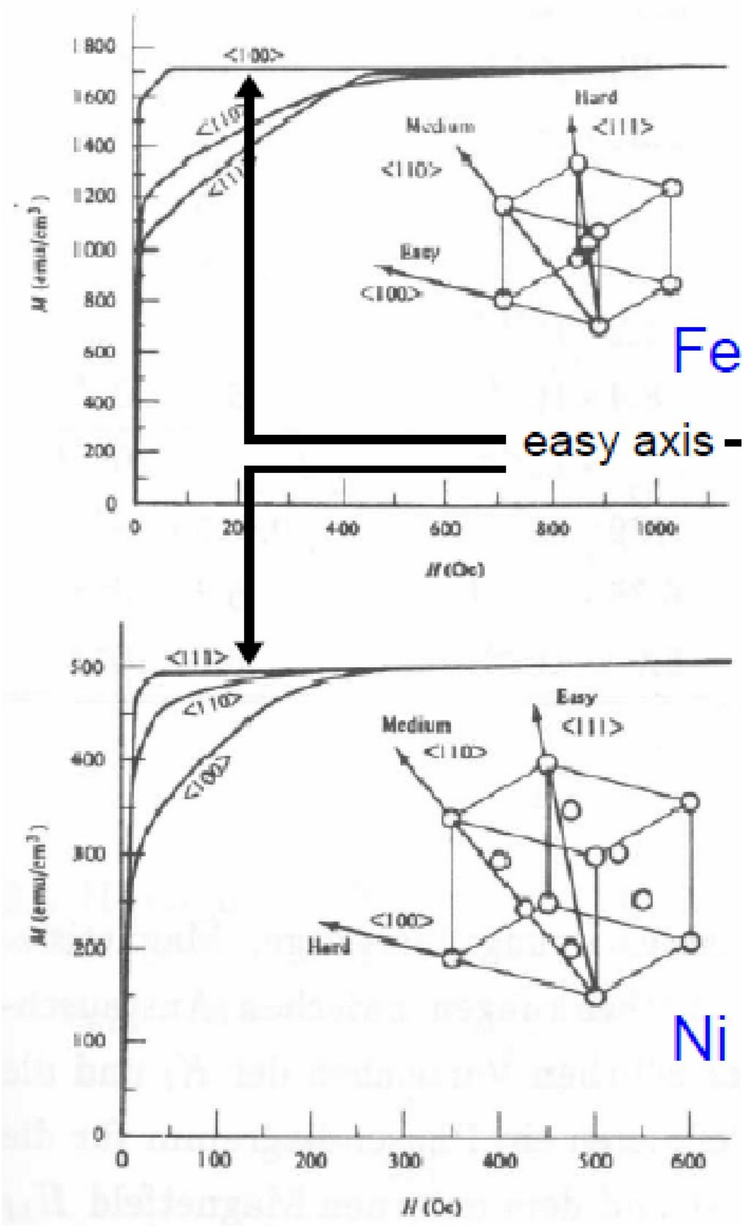


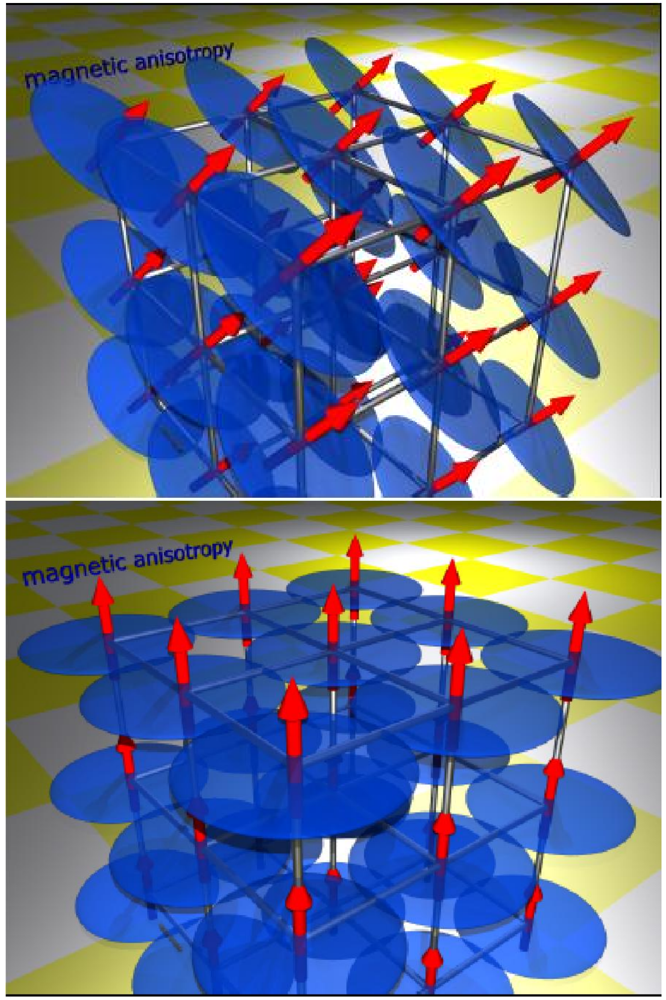
1.0
0.5
0.0
-0.5
-1.0
Sm-Co
1.0
0.5
0.0
-0.5
-1.0
200-Å Fe
- 4
- 2
0
2
4

