

Nanomagnetism

Part 3 — Heterostructures



Olivier Fruchart

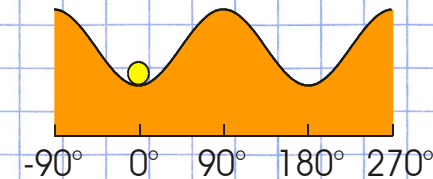
Institut Néel (Univ. Grenoble Alpes – CNRS)
Grenoble – France

<http://neel.cnrs.fr>

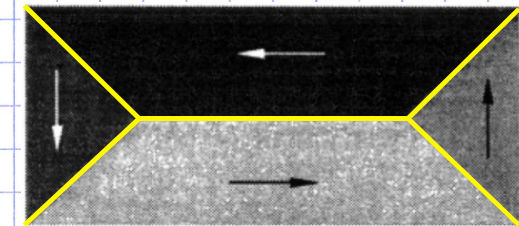
Micro-NanoMagnetism team : <http://neel.cnrs.fr/mnm>



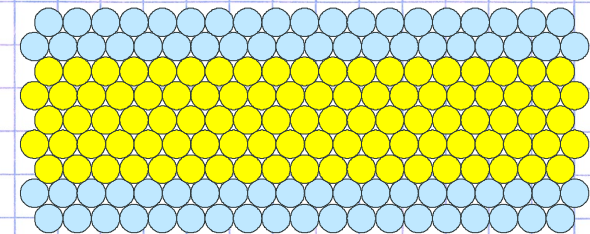
➔ **Part 1 : basics of micromagnetism –
Simple models of magnetization reversal**



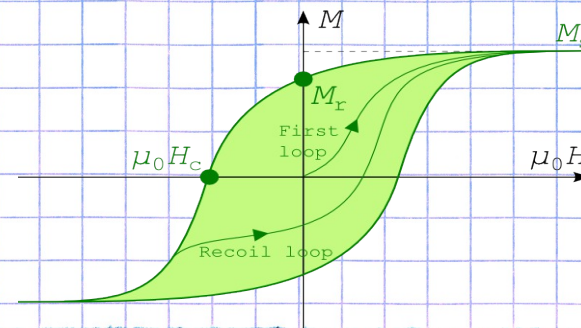
➔ **Part 2 : non-uniform magnetization in
nanostructure: domains, domain walls**

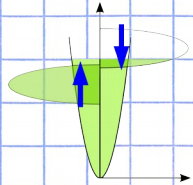


➔ **Part 3 : Low-dimensions,
interfaces and heterostructures**

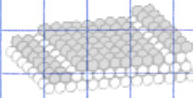


➔ **Part 4 : Learn from
hysteresis loops**

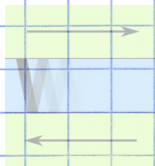




⇒ Ordering and moments



⇒ Interfacial anisotropy

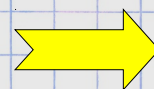


⇒ Heterostructures



Elements of theory

- Ising (1925). No magnetic order at $T > 0K$ in 1D Ising chain.
- Bloch (1930). No magnetic order at $T > 0K$ in 2D Heisenberg (spin-waves)
- → N. D. Mermin, H. Wagner, PRL17, 1133 (1966)
- Onsager (1944) + Yang (1951).
2D Ising model: $T_c > 0K$

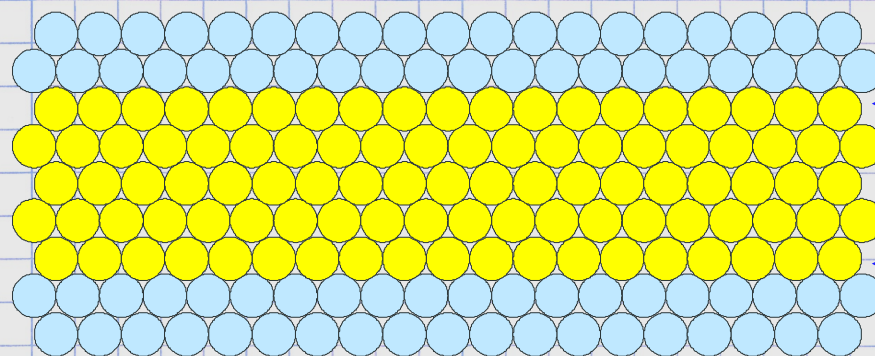


Magnetic anisotropy stabilizes ordering

Naïve views : mean molecular field

$$T_c = \frac{\mu_0 z n_{w,1} n g_J^2 \mu_B^2 J(J+1)}{3k_B}$$

z neighbors



N atomic layers : $\langle z \rangle = z_b - \frac{2(z_b - z_s)}{N}$ $\Rightarrow \Delta T_c(t) \sim t^{-1}$

Less naïve: thickness-dependent mean molecular field

$$\Delta T_c(t) \sim t^{-\lambda}$$

$\lambda = 1$

G.A.T. Allan, PRB1, 352 (1970)

