Nanomagnetism

Part 3 – Heterostructures

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http://neel.cnrs.fr

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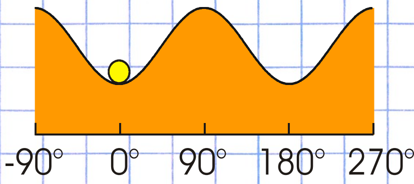

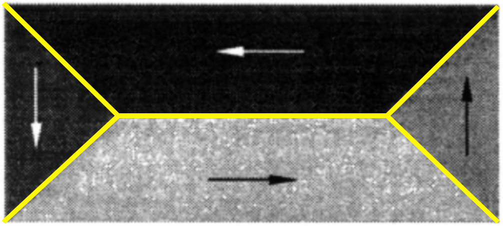

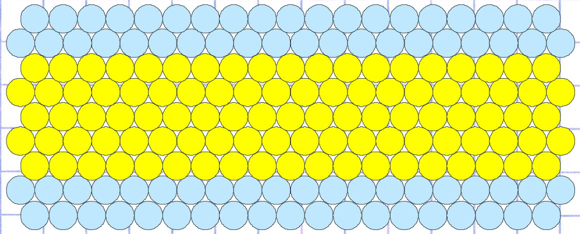

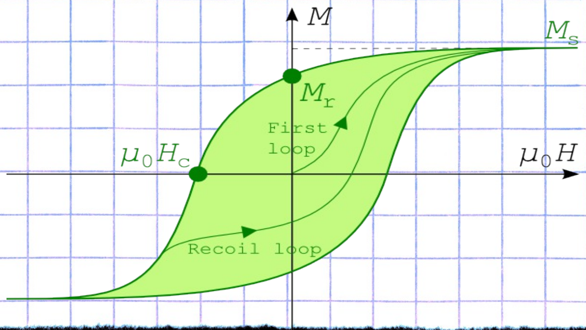

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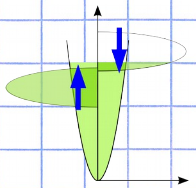
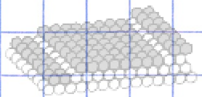
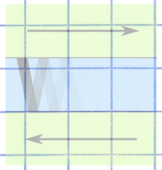






Pt.III : FILMS AND HETEROSTRUCTURES – Ordering and moments (1/4)

Elements of theory

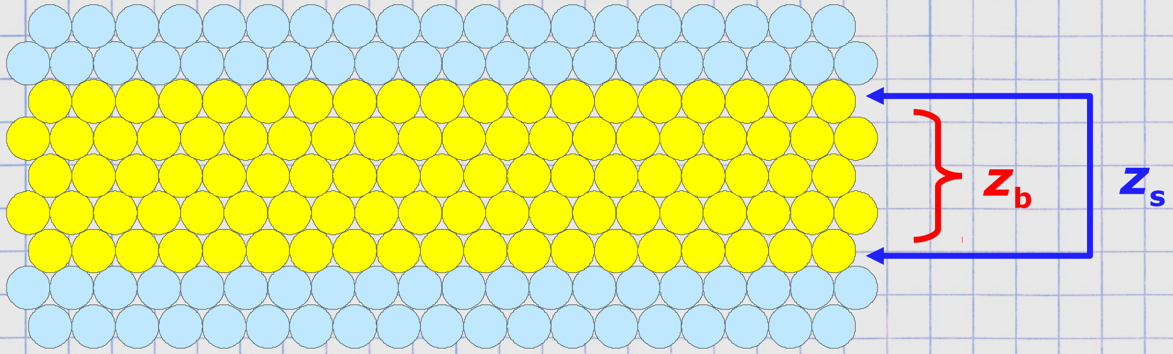
- Ising (1925). No magnetic order at T>0K in 1D Ising chain.
- Bloch (1930). No magnetic order at T>0K in 2D Heisenberg (spin-waves)
- → N. D. Mermin, H. Wagner, PRL17, 1133 (1966)
- Onsager (1944) + Yang (1951).
  2D Ising model: Tc>0K

Magnetic anisotropy stabilizes ordering

Naïve views : mean molecular field

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

z neighbors



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

Less naïve: thickness-dependent mean molecular field

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

$$\lambda = 1$$

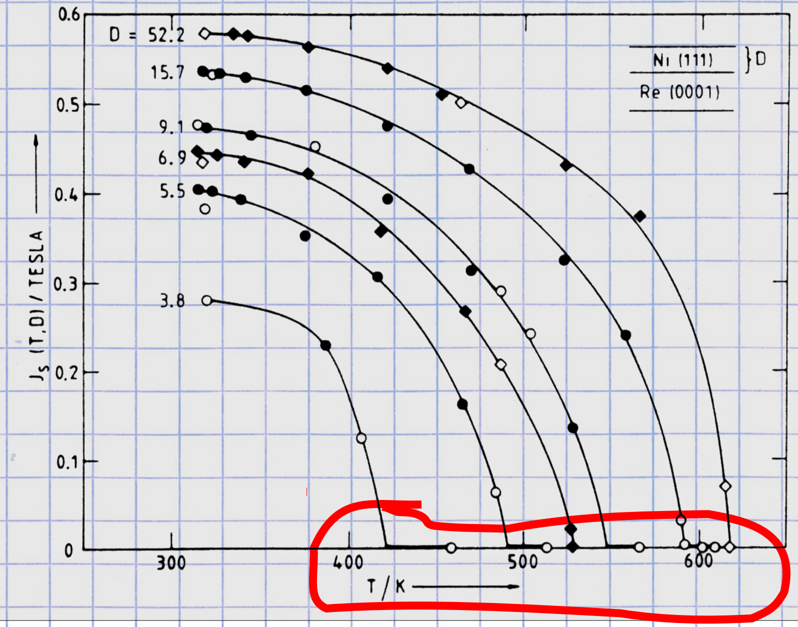
G.A.T. Allan, PRB1, 352 (1970)

