Methoden moderner Röntgenphysik II: Streuung und Abbildung

Lecture 11	Vorlesung zum Haupt- oder Masterstudiengang Physik, SoSe 2017		
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Location	Lecture hall AP, Physics, Jungiusstraße		
Date	Tuesday	12:30 - 14:00	(starting 4.4.)
	Thursday	8:30 - 10:00	(until 13.7.)

Part II

Magnetism – Magnetic Thin Films

by André Philippi-Kobs (AP)

[23.5.] Magnetic small angle scattering of magnetic domain patterns

- Introduction of magnetism in thin films
- Resonant scattering & X-ray magnetic circular dichroism (XMCD),

[30.5.] Imaging of magnetic domains

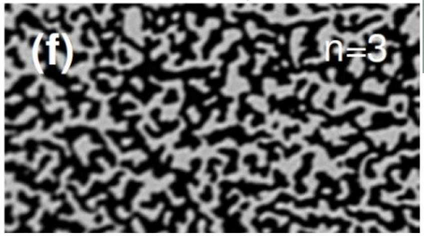
- Fourier transform holography (FTH)
- Scanning transmission X-ray microscopy (STXM)
- Coherent diffraction imaging (CDI), Ptychography

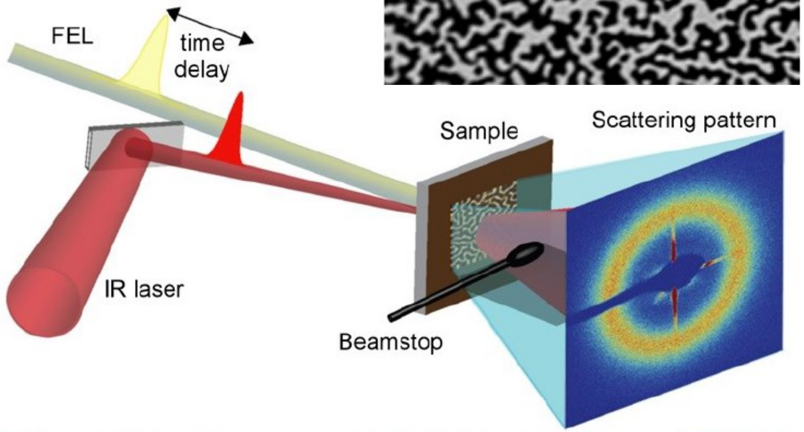
[1.6.] Femtomagnetism

- Introduction of ultrafast magnetization dynamics
- Pump-probe experiments of nano-scale magnetic domain patterns

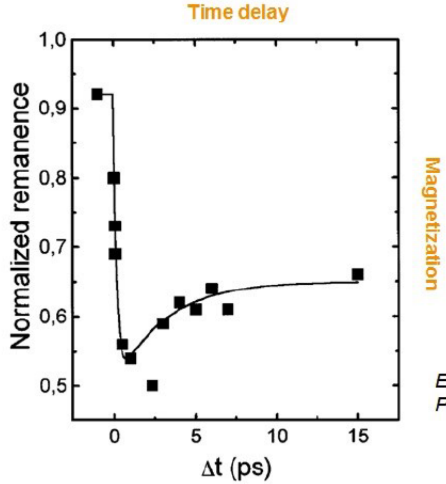
[13.6.] Related aspects

- Determination of coherence via magnetic domain patterns
- Magnetic XRD of antiferromagnets and chiral systems
- Further electronic inhomogeneities probed by X-rays (charge density wave; Abrikosov vortices in superconductors)





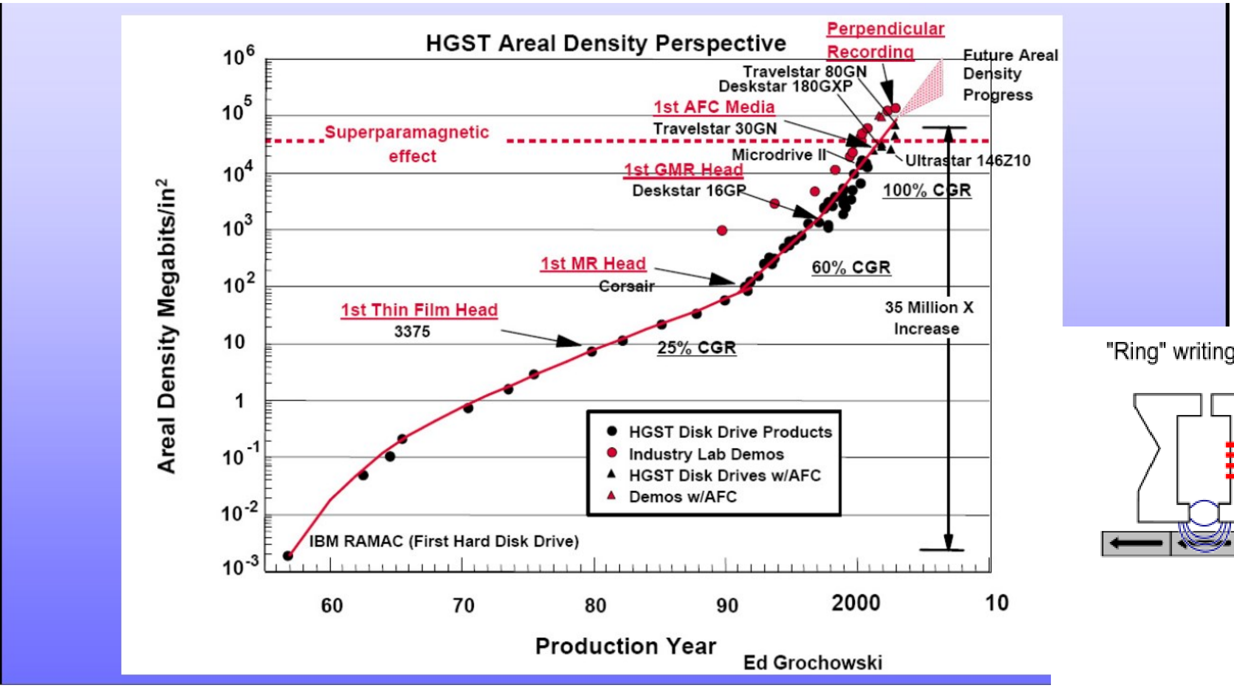
B. Pfau et al., Nature Communications, Vol. 3, 11; DOI:doi:10.1038/ncomms2108 (2012)
L.Müller et al., Rev. Sci. Instrum. 84, 013906 (2013)

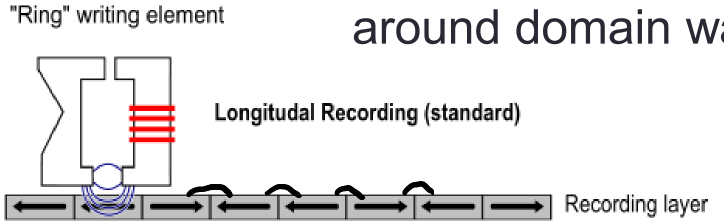


Time-resolved MOKE (Ni 120 fs)

E. Beaurepaire et al., PRL 76 (1996) 4250

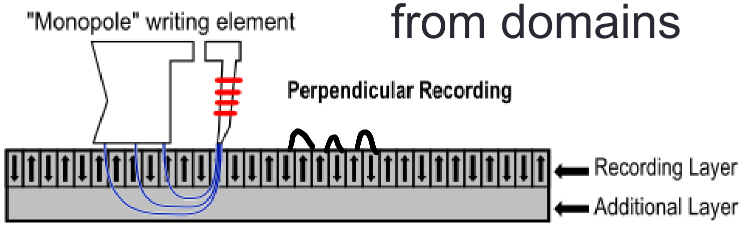
Why thin films with perpendicular anisotropy?