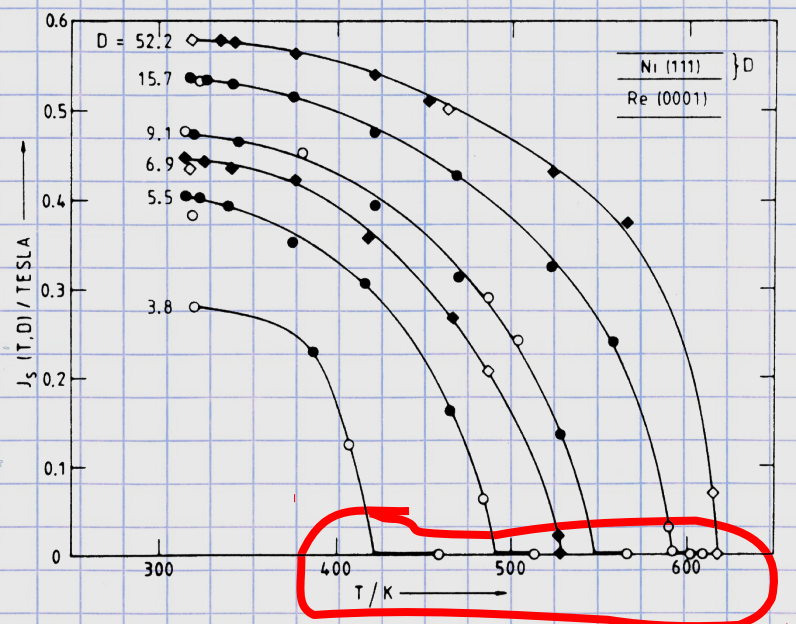
Conclusion:

Naïve views are roughly correct



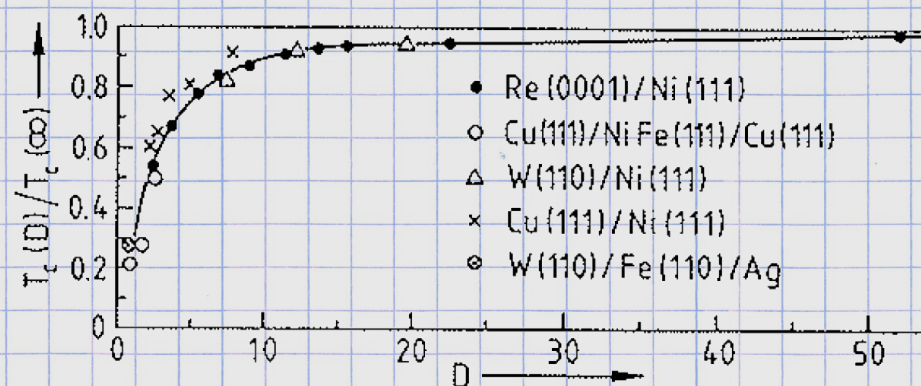
Qualitative

Ni(111)/Re(0001)



R. Bergholz and
U. Gradmann,
JMMM45, 389 (1984)

Quantitative (molecular field)



T_c fitted with molecular field :

$$\Delta T_c(t) \sim t^{-1}$$

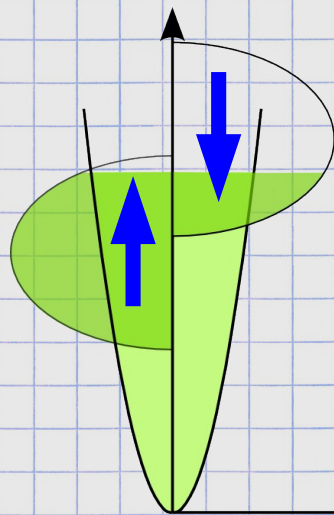
U. Gradmann,
Handbook of Magn. Mater. Vol.7, ch.1 (1993)

Ordering temperature decreases with thickness
Noticeable below ≈ 1 nm

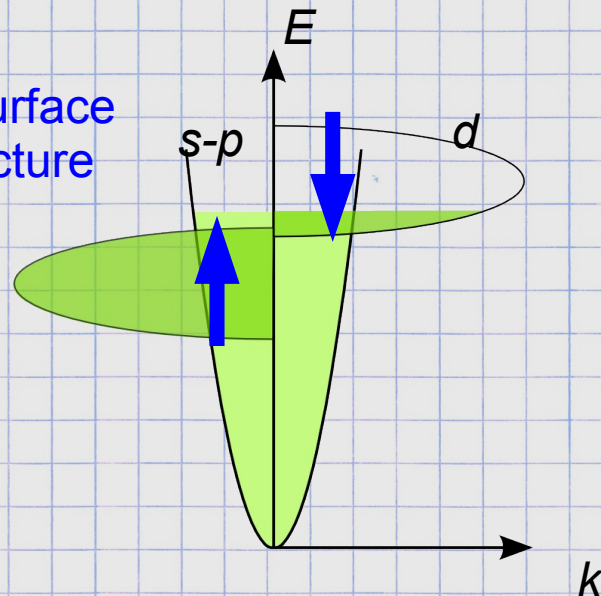
Simple picture: band narrowing at surfaces

Enhanced moment at surfaces

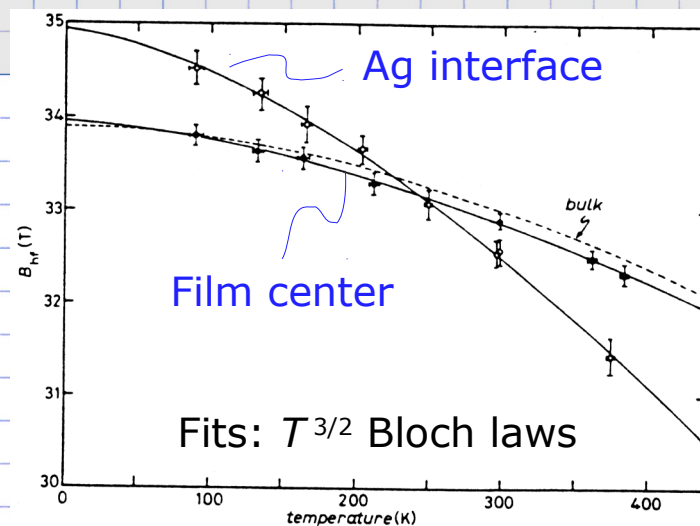
Bulk picture



Surface picture



In practice:
20-30 %, however
decays faster with
temperature



Ag/Fe(110)/W(110)