Conclusion:
Naïve views are roughly correct

Pt.III : FILMS AND HETEROSTRUCTURES – Ordering and moments (2/4)

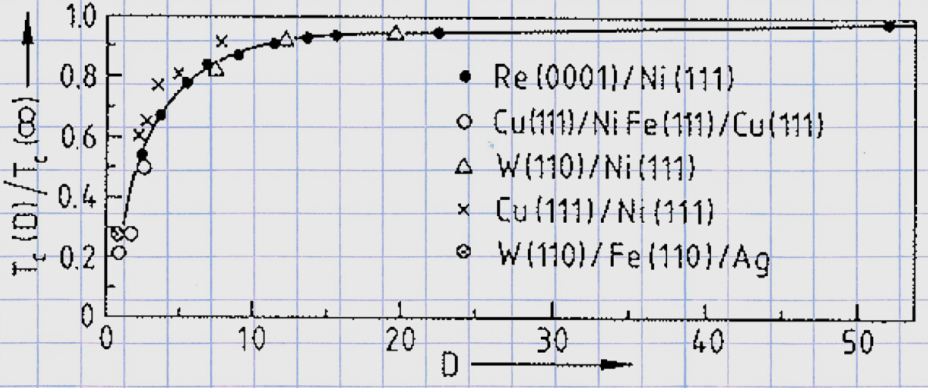
Qualitative

Ni(111)/Re(0001)



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

Quantitative (molecular field)



Tc fitted with molecular field :

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

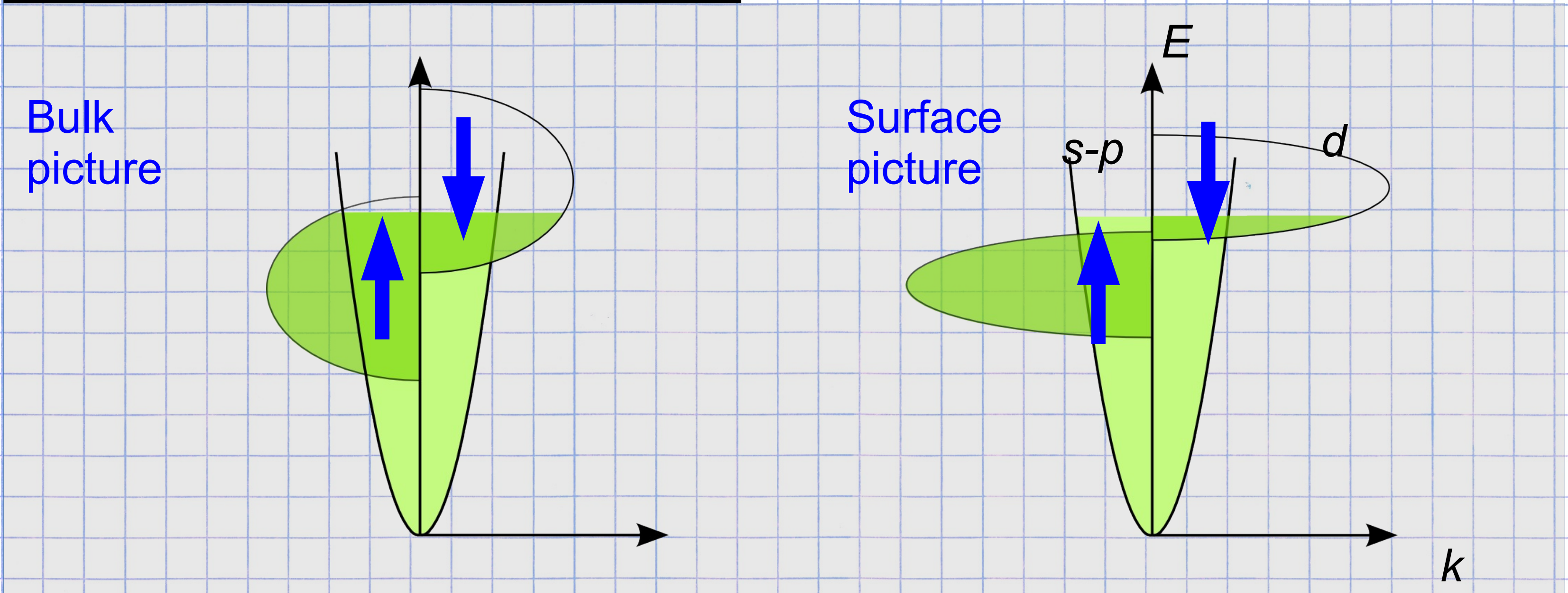
U. Gradmann, Handbook of Magn. Mater. Vol.7, ch.1 (1993)

- Ordering temperature decreases with thickness
- Noticeable below ≈ 1nm

Pt.III : FILMS AND HETEROSTRUCTURES – Ordering and moments (3/4)