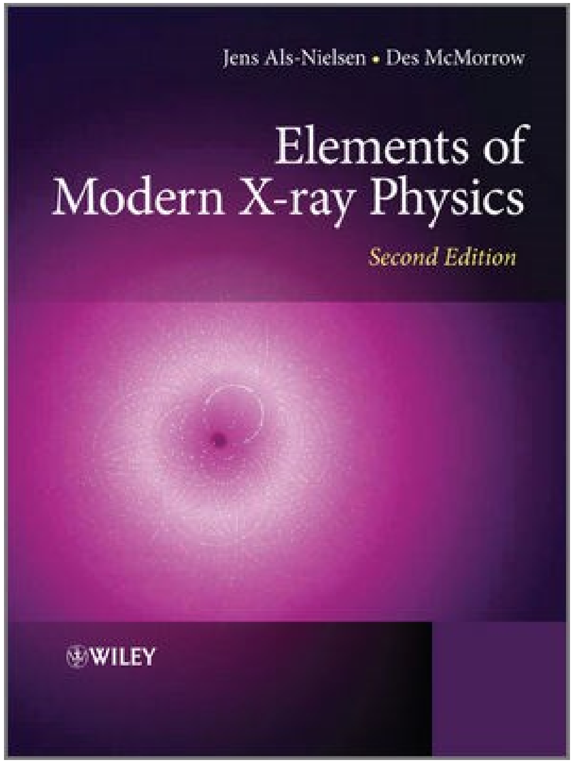


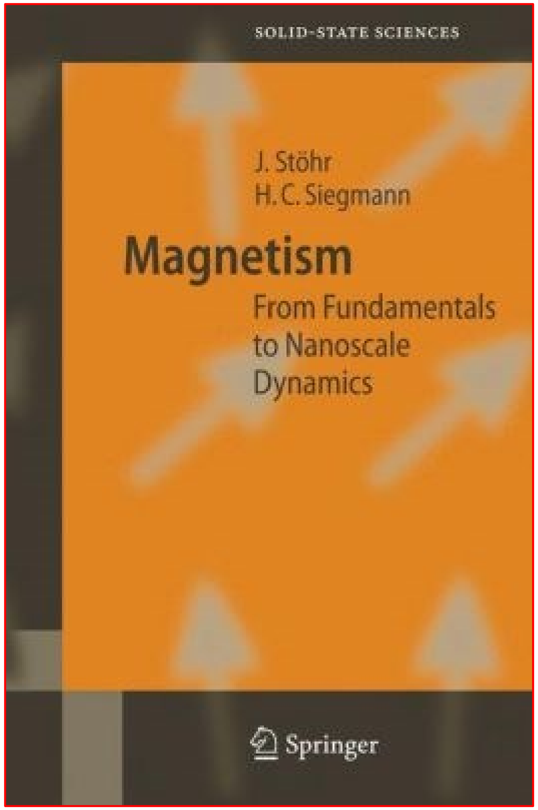
Low stray field around domain walls

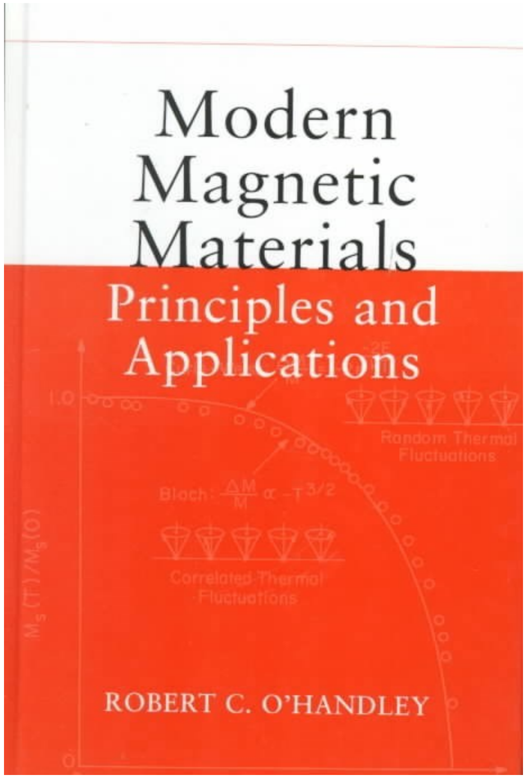
Huge stray field from domains



Literature:







For details about magnetism

Resonant magnetic small angle X-ray scattering (mSAXS) of magnetic domain patterns

1.) Ferromagnetism in a nutshell

- forms of magnetic phenomena
- contributions to free energy
- focus on systems with perpendicular magnetic anisotropy (Co/Pt multilayers)
- magnetic domains and domain walls

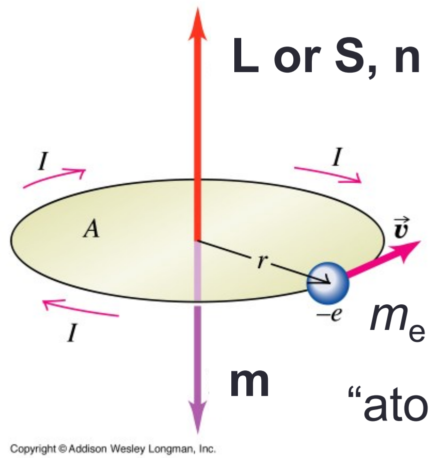
2.) Interaction of **polarized** photons with matter

- Recap: Charge and **Spin** X-ray Scattering by a single electron
- Recap: Resonant Scattering (semi-classical concept, Kramers-Kronig)
- Resonant scattering (quantum-mechanical concept, Fermi's Golden rule)
- Interactions of photons with ferromagnetic materials ➔ XMCD effect
- XMLinearD and X-ray Natural Dichroism

3.) Resonant magnetic SAXS of magnetic domain patterns

Ferromagnetism in thin films – Forms of magnetism

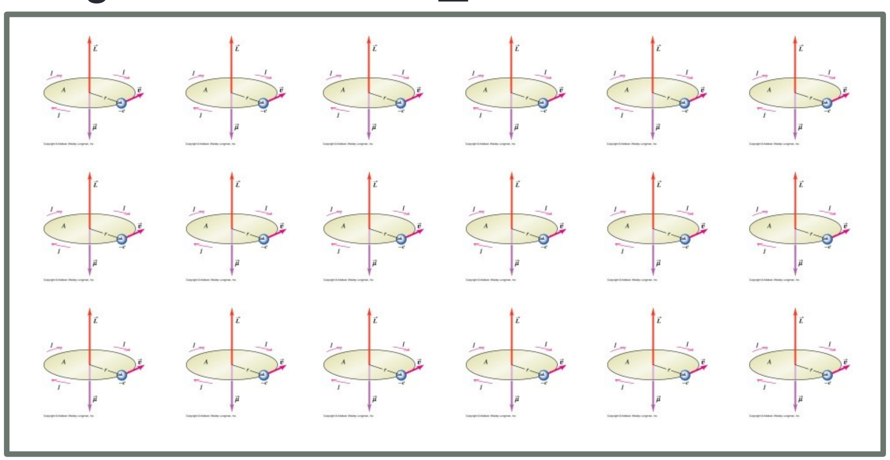
> Magnetic (dipole) moment **m** (basis element of magnetism)



Definition: $\mathbf{m} = I \cdot A \cdot \mathbf{n}$
Unit: $[m] = \mathrm{Am}^2$

“atom“ = conductor (or current) loop (Physik II)

- Magnetization: $\mathbf{M} = \sum \mathbf{m}/V$



Saturation magnetization (“length” of **M**):

$$M_S = |\sum \mathbf{m}|/V$$

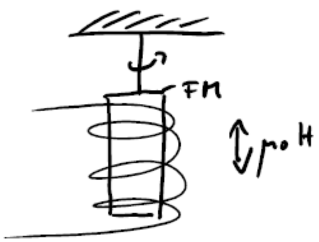
Volume V

Ferromagnetism in thin films – Forms of magnetism

- Connection to angular momentum **L**

Current loop of moving charges with mass m_e exhibits angular momentum

$\mathbf{m} = \gamma \mathbf{L}$ γ: gyromagnetic ratio (proportionality proofed 1915 by Einstein-de Haas)



Torsion of string when **M** is changed by magnetic field

Gyromagnetic ratio γ :

$$|\vec{m}| = I \cdot A \quad , \quad |\vec{L}| = N m r v$$

N : number of particles

$$\gamma = \frac{I \cdot A}{N r m v} = \frac{N q \cancel{\pi} r^{\cancel{2}} \cancel{T}}{\cancel{T} \cancel{N} \cancel{r} m 2 \cancel{\pi} \cancel{r}}$$

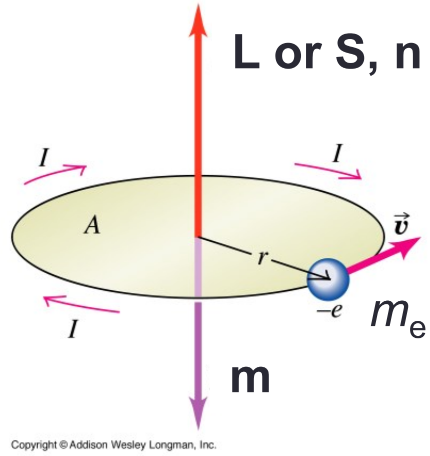
$$\gamma = \frac{q}{2m}$$

$$v = \frac{2\pi r}{T}$$

$$I = \frac{N \cdot q}{T}$$

Ferromagnetism in thin films – Forms of magnetism

Quantization of angular momentum **L** in units of $\hbar$
➔ Quantization of **m** in units of Bohr magneton μ_B



$|\vec{m}| = \gamma \hbar = \frac{q\hbar}{2m_e}$ For q = |e| ➔

$\mu_B = 9.274 \cdot 10^{-24}\,\mathrm{Am}^2$ Bohr magneton

$\gamma < 0$ for e^- $\Rightarrow$ $\vec{L} \uparrow\downarrow \vec{m}$

Landé- or g- (or gyromagnetic-)factor: $\gamma = g\frac{q}{2m}$

$g = 1$ (classical description: angular momentum)

but $g \approx 2$ for spin

Ferromagnetism in thin films – Forms of magnetism

> Forms of magnetic phenomena in solid states

Diamagnetism and Paramagnetism

- Lorentz-force on moving charges in a magnetic field **B**: $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$

- Two further terms in Hamiltonian: $H = H_0 + H'$

- For one electron on circular loop ("atom"):

$$H' = \overbrace{\frac{q}{2m_\mathrm{e}}\mathbf{L}}^{-\mathbf{m}} \cdot \mathbf{B} + \frac{q^2}{8m_\mathrm{e}}(\mathbf{B} \times \mathbf{r})^2$$

electron radius

1.) Paramagnetic term
- energy of magnetic dipole in field
- alignment of **m** with magnetic field **B**
- *T* dependent (later)

2.) Diamagnetic term
- all materials are diamagnetic
- always > 0
- inhomogeneous field: atom can reduce energy when moving to region of lowest field
- *T* independent

Ferromagnetism in thin films – Forms of magnetism

> Forms of magnetic phenomena in solid states

Diamagnetism and Paramagnetism

- Ratio of both corrections:

$$\frac{\frac{q}{2m}\vec{L}\cdot\vec{B}}{\frac{q^2}{8m}(\vec{B}\times\vec{r})^2} \geq \frac{\overbrace{\frac{q}{2m}\hbar}^{\mu_B \text{ for } q=|e|} B}{\frac{q^2}{8m}(\vec{B}\,\vec{r})^2} = \frac{4\hbar}{q B r^2} = 10^4$$

for $r = 1.5\,\text{Å}$, $|\vec{B}| = 10\,T$

- Comparison of paramagnetic term to thermal energy at room temp. for B = 10 T:

$E_{therm} = 25\,meV$

$E_{para} = 0.58\,meV$ → two orders smaller than $k_B T$

- Thermodynamic description:

$$\frac{<m>}{\mu_B} = \tanh\frac{\mu_B B}{k_B T} \approx \frac{\mu_B B}{k_B T} = \frac{E_{para}}{E_{therm}}\ ; \quad \frac{<m>}{\mu_0} = 0.023 \text{ for RT \& } B = 1\,T$$