Magnetic anisotropy

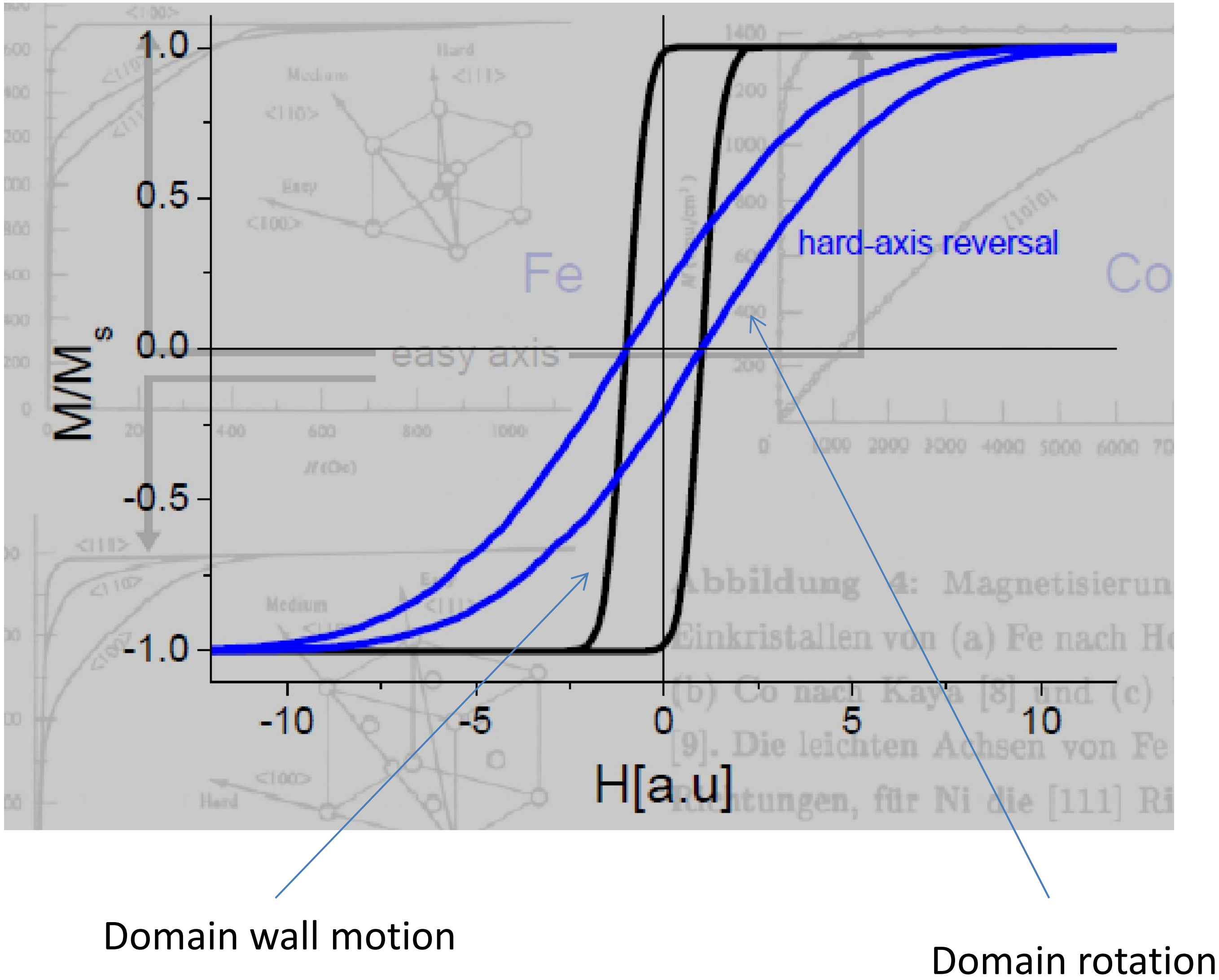
-magneto-crystalline
-stress induced
-surface/interface
  – reduced symmetry
  -surface roughness

Magneto-crystalline anisotropy:





Spin-orbit coupling

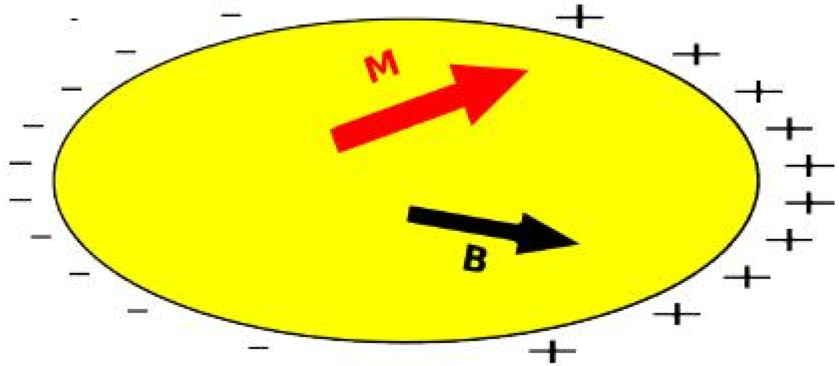


1.0
0.5
0.0
-0.5
-1.0
M/M_s
-10
-5
0
5
10
H[a.u]
hard-axis reversal
easy axis
Fe
Co
Domain wall motion
Domain rotation