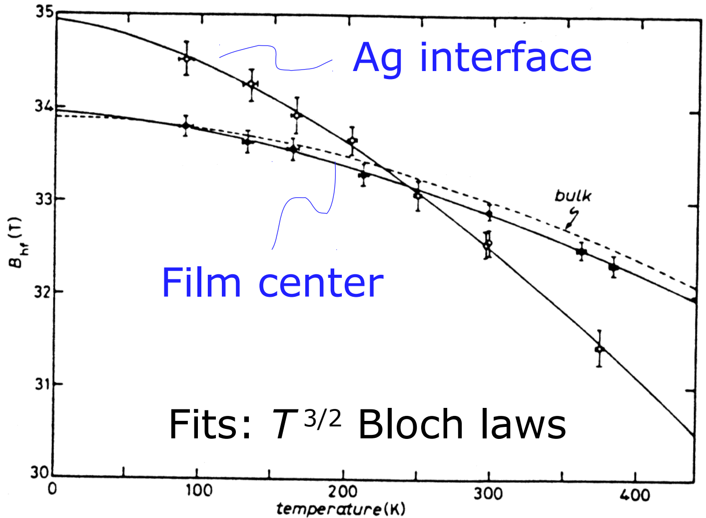
Simple picture: band narrowing at surfaces

Enhanced moment at surfaces



In practice:

20-30 %, however decays faster with temperature



Ag/Fe(110)/W(110)

U. Gradmann et al.

Pt.III : FILMS AND HETEROSTRUCTURES – Ordering and moments (4/4)

Loss of ferromagnetic order

Antiferromagnetism in fcc Fe(001)

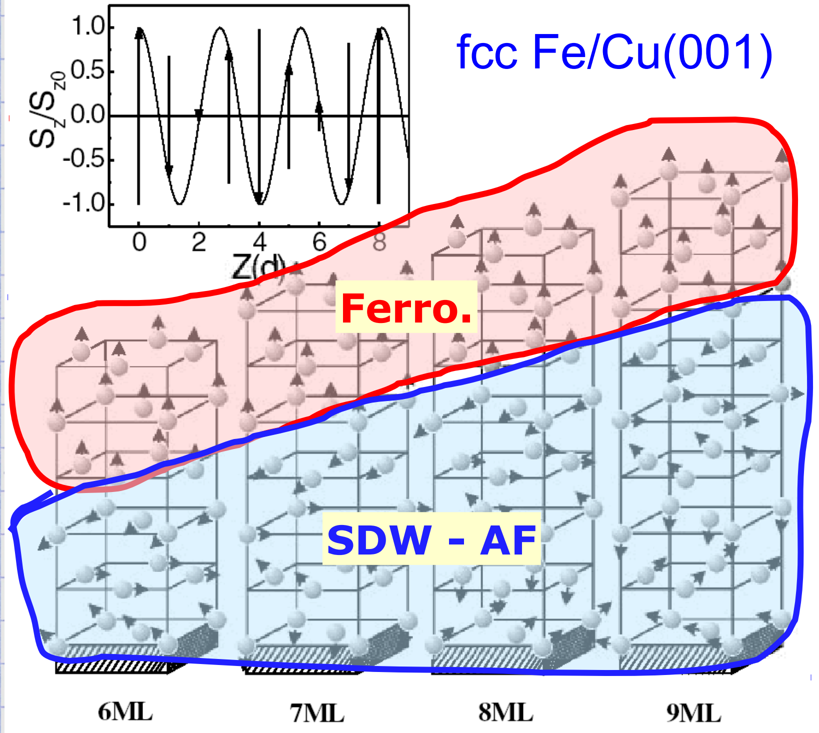


FIG. 4. Magnetic structures proposed for 6, 7, 8, and 9 ML Fe on Cu(100); the inset gives the layer dependent magnetic mo-

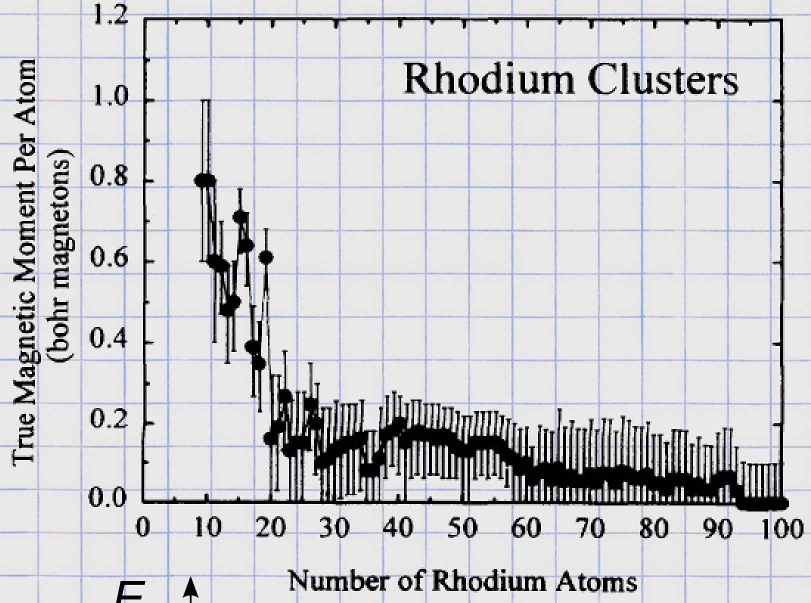
D. Qian et al., PRL87, 227204(2001)
H. L. Meyerheim et al., PRL103, 267202 (2009)

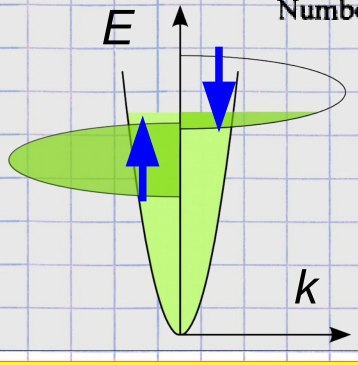
Also high spin phase: V. Cros, EPL49, 807 (2000)

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 !