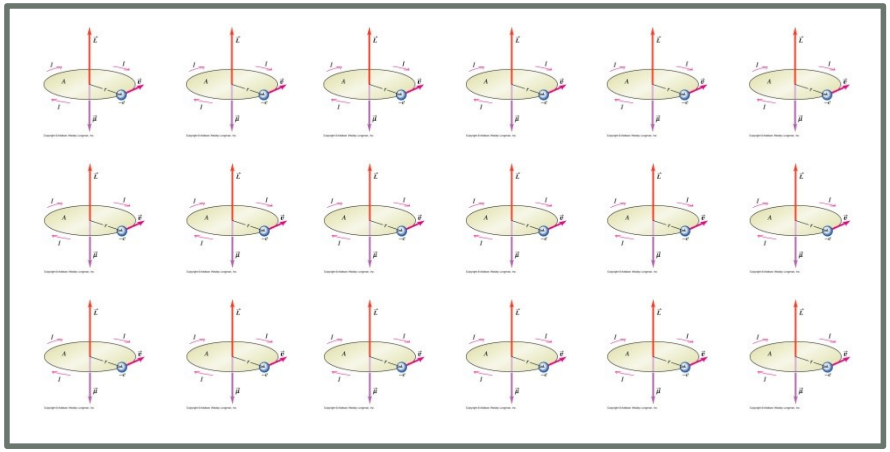
DESY

Ferromagnetism in thin films – Forms of magnetism

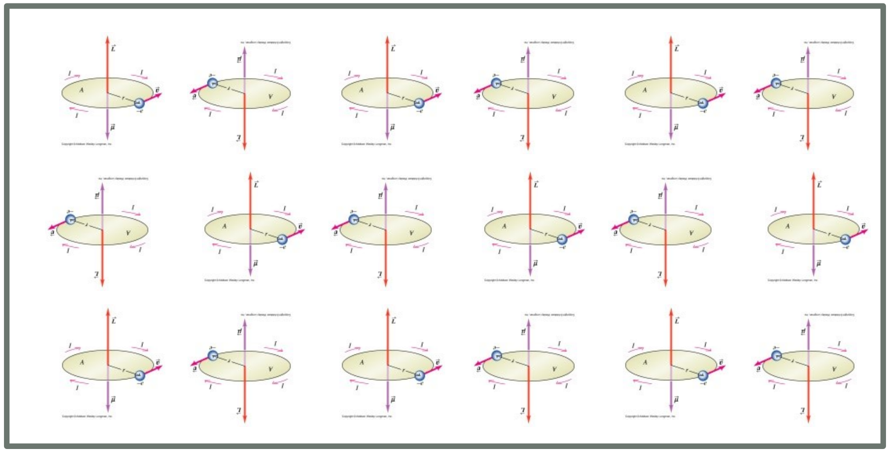
- Forms of magnetic phenomena in solid states

Materials with long range magnetic order (without external magnetic field) due to strong interaction between electron‘s magnetic moments

Ferromagnetism (FM)



Antiferromagnetism (AFM)



Classic description via mean field (Weiß 1907): $|\mathbf{B}_{xc}| = \mu_0 \lambda(J)|\mathbf{M}| = 10^3$ T!

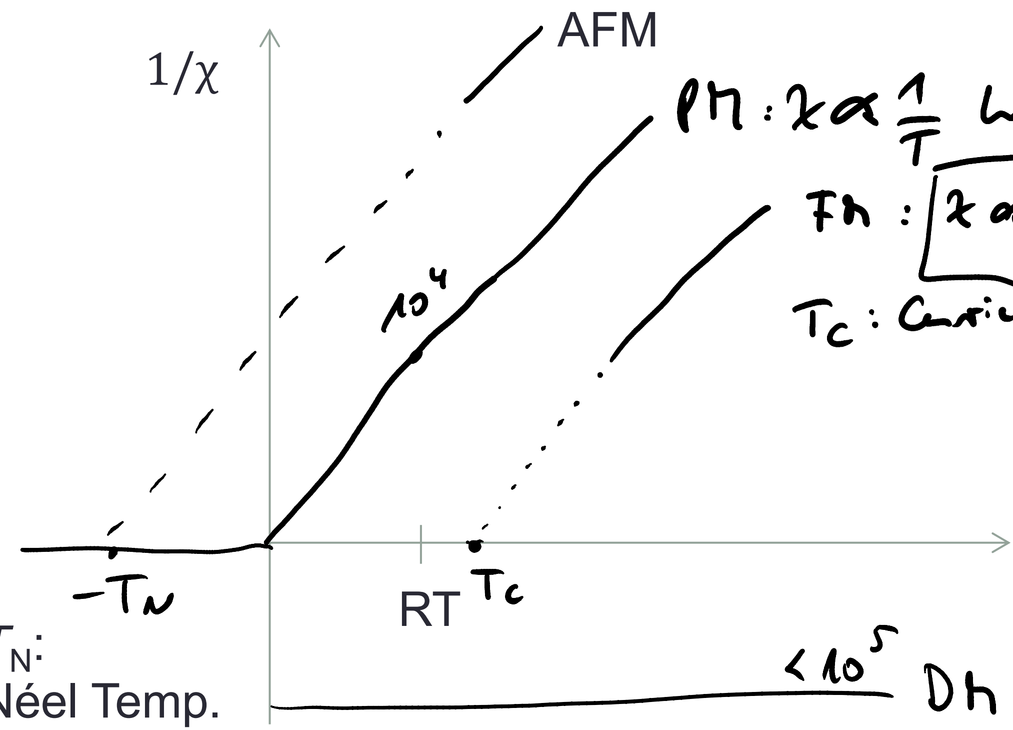
Ferromagnetism in thin films – Forms of magnetism

- Forms of magnetic phenomena ($\vec{M} = \frac{\partial E}{\partial \vec{B}}$ ← free energy $\chi = -\mu_0 \frac{\partial^2 E}{\partial B^2}$)

  Classification by means of magnetic susceptibility χ, i.e., response to of magnetization to magnetic field (in high T regime):

$$\chi = \mu_0 \frac{d\mathbf{M}}{d\mathbf{B}} = \frac{d\mathbf{M}}{d\mathbf{H}}$$

Magnetic flux density **B**, Magnetic field **H**



PM: $\chi \propto \frac{1}{T}$ Weiß law

FM: $\boxed{\chi \propto \frac{1}{T - T_C}}$ Curie-Weiß law

T_C: Curie Temp.

DM ($\chi < 0$)

T_N:
Néel Temp.

Note:
For FM and AFM state (low T)

scalar

$\vec{M} \neq \chi \vec{H}$!!!

a) $\chi = f(\vec{H})$

b) $\chi = f(\text{history})$

c) $\chi = f(\text{shape})$

d) $\chi = f(\text{part})$

:

Ferromagnetism in thin films

- Magnetic free energy

$$E_{\mathrm{total}} = E_{\mathrm{XC}} + E_{\mathrm{MCA}} + E_{\mathrm{demag}} + E_{\mathrm{Zeeman}} + E_{\mathrm{DMI}} + \ldots$$

Exchange energy

Magnetocrystalline Anisotropy

Demagnetization or stray field energy

Zeeman energy

Dzyaloshinskii-Moriya interaction

In equlibrium:

$dE/dm_i = 0$

$(d^2E/dm_i^2 > 0)$

Ferromagnetism in thin films

> Exchange energy

- Origin:

  1.) Coulomb interaction between electrons $H_{\text{Coulomb}} = \frac{1}{2}\sum_{i \neq j} \frac{e^2}{4\pi\epsilon_0 r_{ij}}$

  2.) Pauli‘s exclusion principle: Total wave function $|\phi> = |\Psi>\cdot|\chi>$ is antisymmetric when interchanging two identical = undistinguishable particles

Spatial wave function

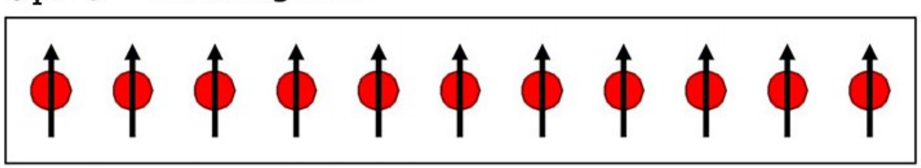
$$J \propto <\Psi_{\text{symmetric}}|H_{\text{Coulomb}}|\Psi_{\text{symmetric}}> - <\Psi_{\text{antisymmetric}}|H_{\text{Coulomb}}|\Psi_{\text{antisymmetric}}>$$

Exchange constant (or integral)

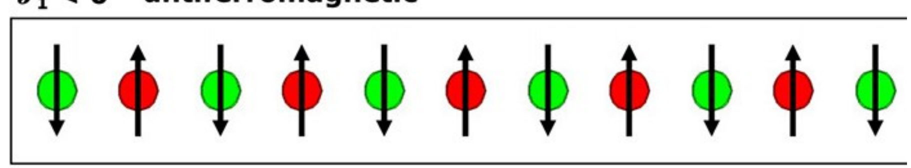
➔ Heisenberg exchange (effective spin-spin interaction)
(generally, only next neighbor interaction)

$$\boxed{E_{\text{XC}} = -\sum_{i \neq j} J_{ij}\ \mathbf{S}_i \cdot \mathbf{S}_j}$$

$J_1 > 0$ **ferromagnetic**



$J_1 < 0$ **antiferromagnetic**



Ferromagnetism in thin films

- Micromagnetic approximation

➔ Define continuous variables like saturation magnetization $M_S = |\sum \mathbf{m}|/V$

➔ Exchange energy $$E_{\mathrm{xc}} = A \int_V \left((\nabla m_x)^2 + (\nabla m_y)^2 + (\nabla m_z)^2 \right) dV$$ $$m_i = \frac{M_i}{M_S}$$