U. Gradmann et al.

Loss of ferromagnetic order

Antiferromagnetism in fcc Fe(001)

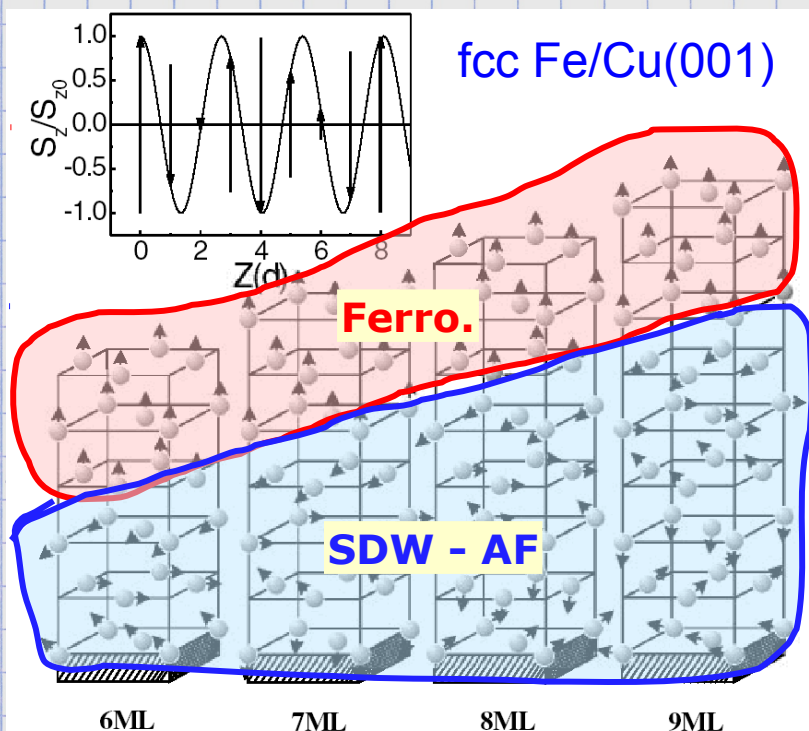


FIG. 4. Magnetic structures proposed for 6, 7, 8, and 9 ML Fe on Cu(100); the inset gives the layer dependent magnetic mo-

D. Qian et al., PRL87, 227204(2001)

H. L. Meyerheim et al., PRL103, 267202 (2009)

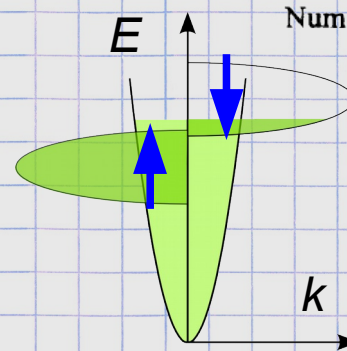
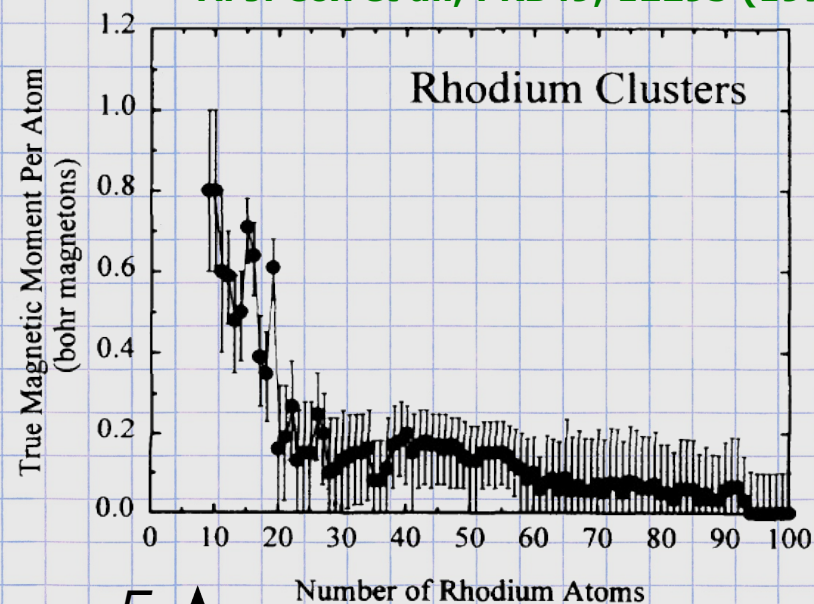
Also high spin phase: V. Cros, EPL49, 807 (2000)

Gain of ferromagnetic order

Ferromagnetism in small Rh clusters

A. J. Cox et al., PRL71, 923 (1993)

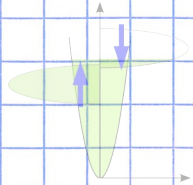
A. J. Cox et al., PRB49, 12295 (1994)



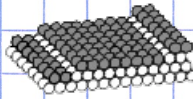
$$I \rho_{\uparrow, \downarrow}(\epsilon_F) > 1$$

Narrowing of bands
allows to fulfill
Stoner criterium

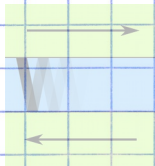
At interfaces and low-dimensions, materials may be a different material !