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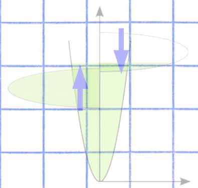
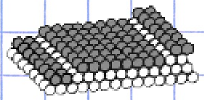
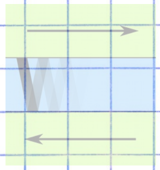


⇨ Ordering and moments



⇨ Interfacial anisotropy



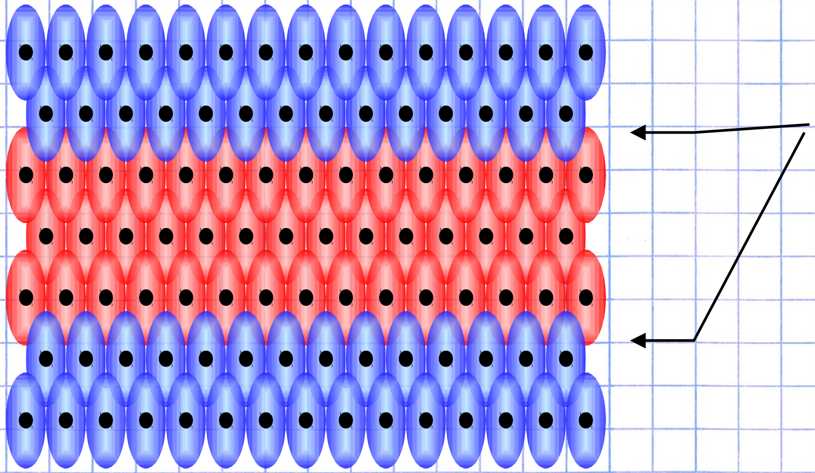
⇨ Heterostructures

Pt.III : FILMS AND HETEROSTRUCTURES – Interfacial anisotropy (1/4)

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

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

« 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:

- ● Ks 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:

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

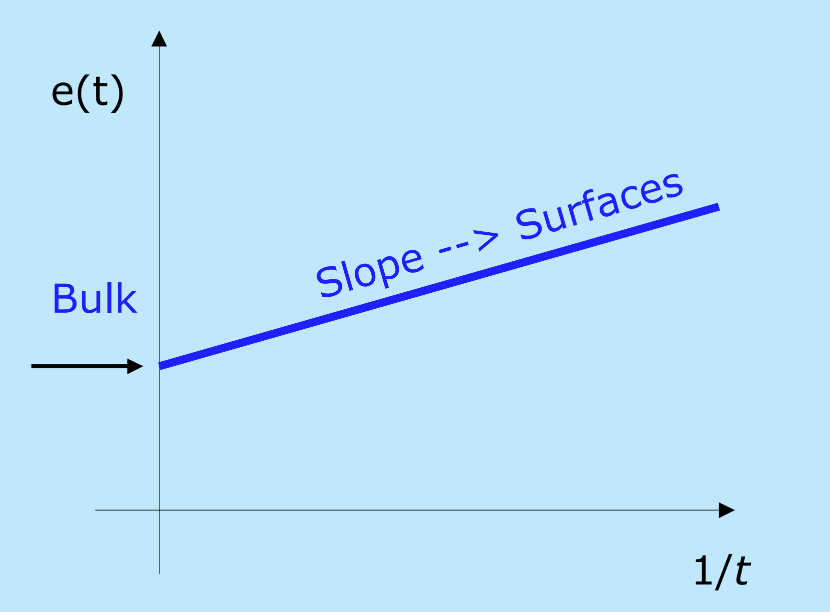
P. Bruno, PRB39, 865 (1989)

Pt.III : FILMS AND HETEROSTRUCTURES – Interfacial anisotropy (2/4)

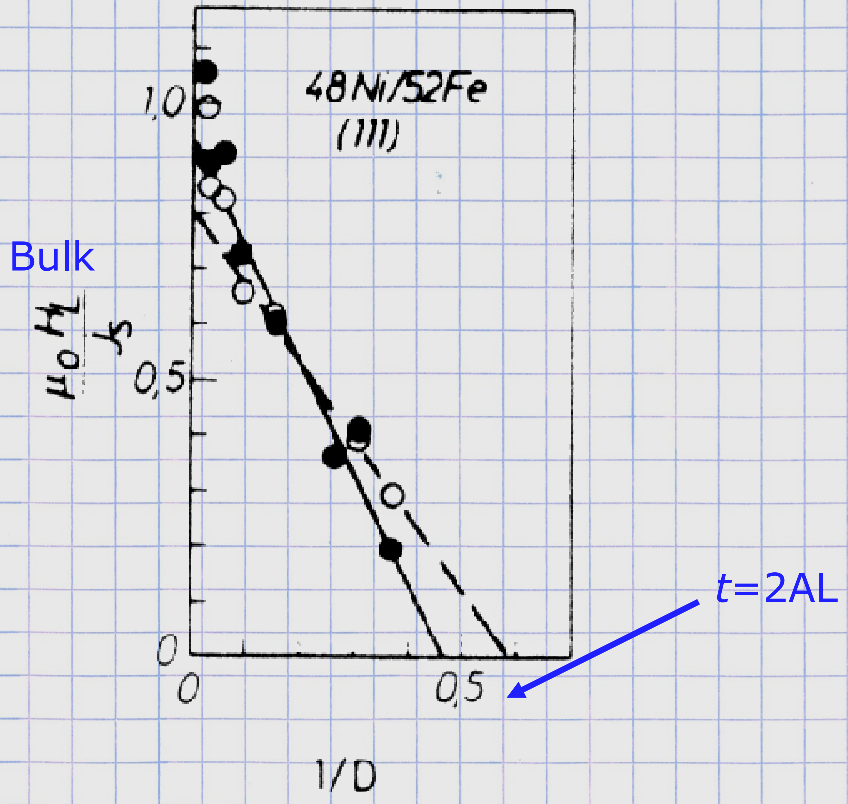
History of surface anisotropy : 1/t plot