A: exchange stiffness
$A \approx 10$ pJ/m

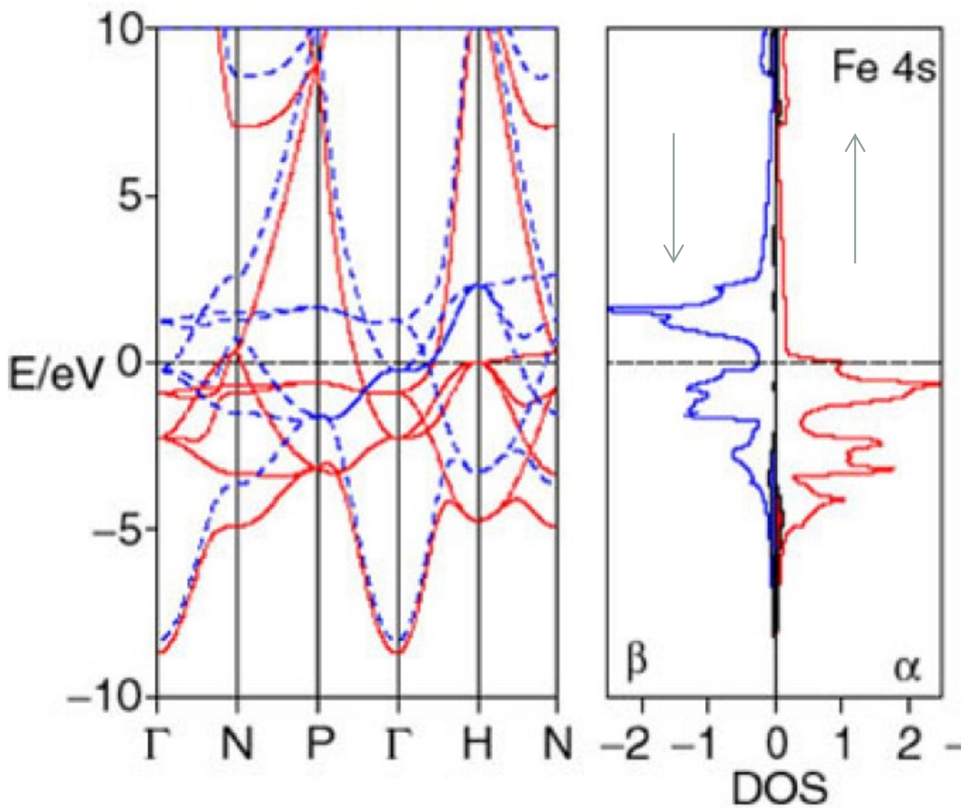
➔ $\Delta E_{xc}/V \approx (E_{\uparrow\downarrow} - E_{\uparrow\uparrow})/V$ = 1 GJ/m³ (0.1 eV/atom ≈ 4 times thermal energy at RT)

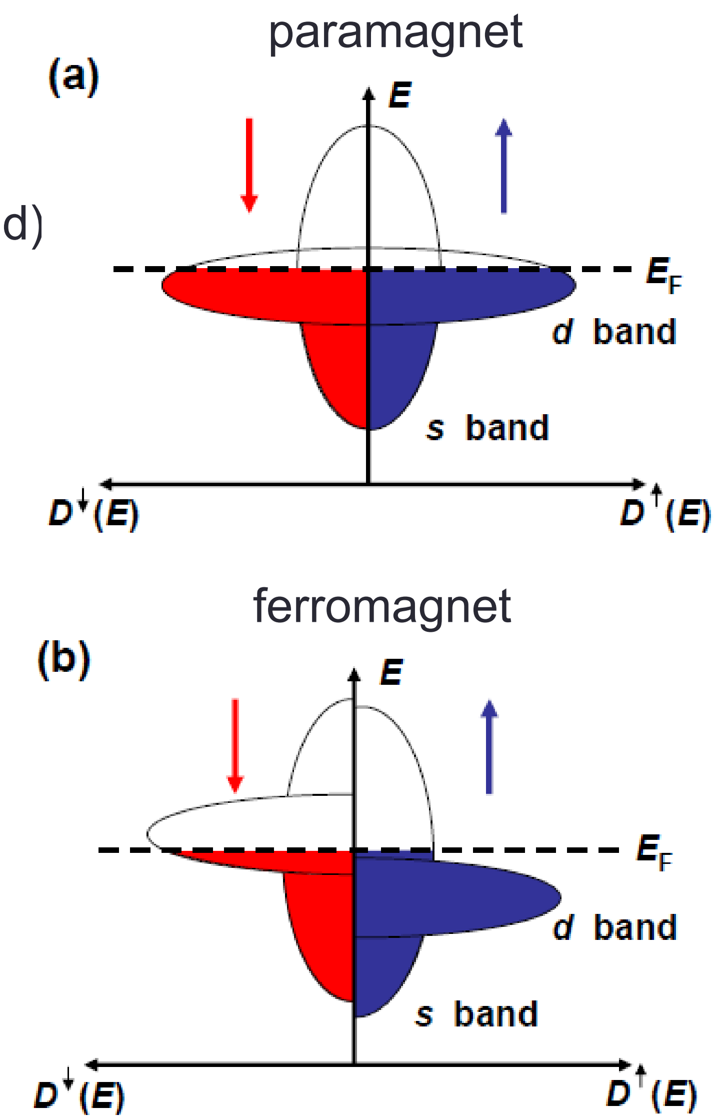
➔ FM at room temperature!

Ferromagnetism in thin films

- Itinerant (band) Ferromagnetism for Ni, Fe, Co

(≠ localized FM for rare earth elements like Dy, Tb, Gd)





- Saturation magnetization: $M_S = \mu_B(n_\uparrow - n_\downarrow) = \mu_B D(E_F)\delta E$

Ferromagnetism in thin films

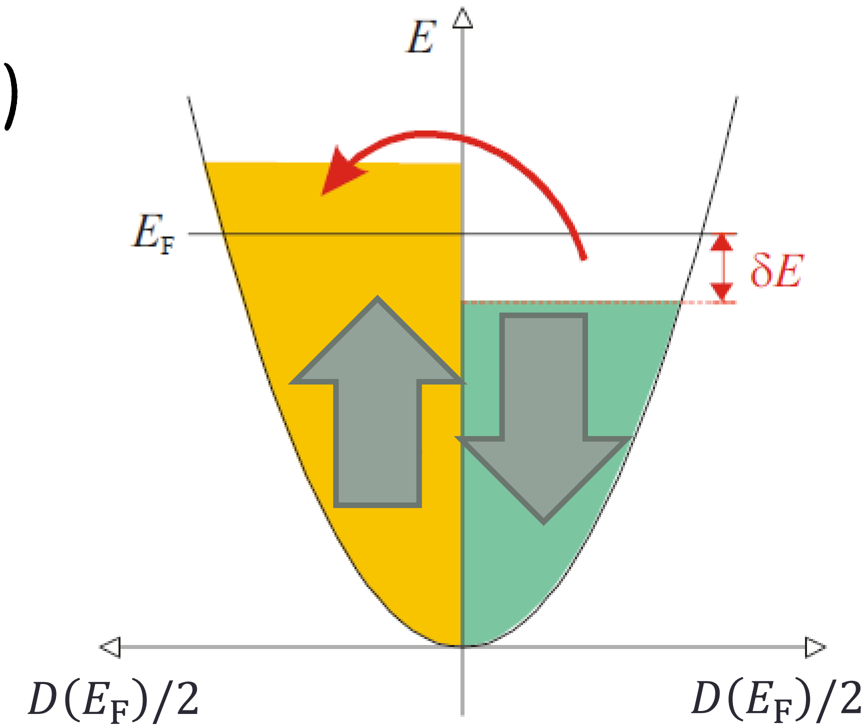
> Itinerant (band) Ferromagnetism for Ni, Fe, Co

- Saturation magnetization: $M_S = \mu_B(n_\uparrow - n_\downarrow) = \mu_B D(E_F)\delta E$

Derivation:

$$n^{\uparrow\downarrow} = \frac{1}{2}\left(n \pm D(E_F)\,\delta E\right)$$

$$M_S = \mu_B \, 2 \, \frac{1}{2} D(E_F)\,\delta E$$



Ferromagnetism in thin films

	$n^o(E_F)[eV^{-1}]$	$I[eV]$	$I\,n^o(E_F)$
Na	0.23	1.82	0.41
Al	0.21	1.22	0.25
Cr	0.35	0.76	0.27
Mn	0.77	0.82	0.63
Fe	1.54	0.93	1.43
Co	1.72	0.99	1.70
Ni	2.02	1.01	2.04
Cu	0.14	0.73	0.11
Pd	1.14	0.68	0.78
Pt	0.79	0.63	0.50

> Itinerant (band) Ferromagnetism

Stoner criterion (1939): $I \cdot D(E_F) > 1$

I : Stoner parameter

- Derivation: Comparison of ferromagnet to paramagnet

1.) Increase of kinetic energy: $\Delta E_{\text{kin}} = \frac{D(E)\delta E}{2}\,\delta E$

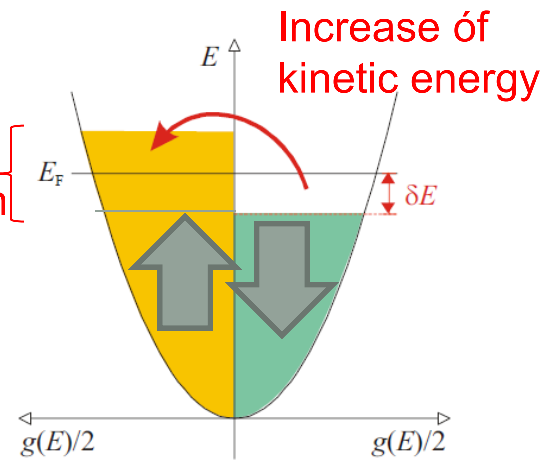
Number of electrons

shift

2.) Decrease of static energy: $dE = -\mu_0 M dH_{xc} = -\mu_0 M \lambda(J) dM$

$$\Delta E_{\text{pot}} = -\int_0^{M_S} M\mu_0\lambda(J)\,\mathrm{d}M = -\frac{\mu_0}{2}\lambda M^2{}_S$$
$$= -\frac{1}{2}\underbrace{\lambda(J)\mu_0\mu_B{}^2}_{I}(D(E_F)\delta E)^2$$

e⁻ without repulsive Coulomb interaciton



3.) Total energy balance:

$$\Delta E = \Delta E_{\text{pot}} + \Delta E_{\text{kin}} = \frac{1}{2}D(E_F)\delta E^2(1 - I \cdot D(E_F))$$

Ferromagnet if $\Delta E < 0 \Rightarrow \boxed{I \cdot D(E_F) > 1}$

Ferromagnetism in thin films

- magnetocrystalline anisotropy

  - Gedankenexperiment:
  Assume an infinite (a) amorphous material/ (b) crystal, which orientation has **M**?