⇒ Ordering and moments



⇒ Interfacial anisotropy

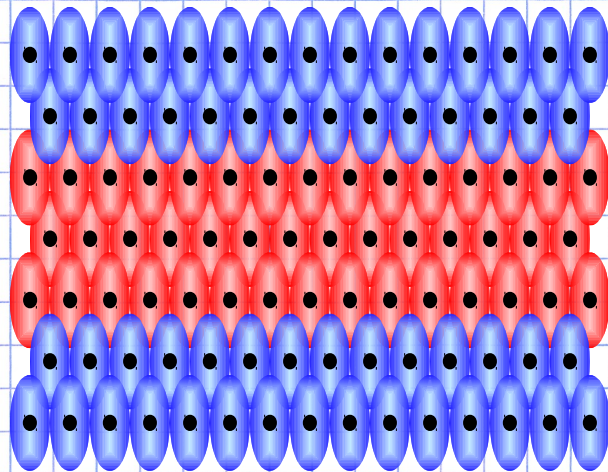


⇒ Heterostructures

Surface anisotropy : prediction

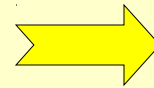
L. Néel,
J. Phys. Radium 15,
15 (1954)

« Superficial magnetic anisotropy and orientational superstructures »



Overview

Breaking of symmetry for
surface/interface atoms



Correction to the
magneto-crystalline energy

$$E_s = K_{s,1} \cos^2 \theta + K_{s,2} \cos^4 \theta + \dots$$

« This surface energy, of the order of 0.1 to 1 erg/cm², is liable to play a significant role in the properties of ferromagnetic materials spread in elements of dimensions smaller than 100Å »

Phenomenology

Pair model of Néel:

- K_s estimated from magneto-elastic constants
- Does not depend on interface material
- Yields order of magnitude only: correct value from experiments or calculations (precision !)

Microscopic understanding

Perturbation theory for 3d metals:

$$MAE = \alpha \frac{\xi}{4\mu_B} \Delta\mu_L$$

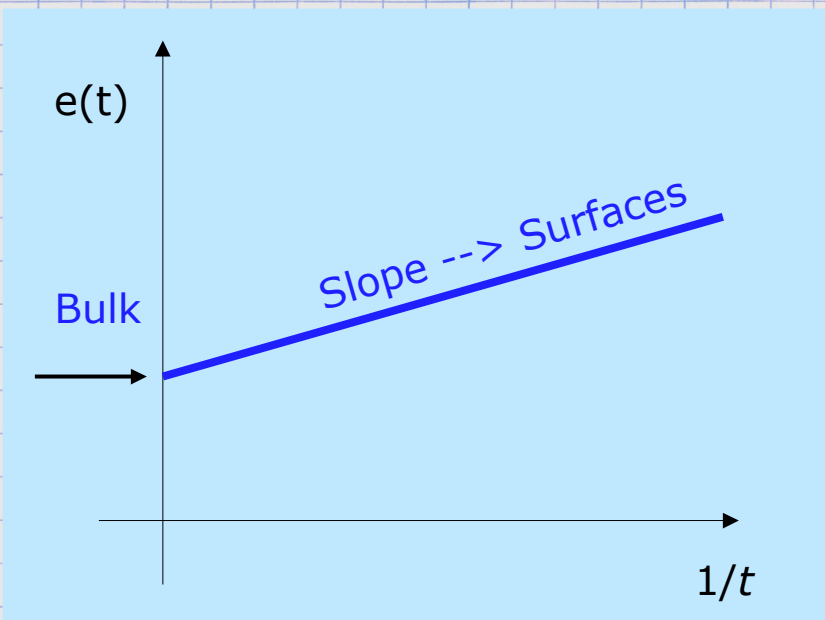
P. Bruno, PRB39, 865 (1989)



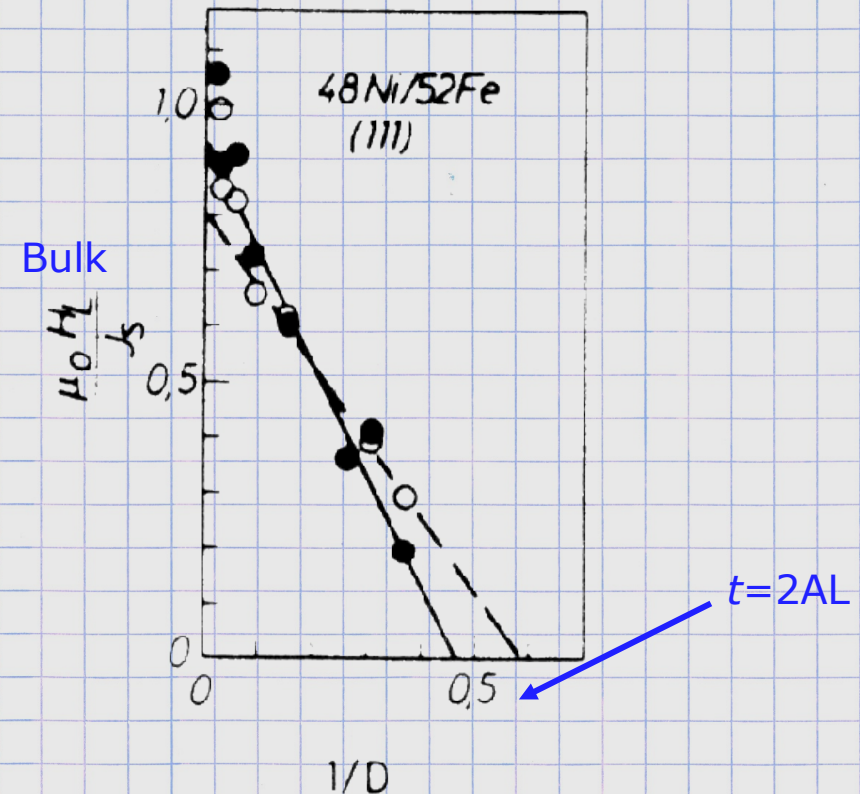
History of surface anisotropy : $1/t$ plot