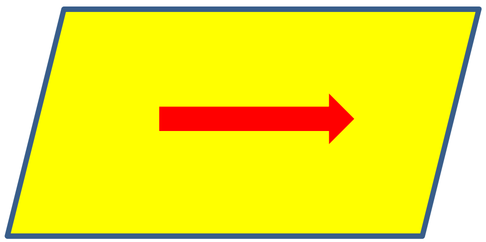
Shape anisotropy:

$$\vec{B} = \mu_0(-N \cdot \vec{M} + \vec{M})$$

N is demagnetizing tensor

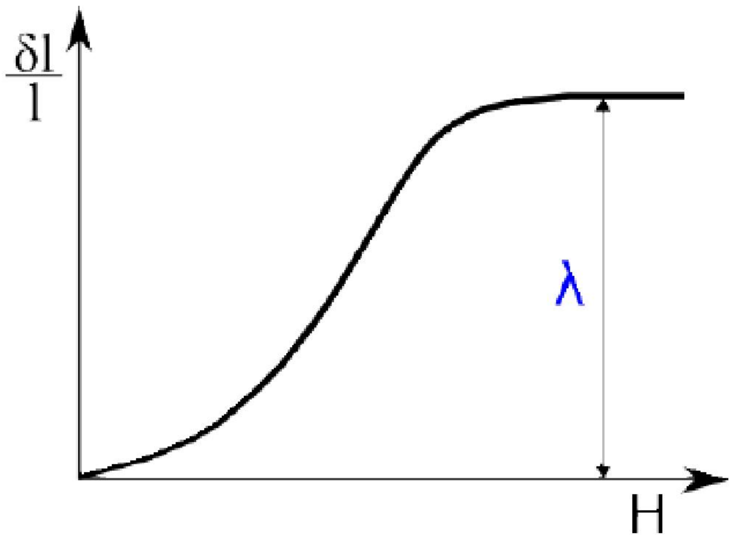


In general, magnetization and magnetic induction are not necessarily parallel

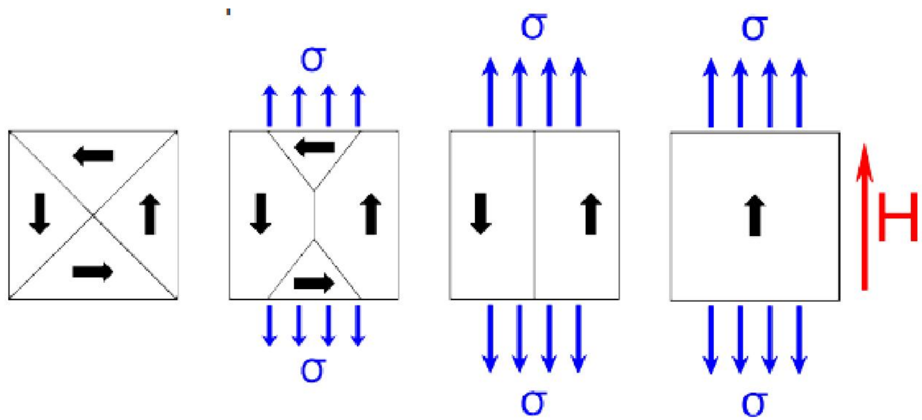


In thin films shape anisotropy dominates over magnetocrystalline anisotropy

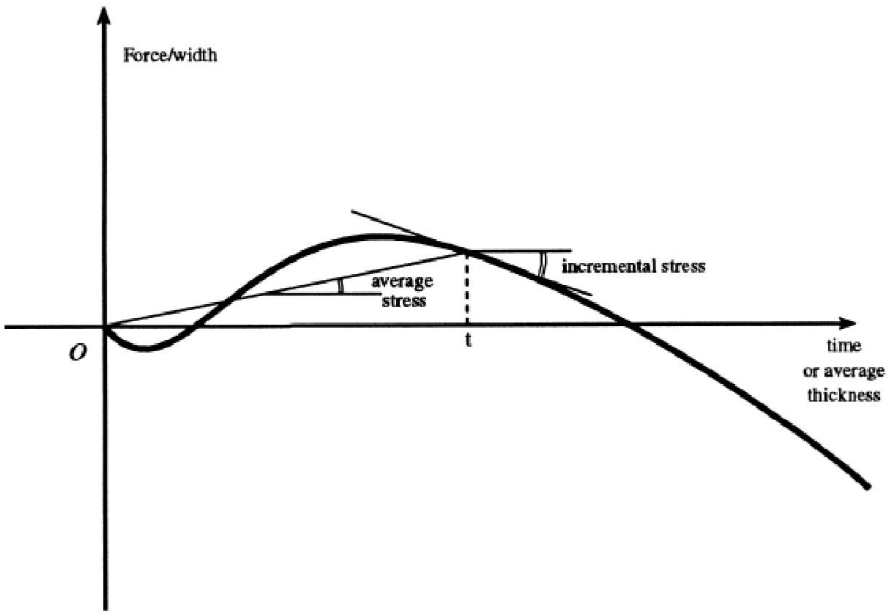
Stress induced anisotropy:

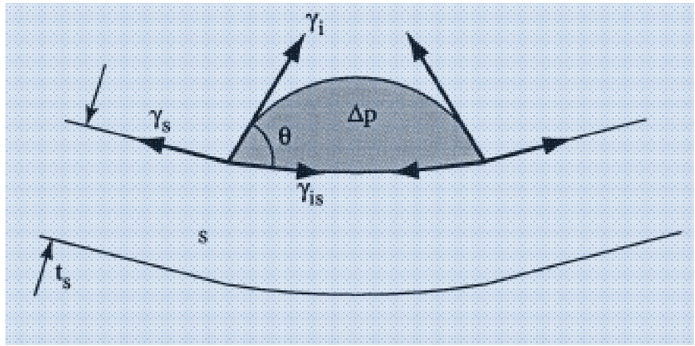


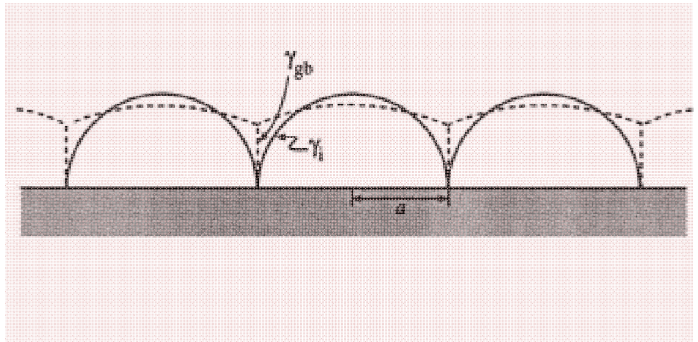
Magnetostriction

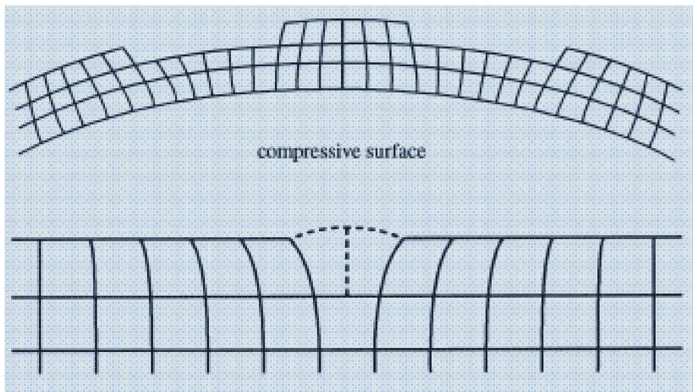


Intrinsic stresses:







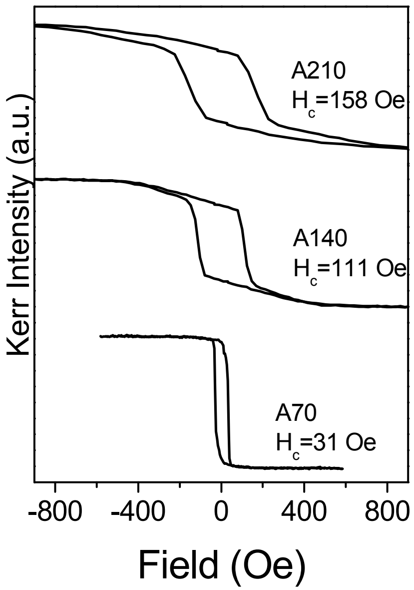


F. SPAEPEN Acta mater. 48 (2000) 31–42

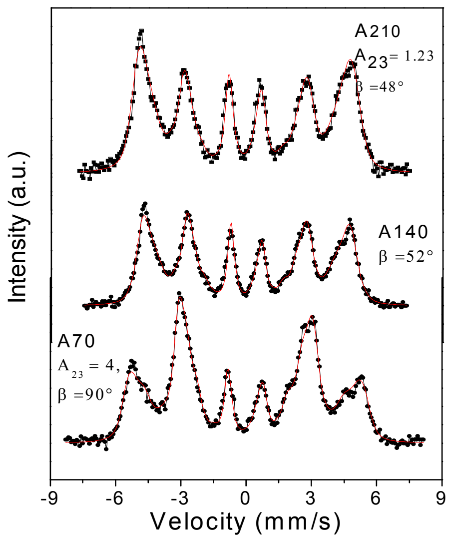
$Fe_{0.88}N_{0.12}$ thin films:

Film thickness dependent properties

MOKE

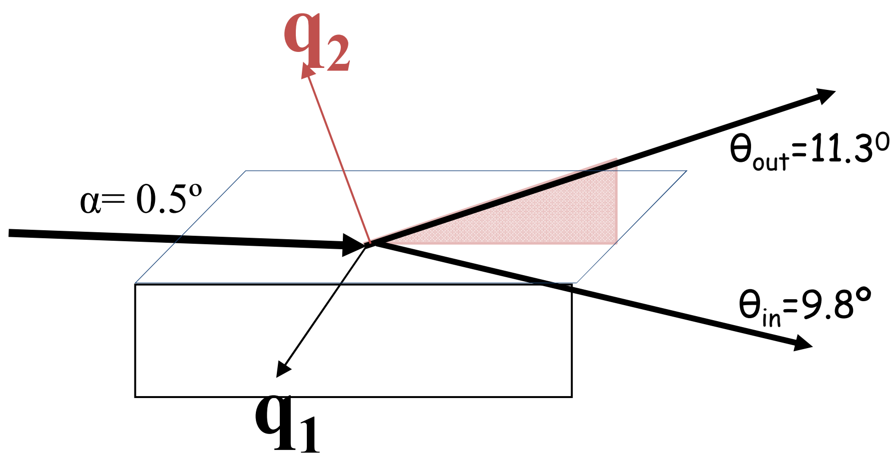


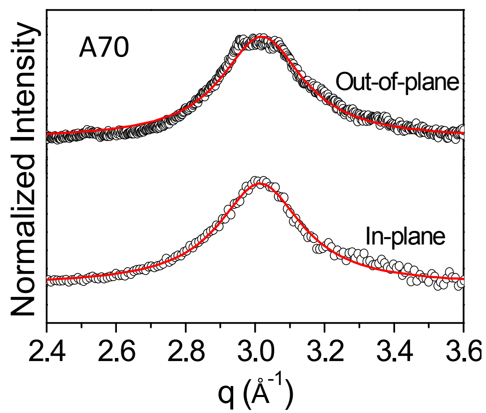
Mossbauer

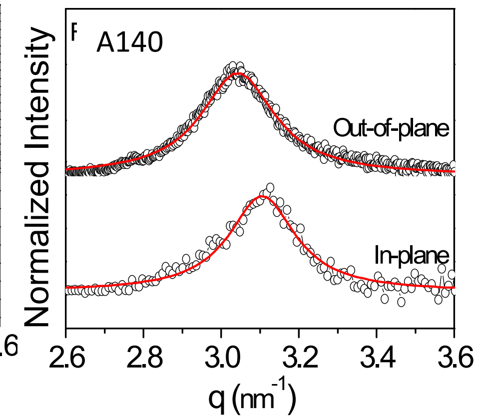


With increasing film thickness soft magnetic properties deteriorate

Strain measurement (XRD)

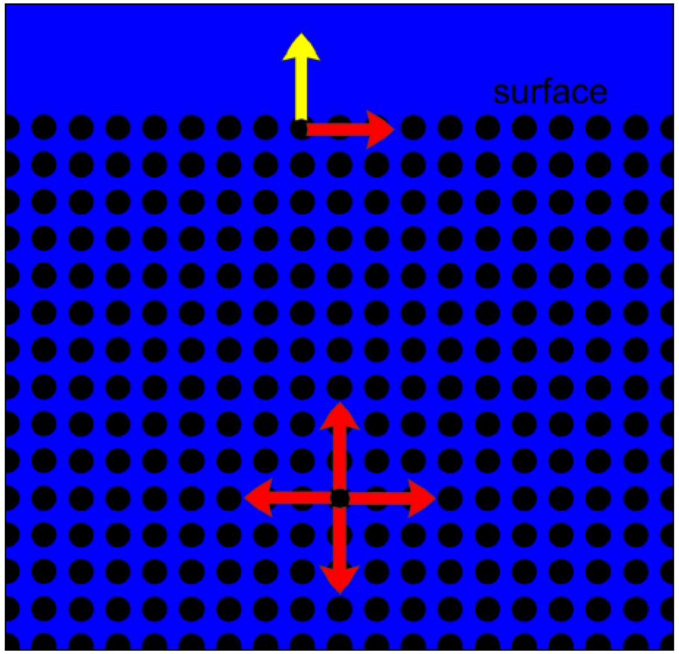






Tensile strain Compressive strain

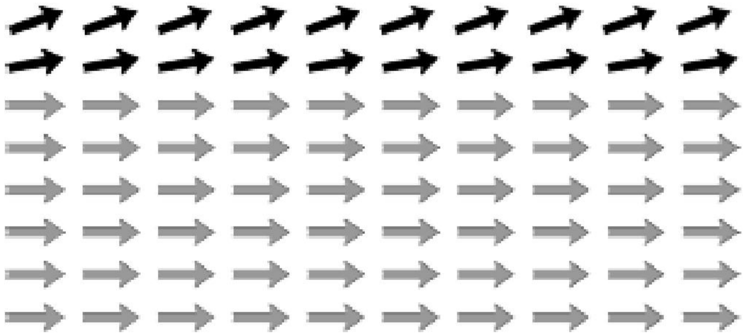
Surface anisotropy:

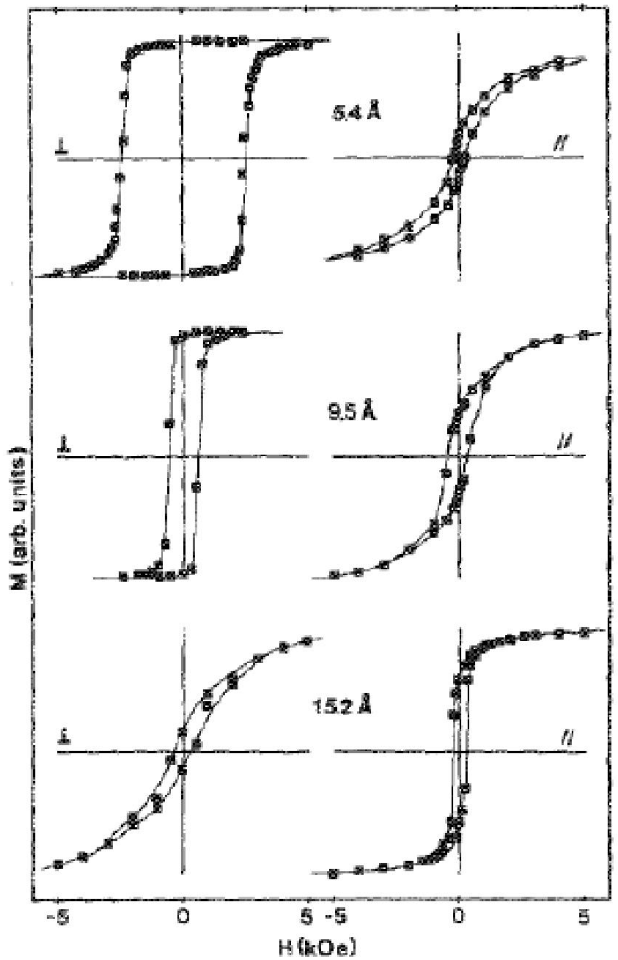


Broken symmetry at the surface / interface

$$K_{tot} = K_V + K_S / t$$

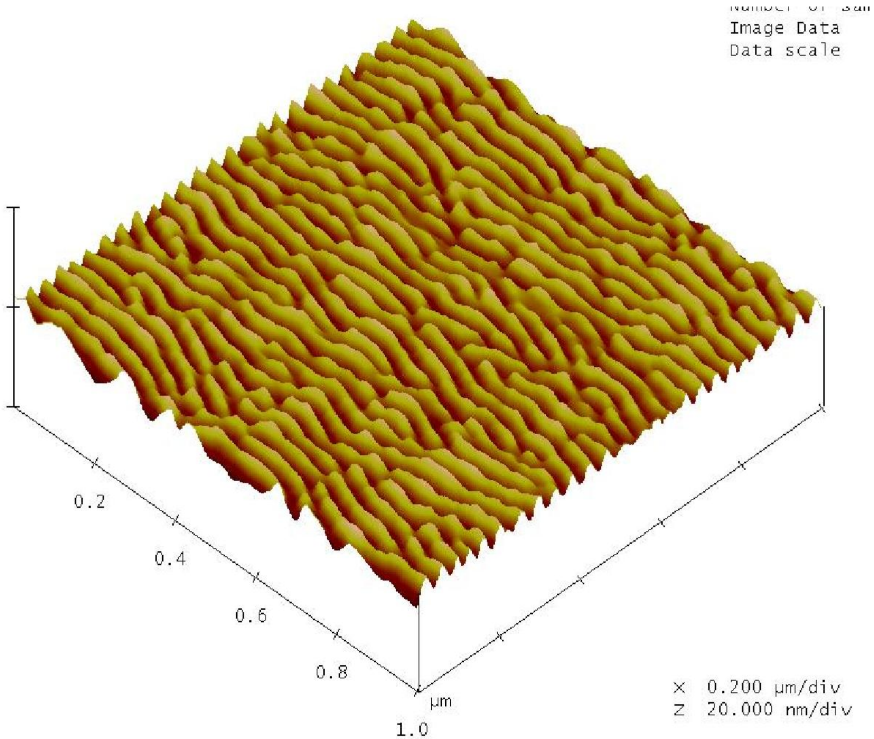
Reorientation phase transition

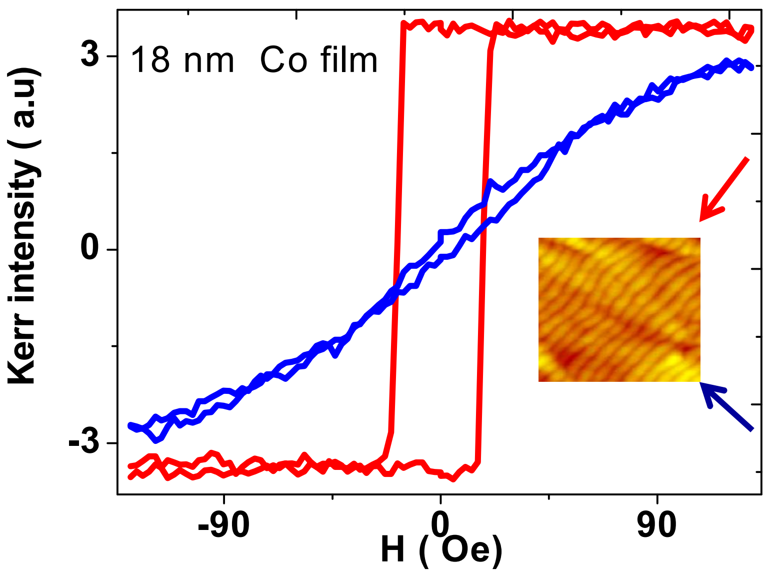