$$\mathcal{E}(t)=K_{\mathrm{V}}t+2K_{\mathrm{s}}$$

$$\Rightarrow \quad E(t)=K_{\mathrm{V}}+\frac{2K_{\mathrm{s}}}{t}$$



First example of perpendicular anisotropy



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

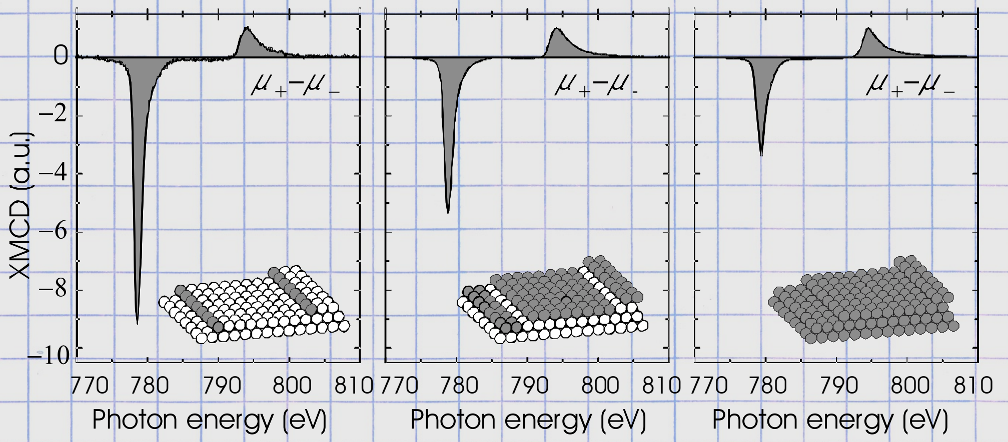
➥ Too simple picture : strain relaxation also yield 1/t law

➥ Non-linear magneto-elasticity may be important (eg : Co)

Pt.III : FILMS AND HETEROSTRUCTURES – Interfacial anisotropy (3/4)

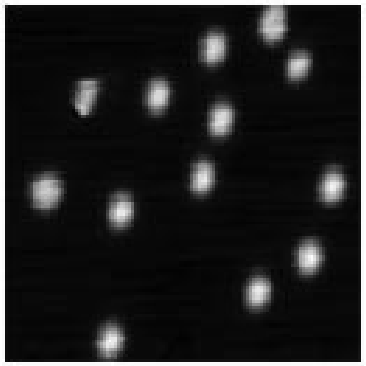
Experimental systems

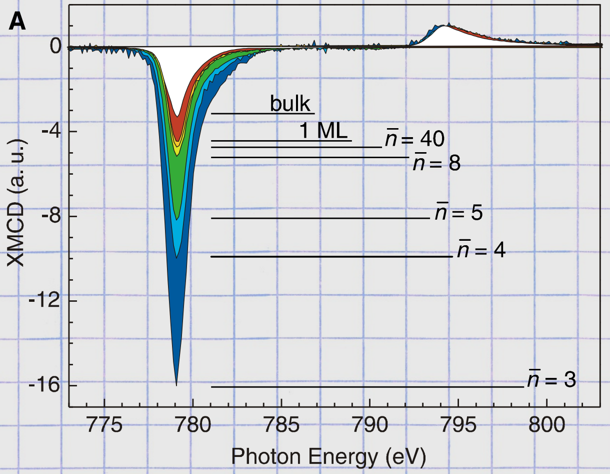
Co on vicinal Pt(111) probed by Xray dichroism



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: 40μeV/atom
- Co ML: 140μeV/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, RPP59, 1409 (1996)

U. Gradmann, Handbook7, Bushow (1993)

⇨ Bonding with oxide : Al$_2$O$_3$, MgO... (→ 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)

Pt.III : FILMS AND HETEROSTRUCTURES – Interfacial anisotropy (4/4)

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 magnetoelasticiv : Co/Ni, NiPd etc.