$$\varepsilon(t) = K_v t + 2K_s$$

$$E(t) = K_v + \frac{2K_s}{t}$$



First example of perpendicular anisotropy



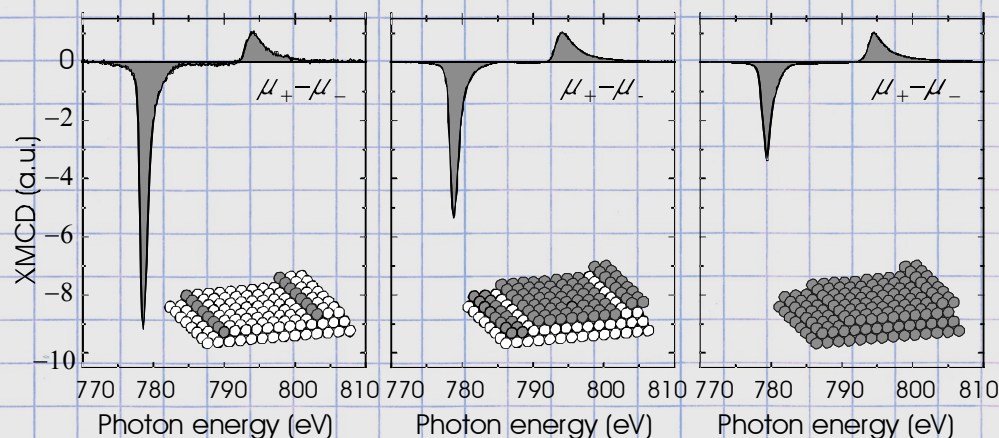
U. Gradmann and J. Müller,
Phys. Status Solidi 27, 313 (1968)



Too simple picture : strain relaxation also yield $1/t$ law
Non-linear magneto-elasticity may be important (eg : Co)

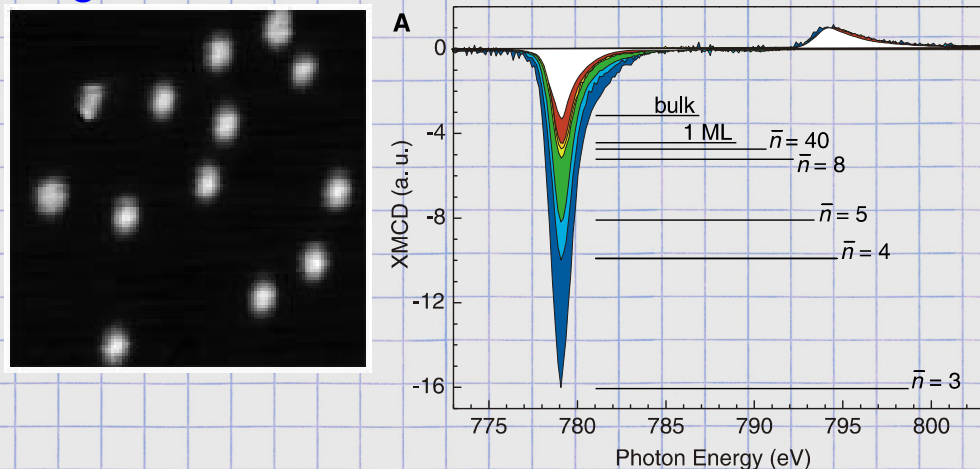
Experimental systems

Co on vicinal Pt(111) probed by Xray dichroism



P. Gambardella et al., *Nature* **416**, 301 (2002)

Single atoms at surface. STM, 8.5nm, 5.5K



P. Gambardella et al., *Science* **300**, 1130 (2003)

Results

- Bulk Co: $40\mu\text{eV/atom}$
- Co ML: $140\mu\text{eV/atom}$
- Co bi-wire: 0.34meV/atom
- Co wire: 2meV/atom
- Co bi-atom: 3.4meV/atom
- Co atom: 9.2meV/atom

↪ **Dramatic dimensional effect**

Practical use : past and trends

⇒ 3d (mostly Co and Co/Ni) with heavy metal (Pt, Au, Pd...). Critical thickness 1-2nm

M. T. Johnson, *RPP* **59**, 1409 (1996)

U. Gradmann, *Handbook* **7**, Bushow (1993)

⇒ Bonding with oxide : Al_2O_3 , MgO ... ($\rightarrow t_c$ up to 3.5nm)

A. Manchon, *JAP* **103**, 07A912 (2008)

I. G. Rau, *Science* **344**, 988 (2014)

⇒ Interface with graphene

J. Coraux, *J. Phys. Chem. Lett.* **3**, 2059 (2012)



What use ?

- ⇒ Well-defined anisotropy
→ do not need exact elliptic shape, better for down-scaling
- ⇒ High magnitude of anisotropy
→ better stability
- ⇒ Provides out-of-plane polarizer for spintronics
- ⇒ Etc.

Materials

- ⇒ 'Bulk-like magnetoelasticity :
Co/Ni, NiPd etc.
- ⇒ Interface : 3d + heavy elements for large spin-orbit coupling :
Co/Au, Co/Pt, Co/Pd
- ⇒ Interface (more recent)
 - 3d / oxides (MgO, Al₂O₃)
 - 3d / graphene

Figures

- ⇒ Interfaces 3d / heavy interfaces : up to 1-2nm
- ⇒ Interfaces 3d / oxide & graphene : up to 3-4nm
- ⇒ Multilayers : tens of nanometers

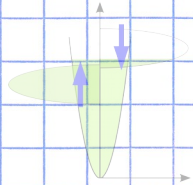
A. Manchon, JAP 103, 07A912 (2008)

I. G. Rau, Science 344, 988 (2014)

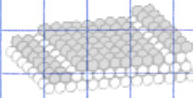
J. Coraux, J. Phys. Chem. Lett. 3, 2059 (2012)

M. T. Johnson et al., Magnetic anisotropy in metallic multilayers, Rev. Prog. Phys. 59, 1409 (1996)

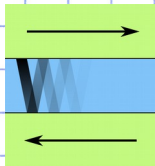
U. Gradmann, Magnetism in ultrathin transition metal films, in Handbook of Magnetism, K. H. J. Buschow (ed.), Elsevier Science Publishers, (1993)