  (a) All spins are aligned in parallel (**M** exists) due to exchange interaction but the direction of **M** is fluctuating

  (b) Crystal field theory: Crystal order breaks isotropy
  + (Quenched) orbital momentum **L** is firmly linked to crystal lattice
  + **Spin orbit interaction** proportional to $\mathbf{L} \cdot \boldsymbol{S}$

  ➔ Energy depends on orientation of **M** with respect to the crystal axes
  = magnetocrystalline anisotropy

Ferromagnetism in thin films

> magnetocrystalline anisotropy

- Most simple case: *Uniaxial* MCA like in hcp crystals (e.g. Co at room temperature)

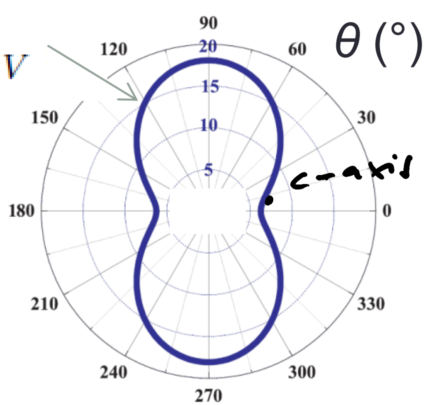
$$(E/V)_{\text{mca, }V} = K_{1V}\sin^2\theta + \underline{K_{2V}\sin^4\theta} + \mathcal{O}(\sin^6\theta) \qquad \theta \sphericalangle (\vec{M}, \hat{c})$$

Higher order is also considered in Übung today (23.5.17)

$K_{1V,\text{ Co}}$ = +0.5 MJ/m³ (three orders of magnitude smaller than XC)

➔ The (0001) axis is the „easy axis of magnetization“ for Co

$(E/V)_{\text{mca, }V}$

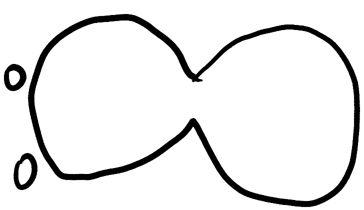


θ (°)

$K_1 > 0$
$K_2 = 0$

θ (°)

$k_1 < 0$
$k_2 = 0$



θ (°)

$k_2 > 0$
$-2k_2 < k_1 < 0$

See today‘s excercise

- Note: Magnetoelastic anisotropy due to lattice strain yields to higher anisotropy constants, e.g. KV = 2.5 MJ/m³ for tetragonally distorted FePt $L1_0$ alloys

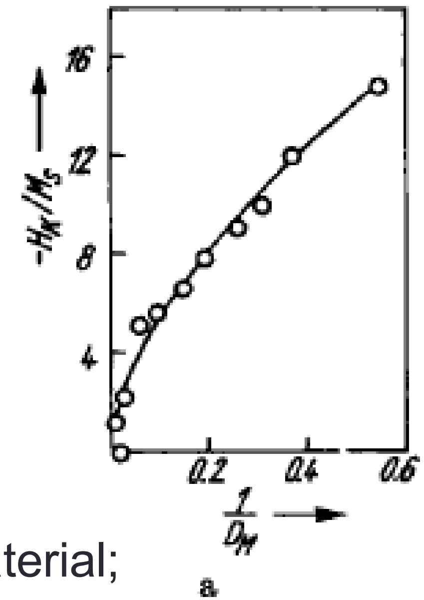
Ferromagnetism in thin films

> (magnetocrystalline) interface anisotropy (Néel‘s pair interaction model 1959)

- origin: Symmetry breaking at interface as atoms at interfaces have less nearest neighbors of the same element

$$(E/V)_{\mathrm{mca},\ S} = \frac{2K_S \sin^2\theta}{t}$$

$$\boxed{E_{\mathrm{MCA,total}}/V = (K_V + 2K_S/t)\sin^2\theta}$$



- Discovery by Gradmann and Müller for NiFe(111) on Cu (1968)

- Strongly depends on interface orientation and paramagentic material; high positive value for Co(0001)/Pt(111); discovered 1988:

$K_{S,\ \mathrm{Co/Pt}}$ = +1 mJ/m² ~10 MJ/m³ (two orders of magnitude smaller than XC interaction)

when considering half atomic layer (1 Å)

➔ The (0001) axis is the „easy axis of magnetization“ for Co/Pt for small t

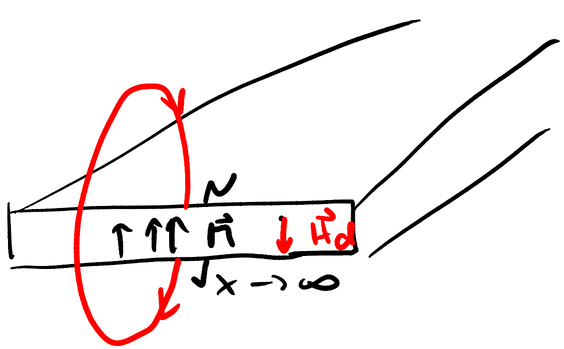
Ferromagnetism in thin films

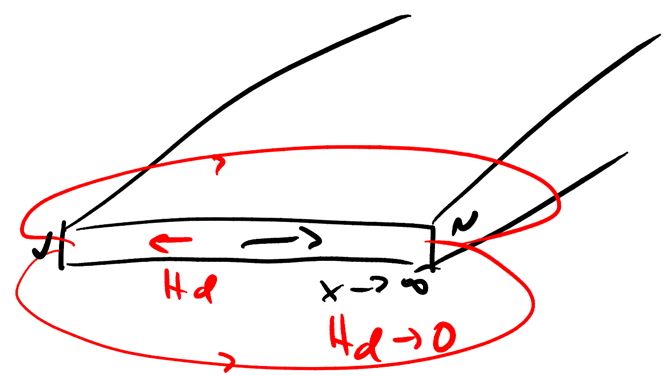
- Demagnetization energy E_d (shape anisotropy)

  - <u>Gedankenexperiment II</u>:
    What happens when cutting out a thin slice of an infinite ferromagnet?

  ➔ (crystalline materials: magnetocrystalline interface anisotropy)

  ➔ Generation of surface charges and demagnetization energy (positive definite) when **M** has components along surface normal
  ➔ **M** prefers to align along the surface (pole avoidance principle)
  ➔ (again) “easy and hard axis of magnetization“





Ferromagnetism in thin films

- Demagnetization energy E_d

=Consequence of Maxwell equation: $\boxed{\mathrm{div}\mathbf{B} = \mu_0 \mathrm{div}(\mathbf{M} + \mathbf{H}_\mathrm{d}) = 0}$

$$E_\mathrm{ms} = -\frac{\mu_0}{2} \int\limits_V \mathbf{M} \cdot \mathbf{H}_\mathrm{d} \, \mathrm{d}V$$

Magnetic volume and surface charges

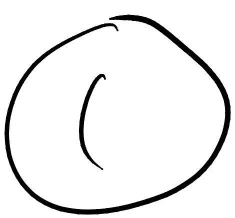
$$\mathbf{H}_\mathrm{d}(\mathbf{r}) = \frac{1}{4\pi} \int_V \frac{(\mathbf{r} - \mathbf{r}')\mathrm{div}\mathbf{M}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV' + \frac{1}{4\pi} \oint_{\delta V} \frac{(\mathbf{r} - \mathbf{r}')\mathbf{M}(\mathbf{r}') \cdot \mathbf{n}}{|\mathbf{r} - \mathbf{r}'|^3} dS'$$

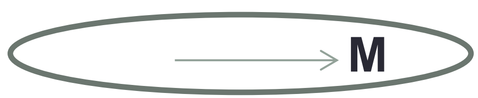
Rotational ellipsoids (single domain state): $\mathbf{H}_\mathrm{d} = -\overleftrightarrow{N} \cdot \mathbf{M}$

Symmetry considerations:

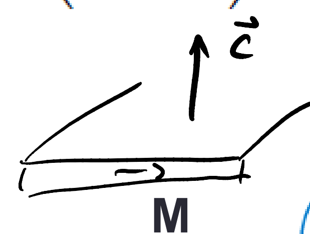
$$\overleftrightarrow{N}_\mathrm{sphere} = \begin{pmatrix} \frac{1}{3} & 0 & 0 \\ 0 & \frac{1}{3} & 0 \\ 0 & 0 & \frac{1}{3} \end{pmatrix}, \quad \overleftrightarrow{N}_\mathrm{wire} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{1}{2} & 0 \\ 0 & 0 & \frac{1}{2} \end{pmatrix}, \quad \overleftrightarrow{N}_\mathrm{film} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Isotrope
➔ No shape anisotropy





Cut through cylindrical wire ("cigar")



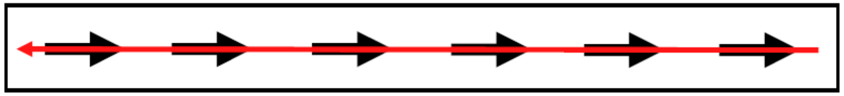
Ferromagnetism in thin films

> Demagnetization energy Ed

$$(E/V)_{\mathrm{d,\ film}} = \frac{\mu_0}{2}(\overleftrightarrow{N}_{\mathrm{film}} \cdot \mathbf{M}) \cdot \mathbf{M} = \frac{\mu_0}{2} M_z^2 = \frac{\mu_0}{2} M_S^2 \cos^2 \Theta$$

$E_{demag} = \mu_0/2\ M_s^2$

$E_{demag} \approx 0$



Redefinition of zero: $$(E/V)_{\mathrm{d,\ film}} = \frac{\mu_0}{2} M_S^2 \cos^2 \Theta = -\frac{\mu_0}{2} M_S^2 \sin^2 \Theta + \mathrm{const.}$$

$$\boxed{(E/V)_d = -\mu_0/2\ M_s^2 \sin^2 \theta = K_d \sin^2 \theta}$$

For Co at room temperature: M_S =1.44 MA/m ➔
$K_d = -\mu_0 M_S^2 /2 = -1.3$ MJ/m³

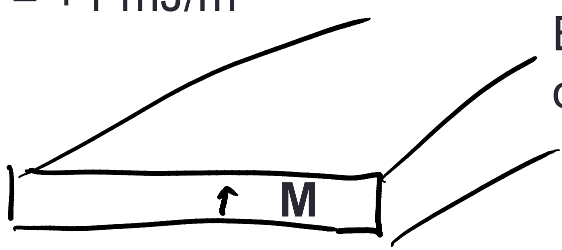
Ferromagnetism in thin films

> Effective anisotropy constant for uniaxial thin films:

$$K_{1,\mathrm{eff}} = \underbrace{K_{1V} - \frac{\mu_0}{2} M_S^2}_{K_{1V,\mathrm{eff}}} + \frac{2K_{1S}}{t}$$

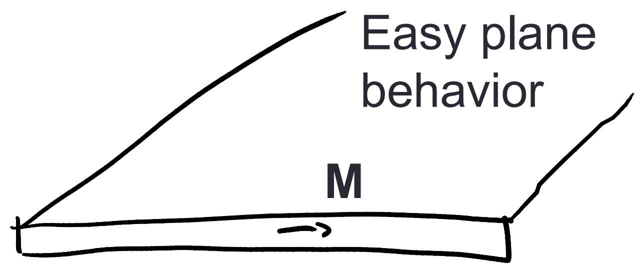
For Co(0001)/Pt(111) system:

K_d = -1.3 MJ/m³
K_{1V} = +0.5 MJ/m³
K_{1S} = +1 mJ/m²



Easy axis out-of-plane!