⇨ Interface : 3d + heavy elements for large spin-orbit coupling : Co/Au, Co/Pt, Co/Pd

⇨ Interface (more recent)

- 3d / oxydes (Mg0, 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)

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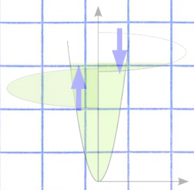
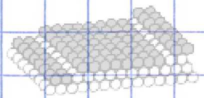
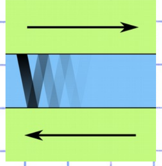


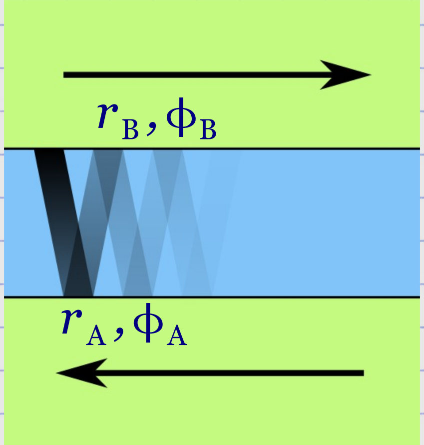




Pt.III : FILMS AND HETEROSTRUCTURES – Heterostructure effects (1/6)

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

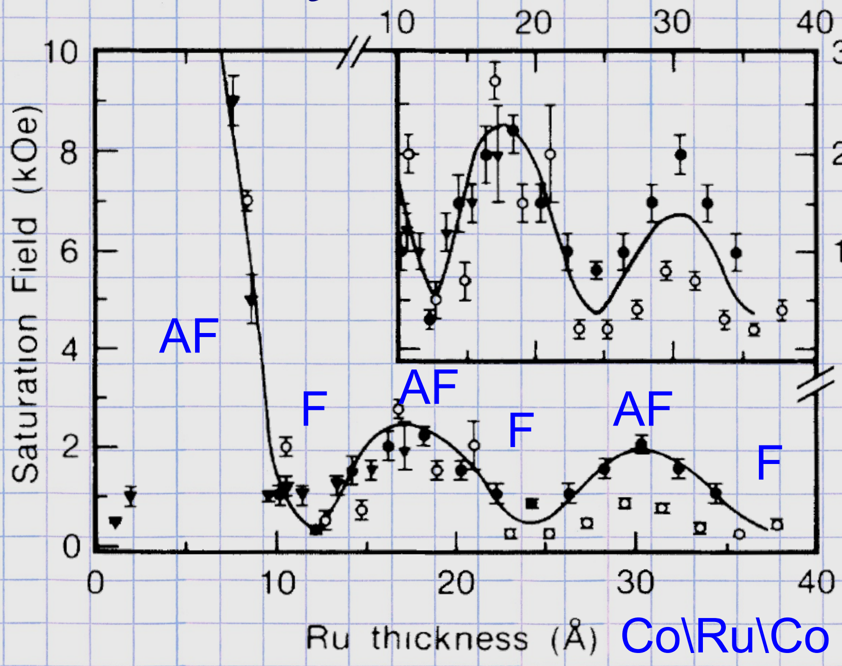
Illustration

Coupling strength:

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

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

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

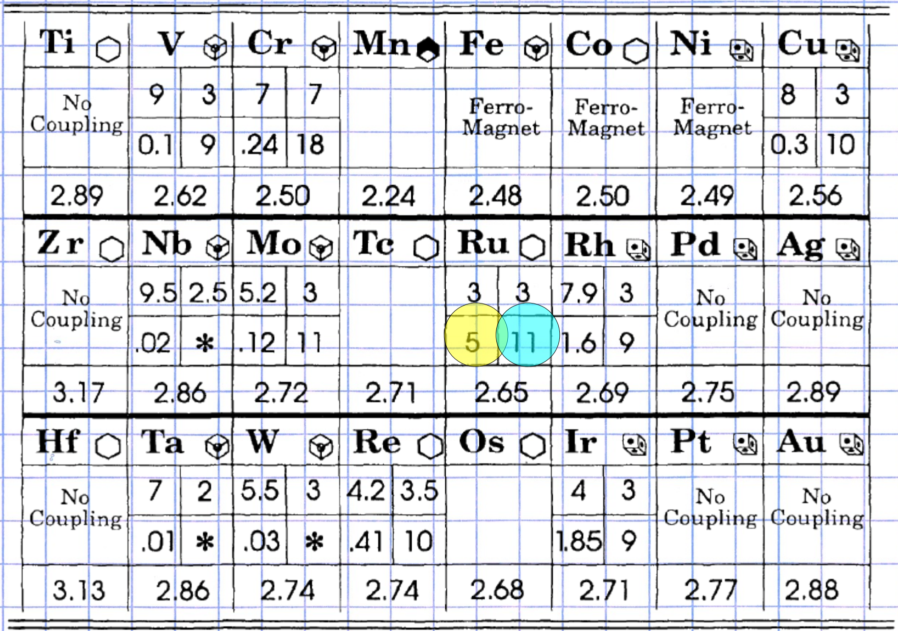


S. S. P. Parkin et al., PRL64, 2304 (1990)

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

Pt.III : FILMS AND HETEROSTRUCTURES – Heterostructure effects (2/6)