⇒ Ordering and moments



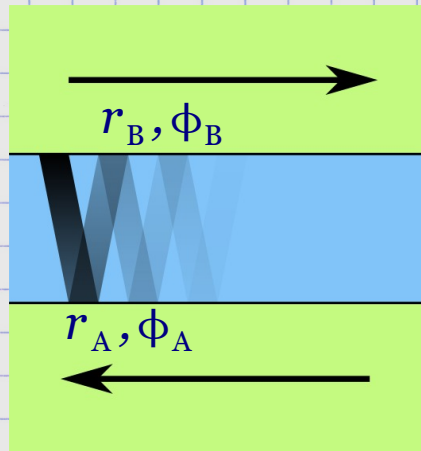
⇒ Interfacial anisotropy



⇒ Heterostructures

The physics

Spin-dependent quantum confinement in the spacer layer



Forth & back
phase shift

$$\Delta\phi = qt + \phi_A + \phi_B$$

Spin-independent

$$q = k^+ - k^-$$

Spin-dependent

$$r_A, \phi_A, r_B, \phi_B$$

⇒ Constructive or destructive interferences depending on spacer thickness

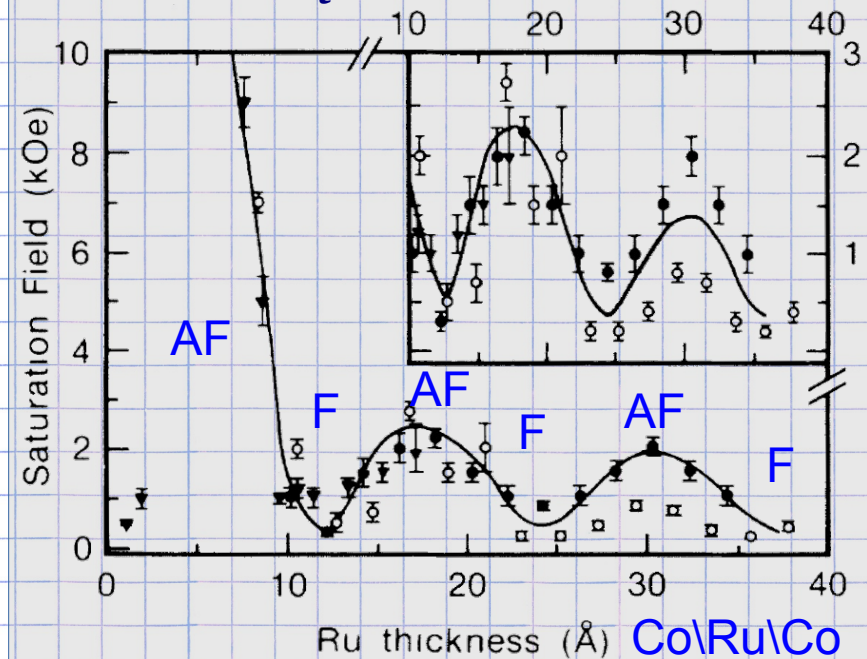
Illustration

Coupling strength:

$$E_s = J(t) \cos \theta \quad \text{in } J/m^2$$

$$\theta = \langle m_1, m_2 \rangle$$

with: $J(t) = \frac{A}{t^2} \sin(q_\alpha t + \Psi)$



S. S. P. Parkin et al., PRL64, 2304 (1990)

P. Bruno, J. Phys. Condens. Matter 11, 9403 (1999)



Illustration of coupling strength

Ti 	V 	Cr 	Mn 	Fe 	Co 	Ni 	Cu 		
No Coupling	9	3	7	7	Ferro-Magnet	Ferro-Magnet	Ferro-Magnet	8	3
	0.1	9	.24	18				0.3	10
2.89	2.62	2.50	2.24	2.48	2.50	2.49	2.56		
Zr 	Nb 	Mo 	Tc 	Ru 	Rh 	Pd 	Ag 		
No Coupling	9.5	2.5	5.2	3	3	7.9	3	No Coupling	No Coupling
	.02	*	.12	11	5	11	1.6		
3.17	2.86	2.72	2.71	2.65	2.69	2.75	2.89		
Hf 	Ta 	W 	Re 	Os 	Ir 	Pt 	Au 		
No Coupling	7	2	5.5	3	4.2	3.5	No Coupling	No Coupling	
	.01	*	.03	*	.41	10			1.85
3.13	2.86	2.74	2.74	2.68	2.71	2.77	2.88		



fcc
hcp
bcc
complex cubic

Element	
A_1 (Å)	ΔA_1 (Å)
J_1 (erg/cm ²)	P (Å)
r_{ws} (Å)	