Easy plane behavior



➔ $K_{1,\mathrm{eff}} > 0$ for $t < 2$ nm !!!

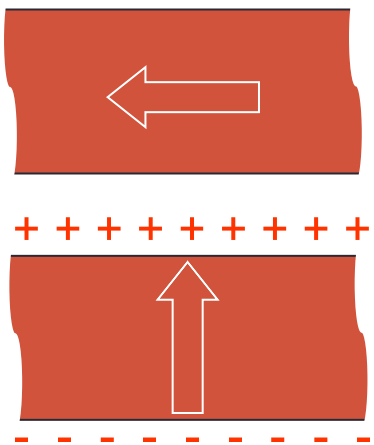
$K_{1,\mathrm{eff}} < 0$ for $t > 2$ nm

Ferromagnetism in thin films

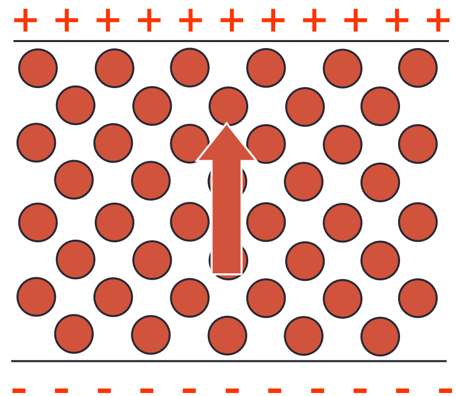
How to realize a perpendicular magnetic anisotropy in a thin film (Summary)?

Lower State "costs" $\mu_0 M_S^2/2$

Shape anisotropy



MCA (volume)



$$\underbrace{K_{eff} = -\frac{\mu_0}{2}M_S^2 + K_V}_{}$$

>0, e.g. for FePt $L1_0$ alloys

Ferromagnetism in thin films

How to realize a perpendicular magnetic anisotropy in a thin film (Summary)?

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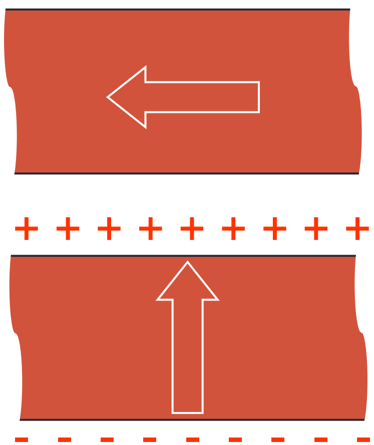
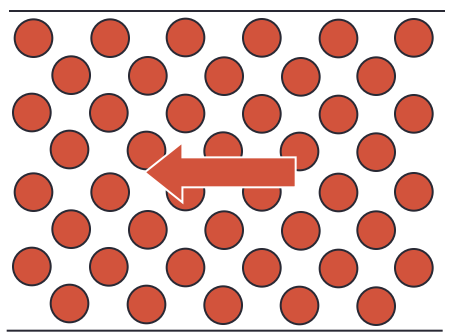
Shape anisotropy



MCA (volume)



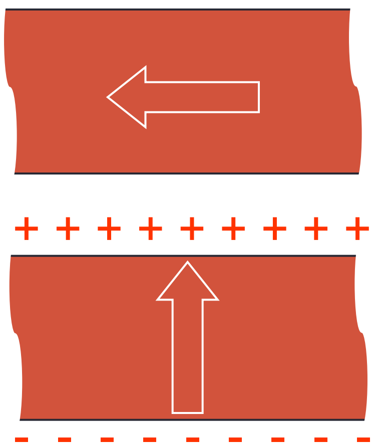
$$K_{eff} = \underbrace{-\frac{\mu_0}{2} M_S^2 + K_V}_{<0,\ \text{e.g. for Co}}$$

Ferromagnetism in thin films

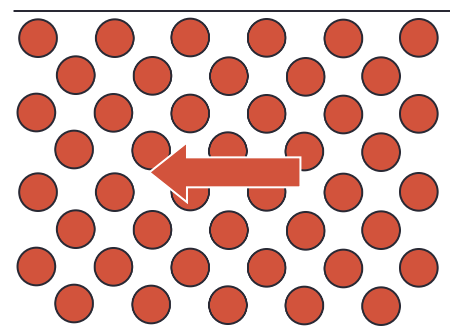
How to realize a perpendicular magnetic anisotropy in a thin film (Summary)?

Lower State "costs" $\mu_0 M_S^{\,2}/2$

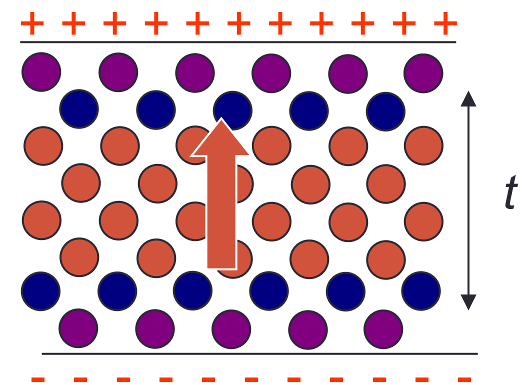
Shape anisotropy



MCA (volume)



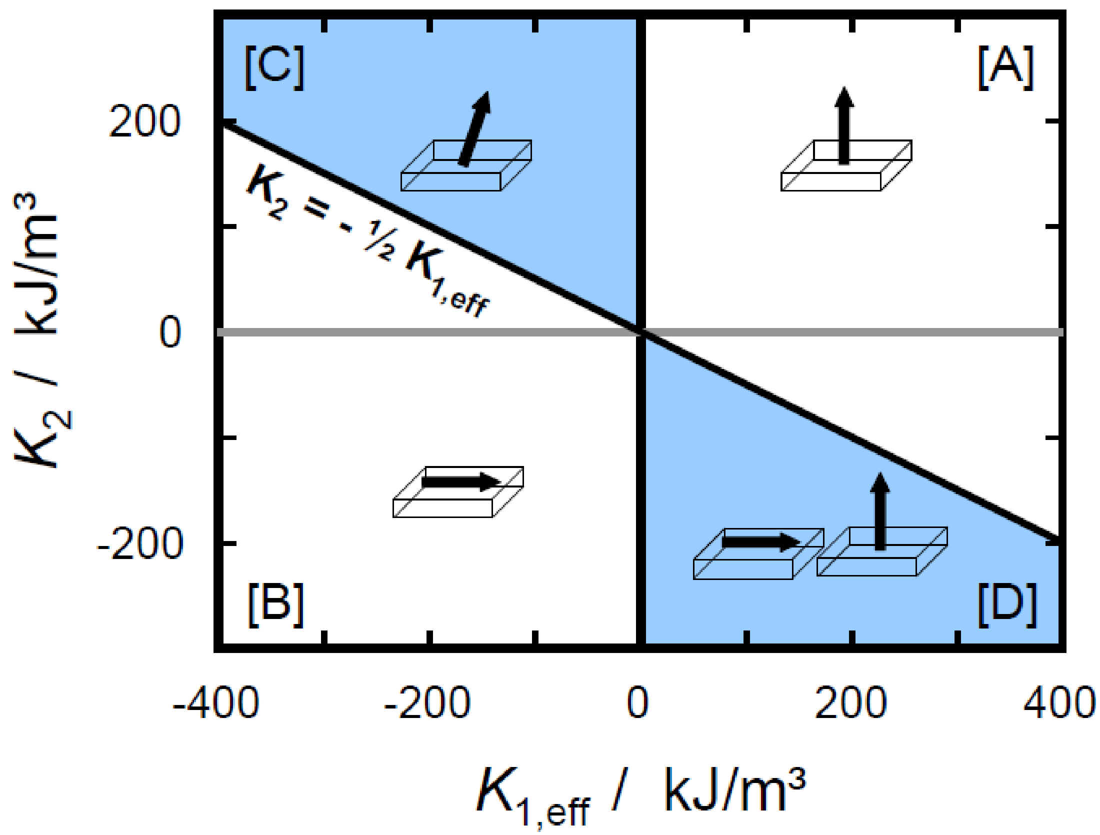
MCA (interface)



$$K_{eff} = \underbrace{-\frac{\mu_0}{2}M_S^2 + K_V + \frac{2K_S}{t}}_{>0,\ \text{e.g. for } \mathbf{Co/Pt},\ \text{if } t < 2\ \text{nm}}$$

Ferromagnetism in thin films

> Phase diagram (considering higher orders in anisotropy constants; today's excercise)



Ferromagnetism in thin films

> Zeeman energy

=Energy of magnetization **M** in external magnetic field **H**

$$(E/V)_Z = -\mu_0 \mathbf{M} \cdot \mathbf{H}$$

> Total energy of single domain system (today's Übung):

$$E/V = \underbrace{K_{1,\text{eff}} \sin^2 \Theta + K_2 \sin^4 \Theta}_{\text{MCA+shape anisotropy terms}} - \mu_0 H M_S \cos \Phi$$