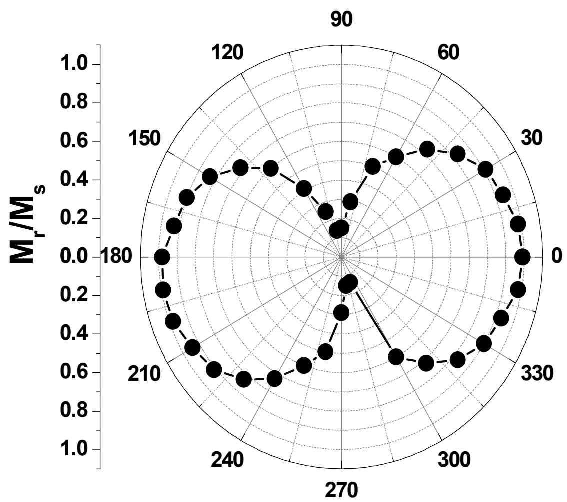


Au/Co/Au

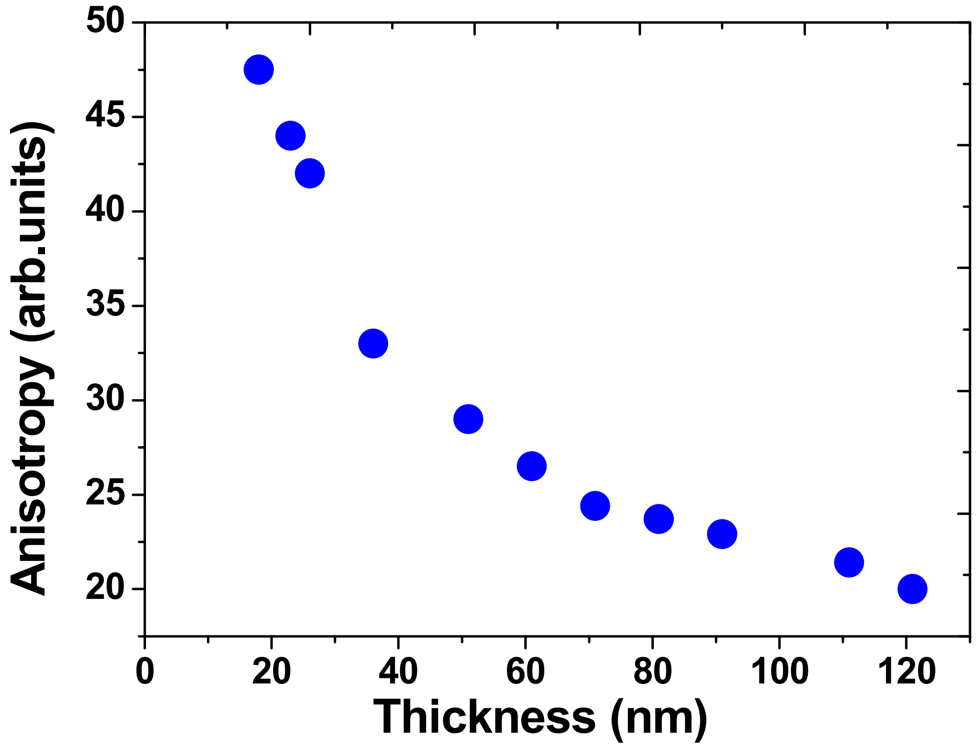
Co film on rippled Si surface





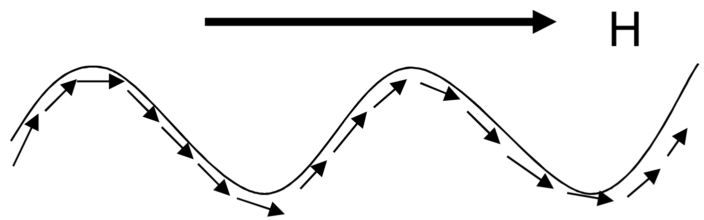


Thickness dependence of anisotropy:



Interplay among:

1. Zeeman energy,
2. Exchange energy
3. Stray dipolar fields

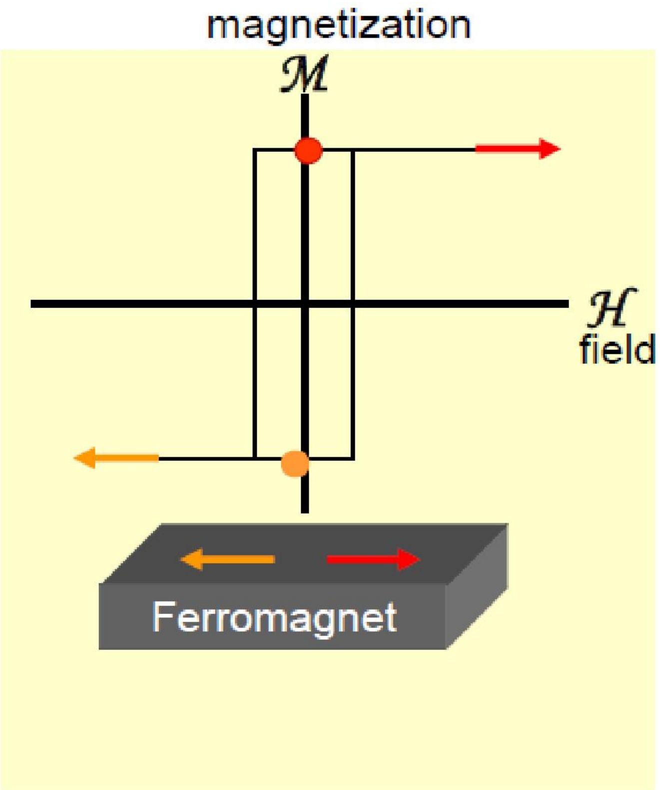


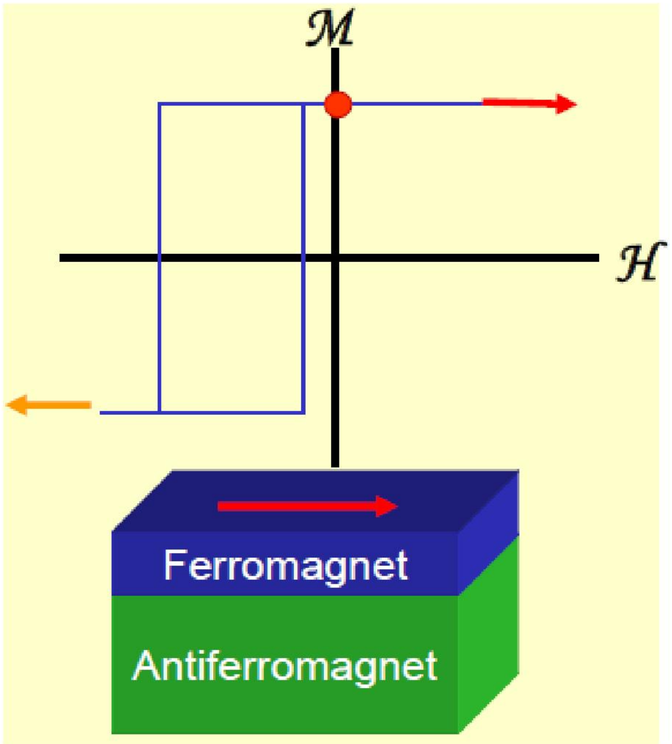
$$K_2^{\mathrm{dip}} = 2\pi M_S^2 \frac{\pi w_{\mathrm{rms}}^2}{\lambda D}$$

E. Schlömann, *J. Appl. Phys.* **41** (1970) 1617

J. Fassbender et al., New J. Phys. **11** (2009) 125002

Exchange anisotropy:

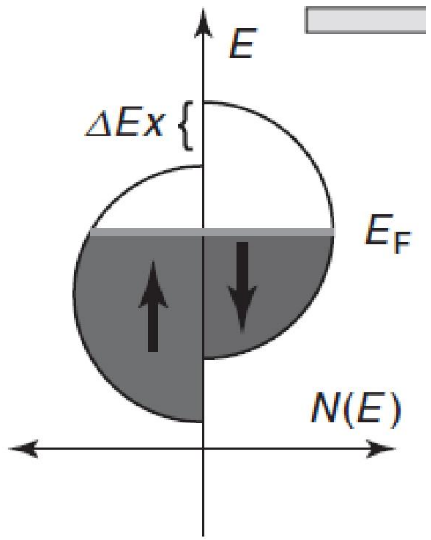


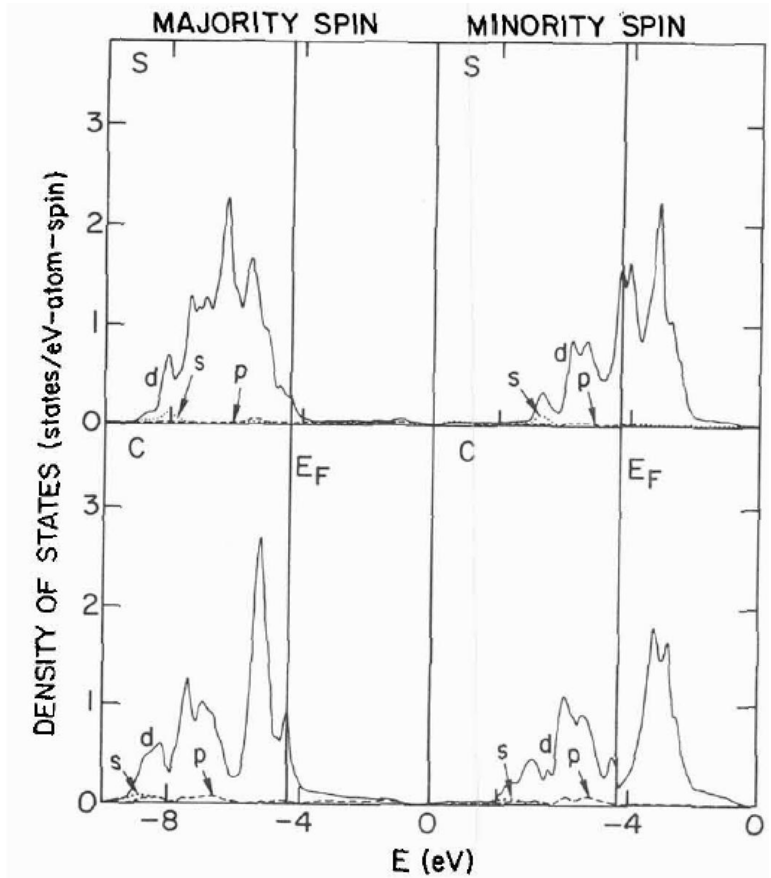


$\mathcal{M}$ of blue layer is "pinned" or "exchange biased"

$$h_b = \frac{J_{exchange}}{M_{FM}\, t_{FM}}$$

Magnetism at surface and interfaces





Fe (001)

Enhanced magnetic moment at the surface