$$J(t) = \frac{A}{t^2} \sin\left(\frac{2\pi t}{P} + \Psi\right)$$

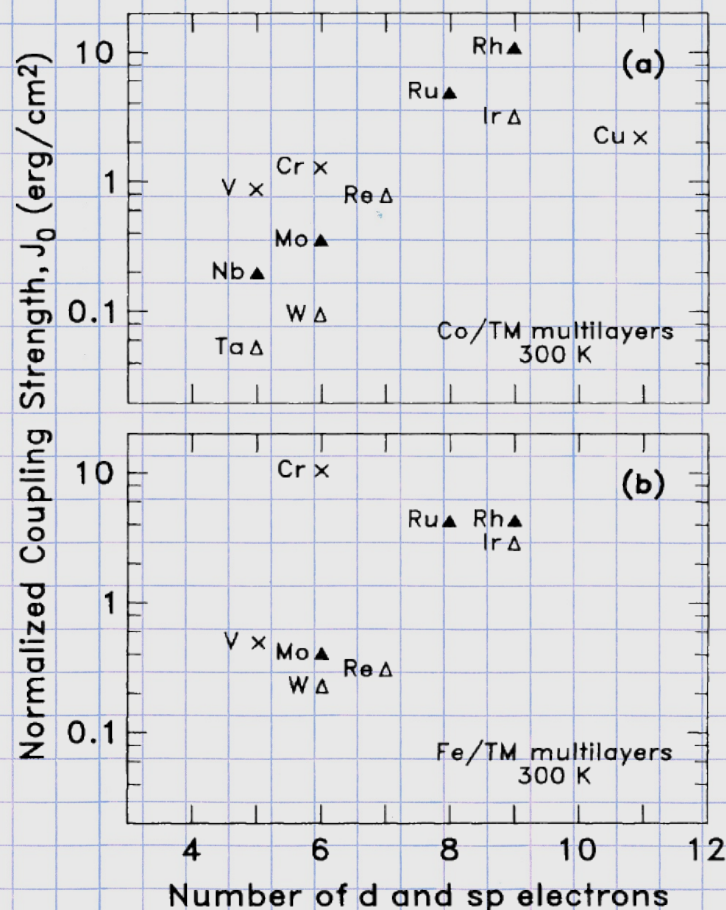


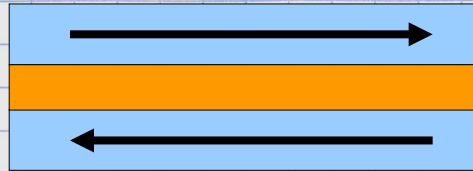
FIG. 3. Dependence of the normalized exchange coupling constant on the 3d, 4d and 5d transition metals in (a) Co/TM and (b) Fe/TM multilayers.

Note: $J(t)$ extrapolated for $t=3\text{\AA}$

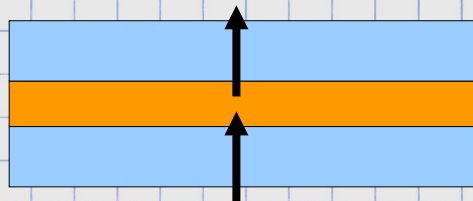
S. S. P. Parkin, Phys. Rev. Lett. 67, 3598 (1991)

Stacked dots : dipolar coupling

In-plane magnetization



Out-of-plane magnetization



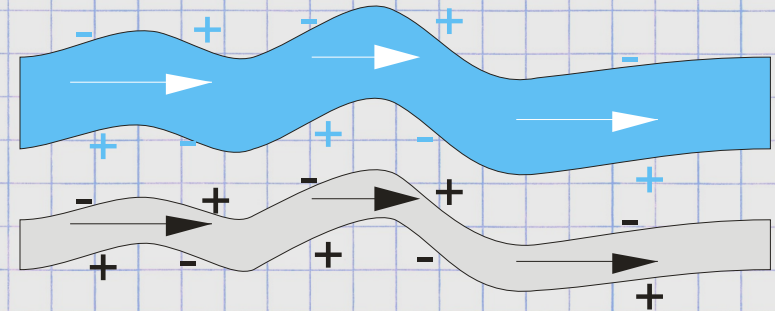
Hint:

An upper bound for the dipolar coupling is the self demagnetizing field

Notice: similar situation as for RKKY coupling

Stacked dots : orange-peel coupling

In-plane magnetization



Always parallel coupling

L. Néel, C. R. Acad. Sci. 255, 1676 (1962)
(valid only for thick films)

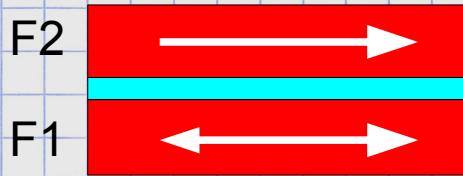
J. C. S. Kools et al., J. Appl. Phys. 85, 4466 (1999)
(valid for any films)

Out-of-plane magnetization

May be parallel or antiparallel

J. Moritz et al., Europhys. Lett. 65, 123 (2004)

Synthetic Ferrimagnets (SyF) — Crude description



Hypothesis:

- ⇒ Two layers rigidly coupled
- ⇒ Reversal modes unchanged
- ⇒ Neglect dipolar coupling



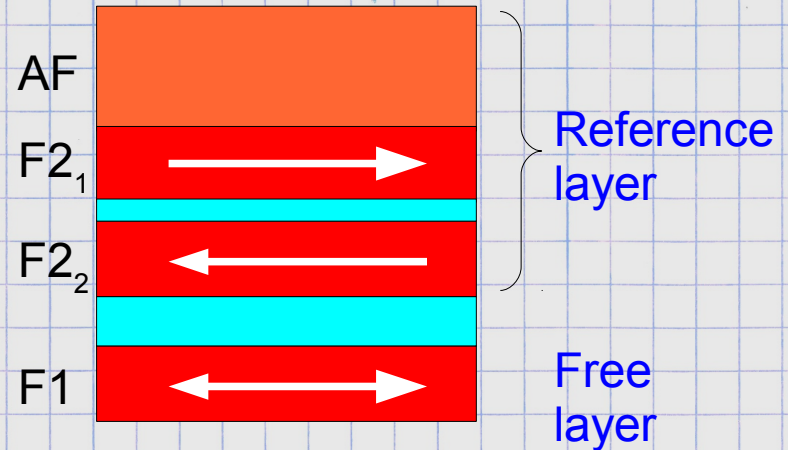
$$M = \frac{|e_1 M_1 - e_2 M_2|}{e_1 + e_2}$$

$$K = \frac{e_1 K_1 + e_2 K_2}{e_1 + e_2}$$

$$H_c = \frac{e_1 M_1 H_{c,1} + e_2 M_2 H_{c,2}}{|e_1 M_1 - e_2 M_2|}$$

What use?