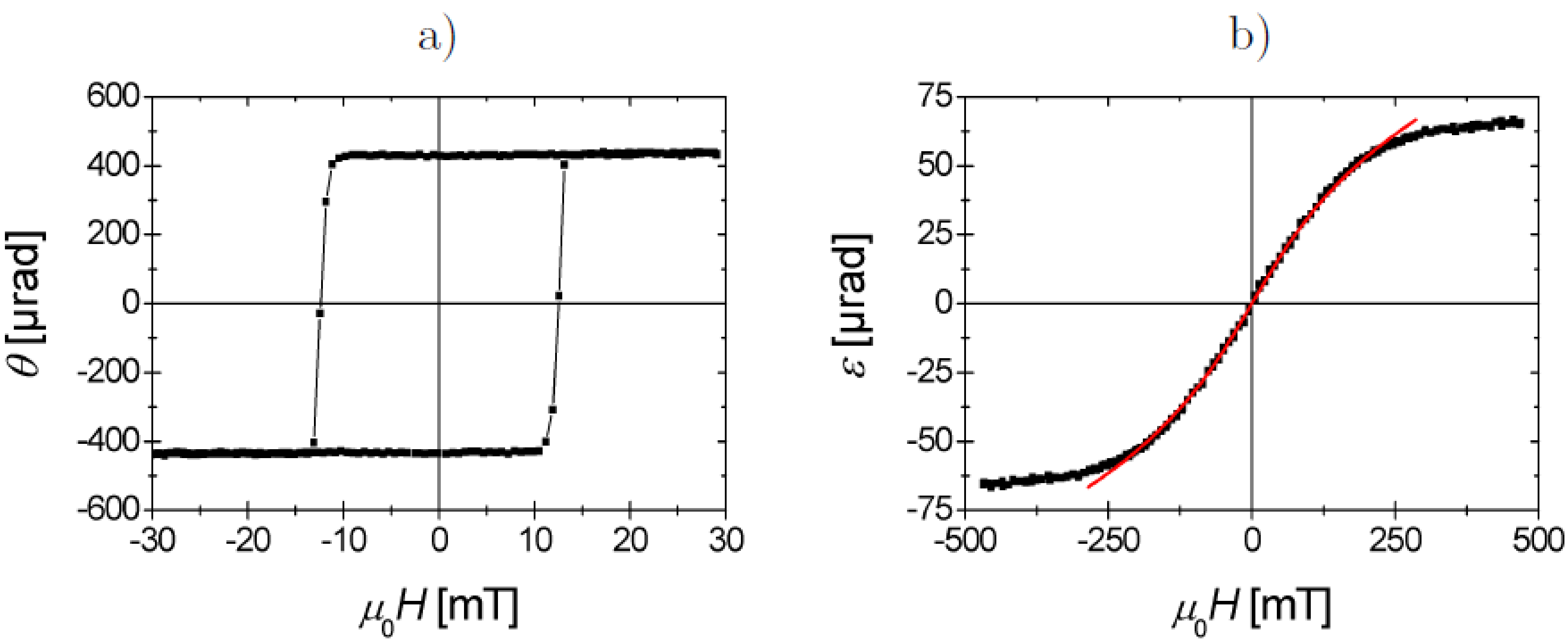
MCA+shape anisotropy terms Zeeman term

-> exp. determination of $K_{1,\text{eff}}$ and K_2 !
from hard axis hysteresis (today's Übung)

DESY

Ferromagnetism in thin films

- Magnetic hysteresis curves

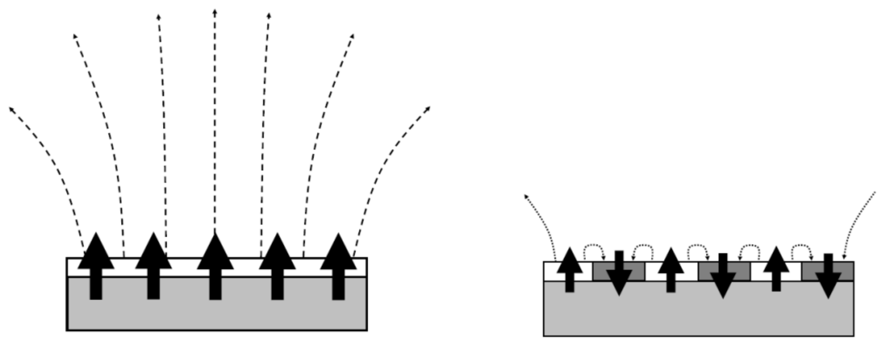


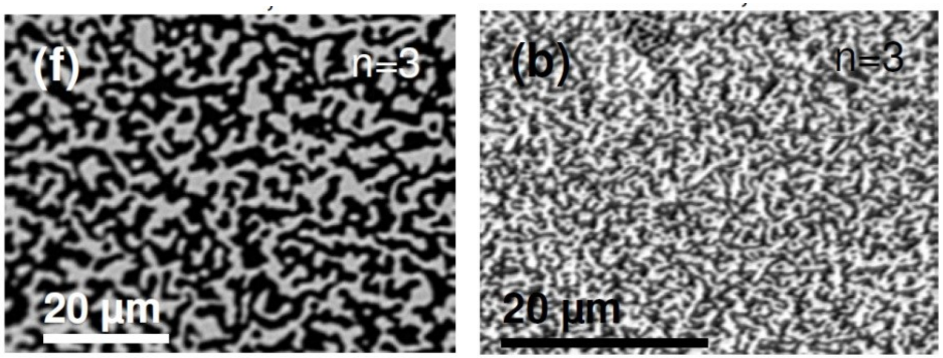
Easy axis
(domain nucleation and domain wall motion)

Hard axis
(coherent rotation of magnetization, today's Übung)

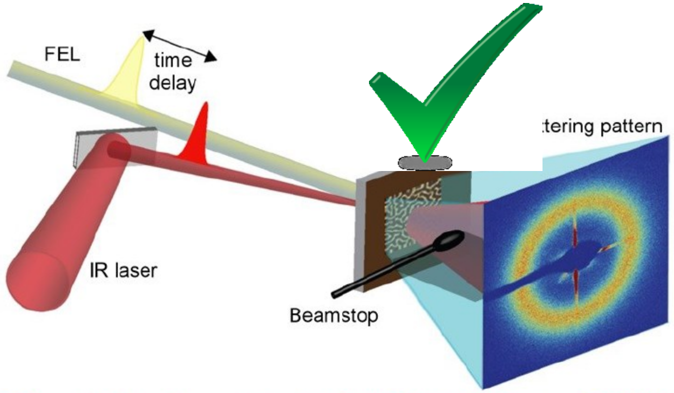
Ferromagnetism in thin films

> Magnetic domains and domain walls





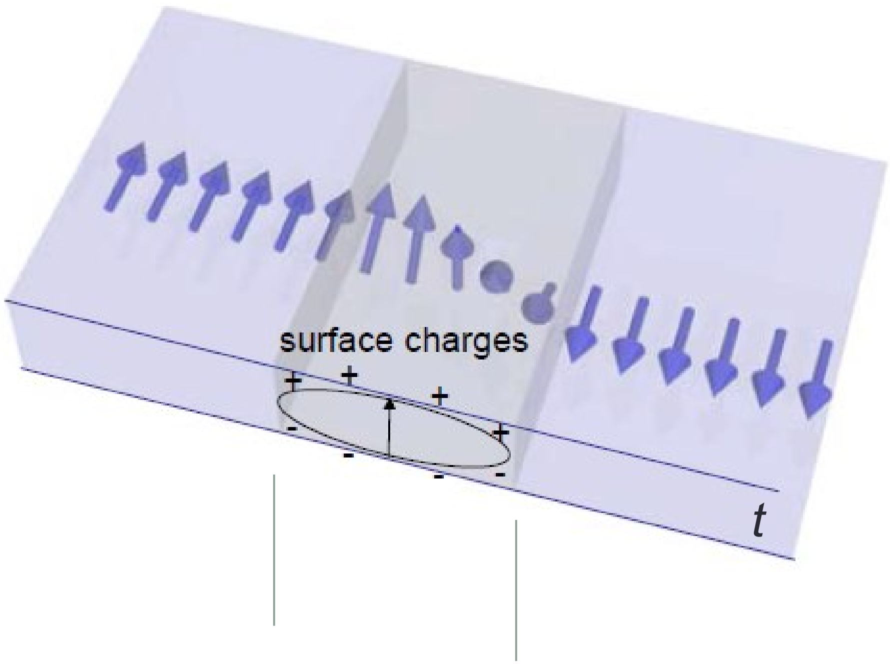
- Domain walls cost exchange E_{XC} and magnetocrystalline anisotropy energy E_{MCA}
- But: Domain formation reduces stray field energy E_d



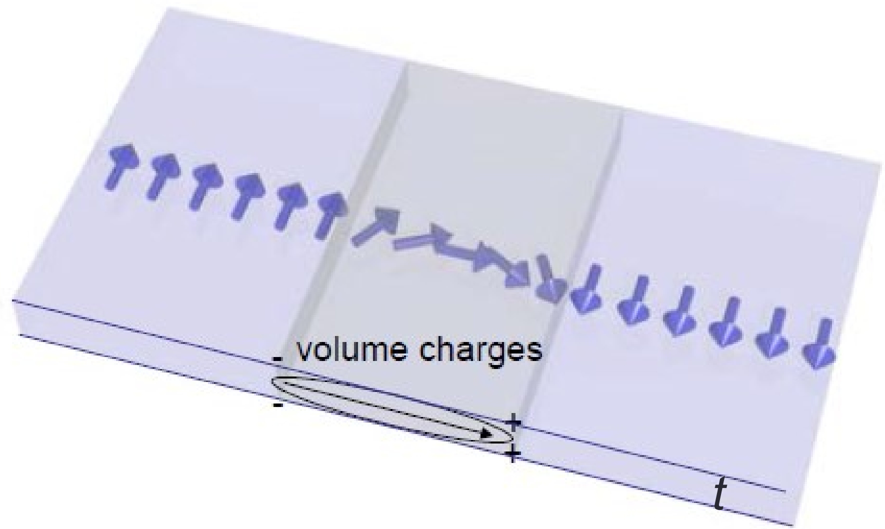
B. Pfau et al., Nature Communications, Vol. 3, 11; DOI:doi:10.1038/ncomms2108 (2012)
L.Müller et al., Rev. Sci. Instrum. 84, 013906 (2013)

Ferromagnetism in thin films

> Néel and Bloch domain walls for in-plane magnetized systems



Domain wall width $d_w < t$

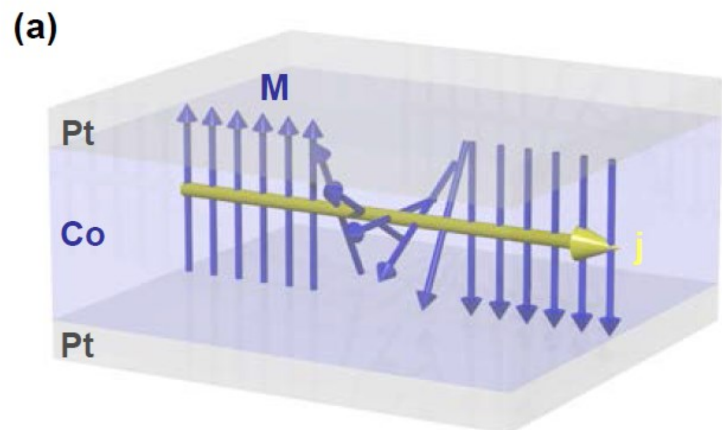


Domain wall width $d_w > t$

Ferromagnetism in thin films

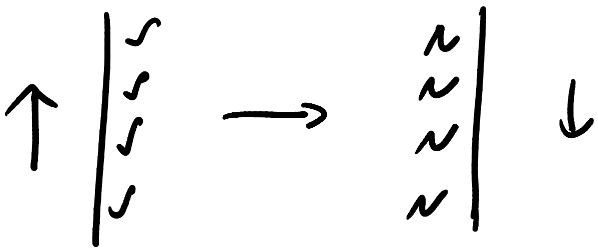
> Néel and Bloch domain walls for films with perpendicular anisotropy

Bloch wall



- No magnetic charges in wall!