Illustration of coupling strength



Element	Structure	A_1 (Å)	ΔA_1 (Å)	J_1 (erg/cm²)	P (Å)	r_{ws} (Å)
Ti	hcp	No Coupling				2.89
V	bcc	9	3	0.1	9	2.62
Cr	bcc	7	7	.24	18	2.50
Mn	complex cubic					2.24
Fe	bcc	Ferro-Magnet				2.48
Co	hcp	Ferro-Magnet				2.50
Ni	fcc	Ferro-Magnet				2.49
Cu	fcc	8	3	0.3	10	2.56
Zr	hcp	No Coupling				3.17
Nb	bcc	9.5	2.5	.02	*	2.86
Mo	bcc	5.2	3	.12	11	2.72
Tc	hcp					2.71
Ru	hcp	3	3	5	11	2.65
Rh	fcc	7.9	3	1.6	9	2.69
Pd	fcc	No Coupling				2.75
Ag	fcc	No Coupling				2.89
Hf	hcp	No Coupling				3.13
Ta	bcc	7	2	.01	*	2.86
W	bcc	5.5	3	.03	*	2.74
Re	hcp	4.2	3.5	.41	10	2.74
Os	hcp					2.68
Ir	fcc	4	3	1.85	9	2.71
Pt	fcc	No Coupling				2.77
Au	fcc	No Coupling				2.88

fcc
bcc
hcp
complex cubic

Element	
A_1 (Å)	ΔA_1 (Å)
J_1 (erg/cm²)	P (Å)
r_{ws} (Å)	

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

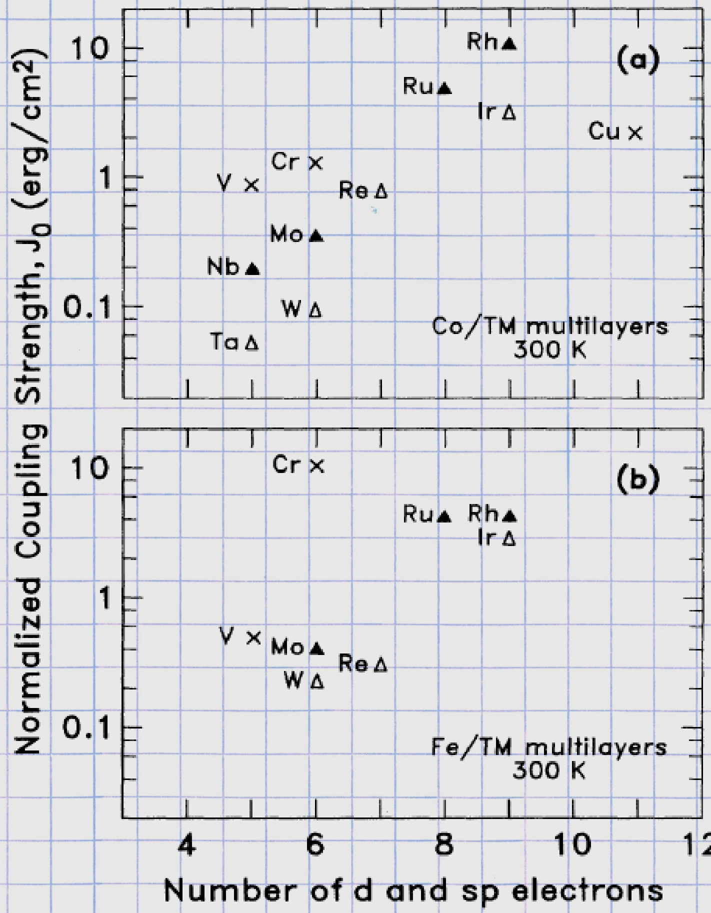


FIG. 3. Dependence of the normalized exchange coupling constant on the 3*d*, 4*d* and 5*d* transition metals in (a) Co/TM and (b) Fe/TM multilayers.

Note: *J*(*t*) extrapolated for t=3Å

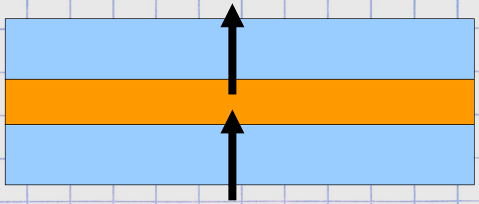
S. S. P. Parkin, Phys. Rev. Lett. 67, 3598 (1991)

Pt.III : FILMS AND HETEROSTRUCTURES – Heterostructure effects (3/6)

Stacked dots : dipolar coupling

In-plane magnetization

Out-of-plane magnetization



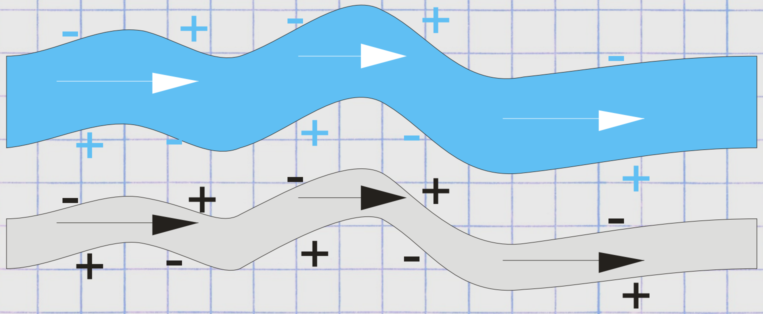
Hint:

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)

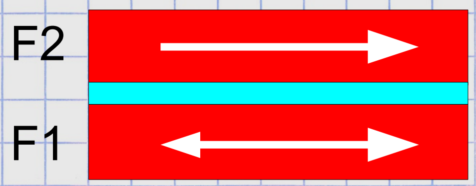
Out-of-plane magnetization

May be parallel or antiparallel

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

Pt.III : FILMS AND HETEROSTRUCTURES – Heterostructure effects (4/6)

Synthetic Ferrimagnets (SyF) – Crude description



Hypothesis:

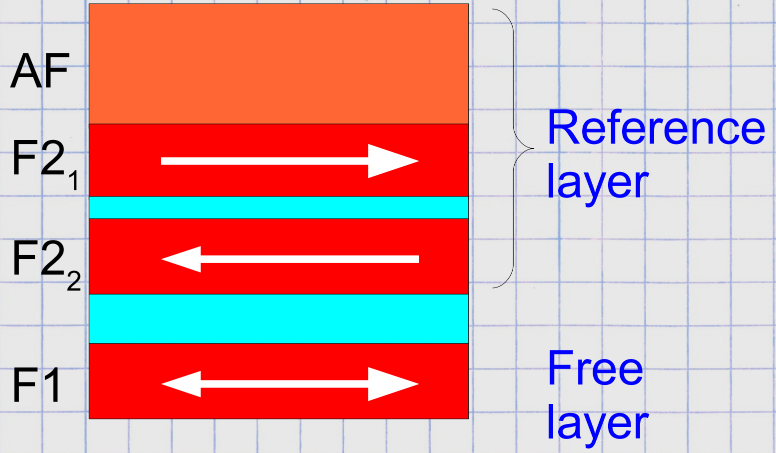
- Two layers rigidly coupled
- Reversal modes unchanged
- Neglect dipolar coupling

$$M=\frac{\left|e_1 M_1 - e_2 M_2\right|}{e_1+e_2} \qquad K=\frac{e_1 K_1 + e_2 K_2}{e_1+e_2}$$

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

What use?

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



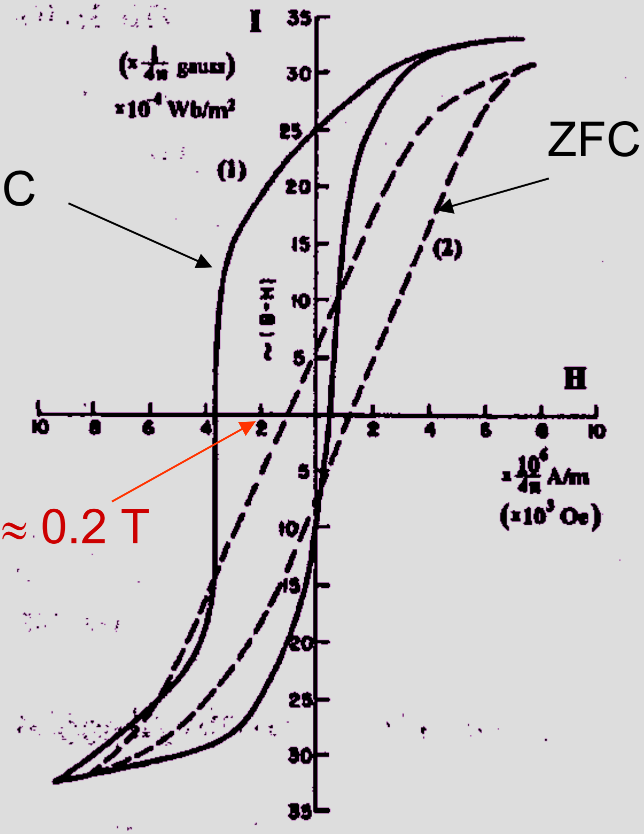
Practical aspects

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

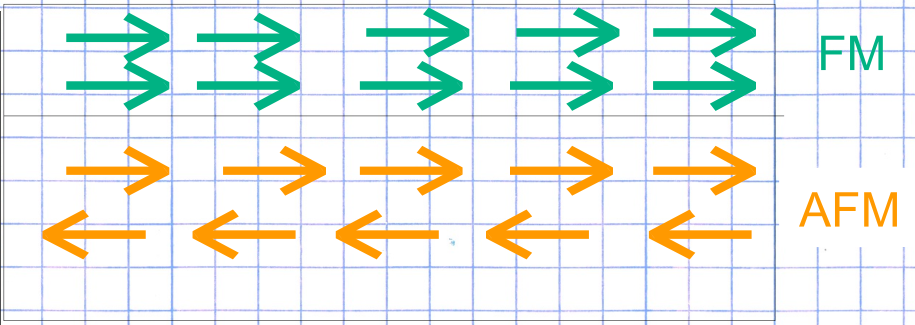
Pt.III : FILMS AND HETEROSTRUCTURES – Heterostructure effects (5/6)

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)

Pt.III : FILMS AND HETEROSTRUCTURES – Heterostructure effects (6/6)

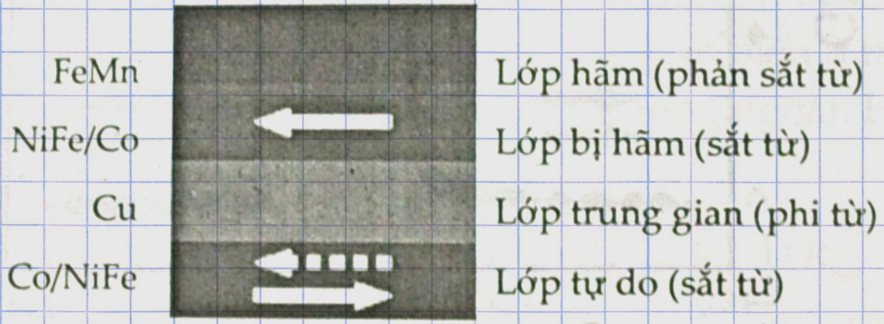
Increase coercivity of layers

Crude approximation for thin layers:

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

Application

Concept of spin-valve in magneto-resistive elements



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

⇨ Sensors

⇨ Memory cells

⇨ Etc.