- ⇒ Increase coercivity of layers
- ⇒ Decrease intra- and inter- dot dipolar coupling

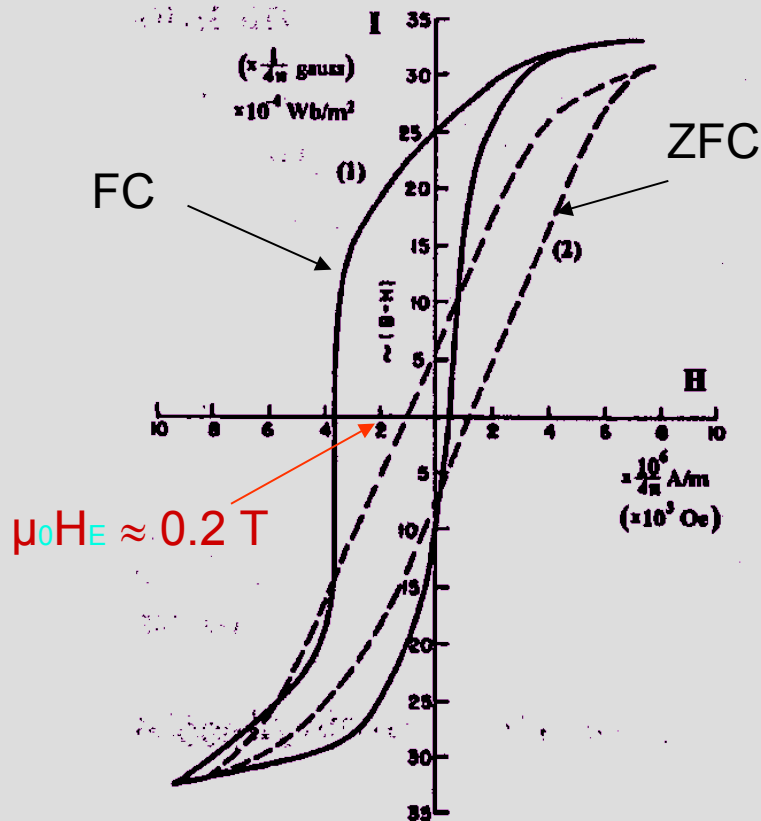


Practical aspects

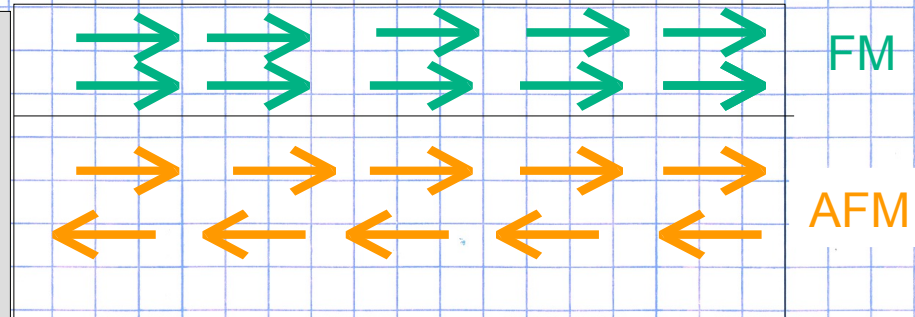
- ⇒ Ru spacer layer (largest effect)
- ⇒ Control thickness within a few Angströms !

Seminal studies

Oxidized Co nanoparticles



Meiklejohn and Bean,
 Phys. Rev. 102, 1413 (1956),
 Phys. Rev. 105, 904, (1957)



Field-cooled hysteresis loops

↺ Shift in field
 ↺ Increase coercivity

Exchange bias

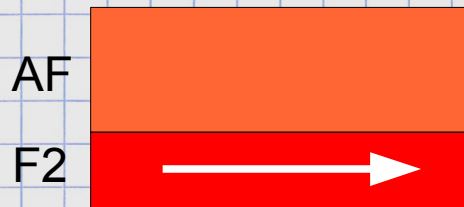
J. Nogués and Ivan K. Schuller
 J. Magn. Magn. Mater. 192 (1999) 203

Exchange anisotropy—a review

A E Berkowitz and K Takano
 J. Magn. Magn. Mater. 200 (1999)



Increase coercivity of layers

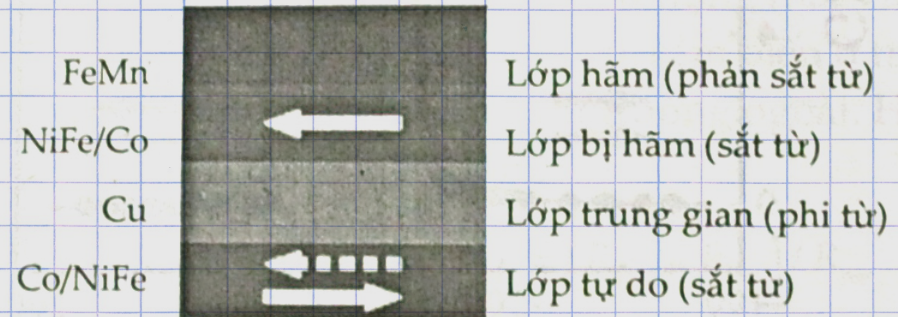


Crude approximation for thin layers:

$$H_{F-AF} \approx H_F \left(1 + \frac{K_{AF} t_{AF}}{K_F t_F} \right)$$

Application

Concept of spin-valve in magneto-resistive elements



B. Diény et al., Phys. Rev. B 43, 1297 (1991)

- ⇒ Sensors
- ⇒ Memory cells
- ⇒ Etc.