Néel wall



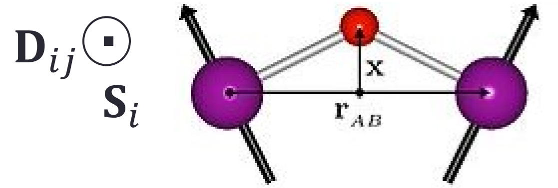
- exhibits volume charges (unfavorable due to magnetostatic energy)
  but
- Néel wall favored by Dzyaloshinskii-Moriya interaction (considered since 2013!)

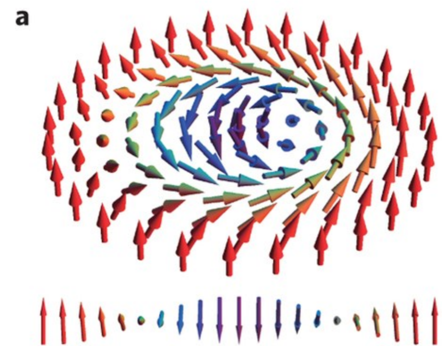
Ferromagnetism in thin films

- Dzyaloshinskii-Moriya interaction (DMI):
  Asymmetric exchange interaction

$$E_{\mathrm{DMI}} = \sum_{i \neq j} \mathbf{D}_{ij} \ (\mathbf{S}_i \times \mathbf{S}_j)$$

DMI-Vector





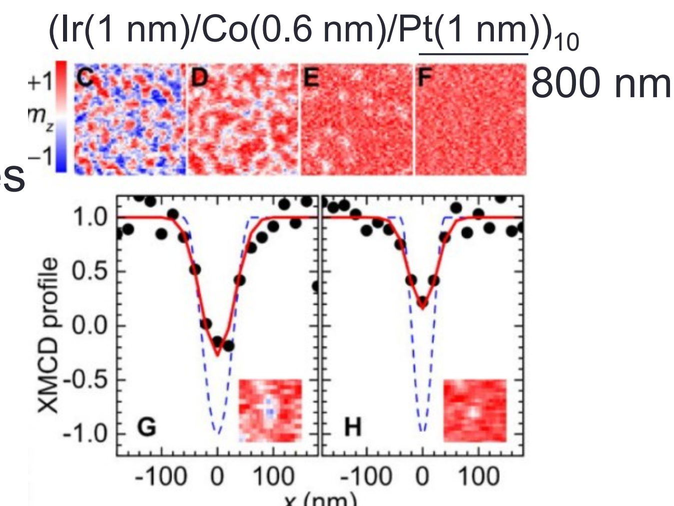
➔ Mininization of total energy yields to formation of chiral structures = skyrmions

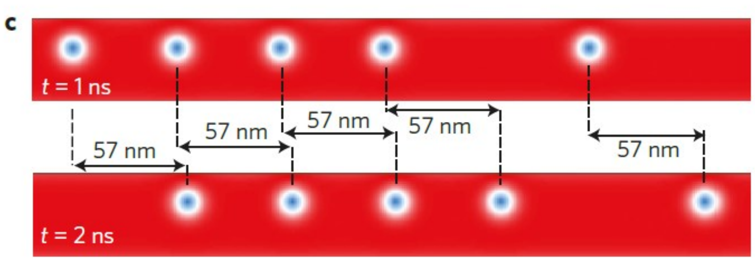
- **Asymmetric magnetic multilayers like Pt/Co/Ir**

  Different sign of $\mathbf{D}_{ij}$ for Co/Pt and Co/Ir interface

  ➔ additive, large effective DMI

- Future Skyrmion-based memory & data storage devices





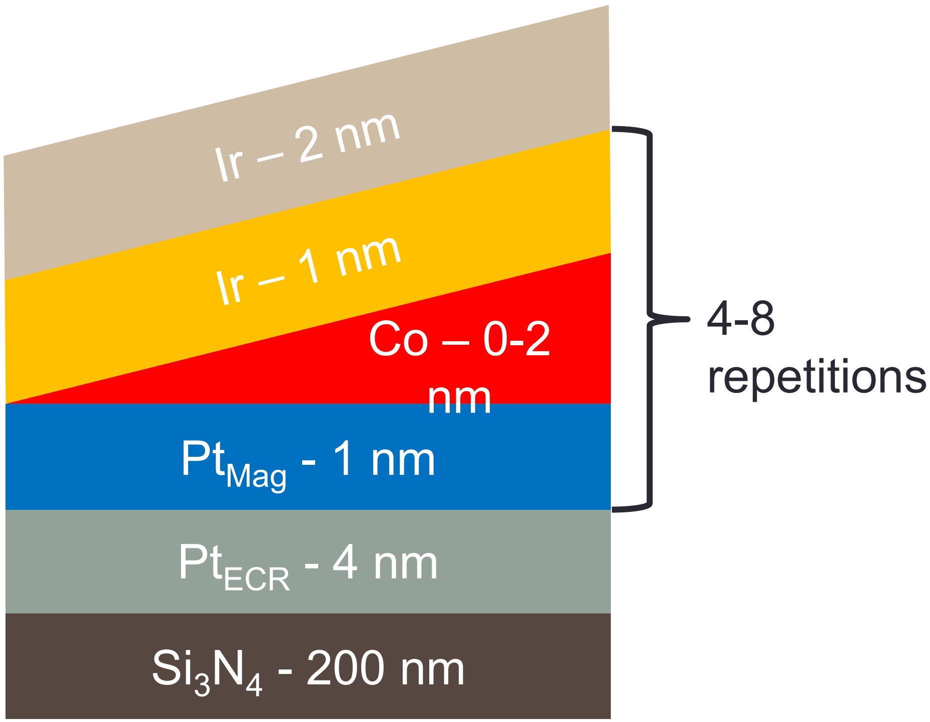
J. Sampaio, A. Fert et al., Nat. Nanotech. 8, 839 (2013)

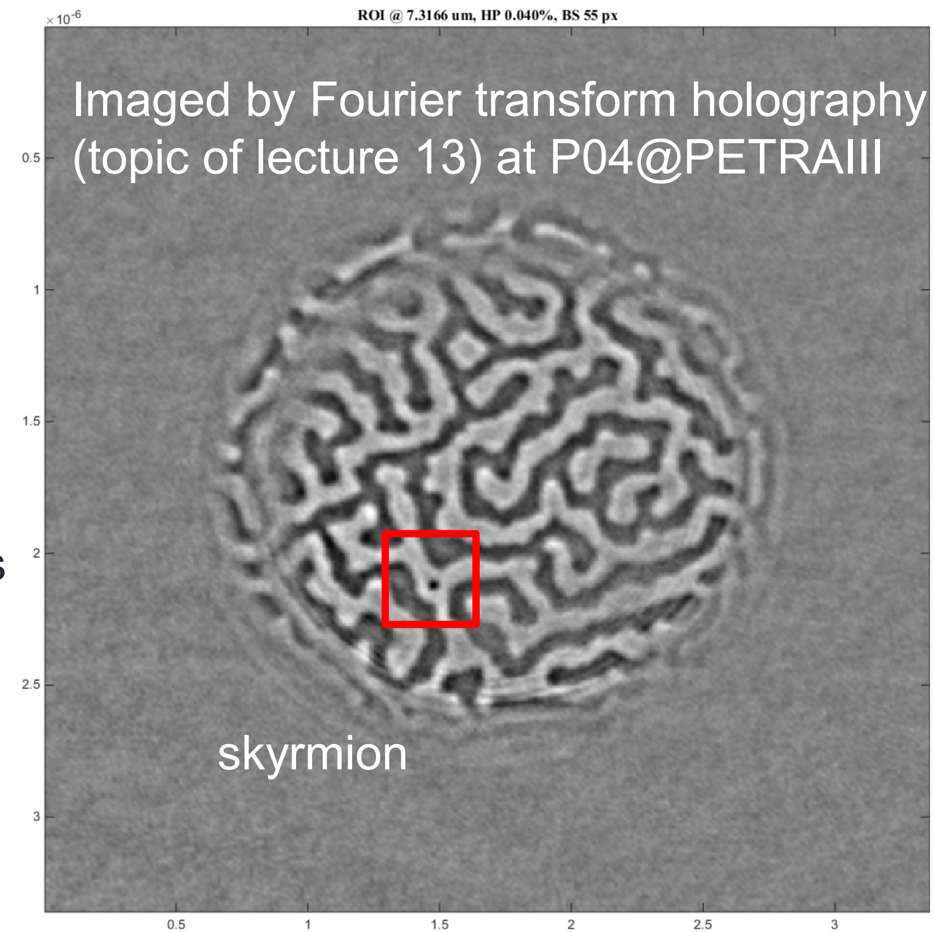
C. Moreau-Luchaire, A. Fert et al., arXiv:1502.07853v1 (2015)

Ferromagnetism in thin films

- What we are doing

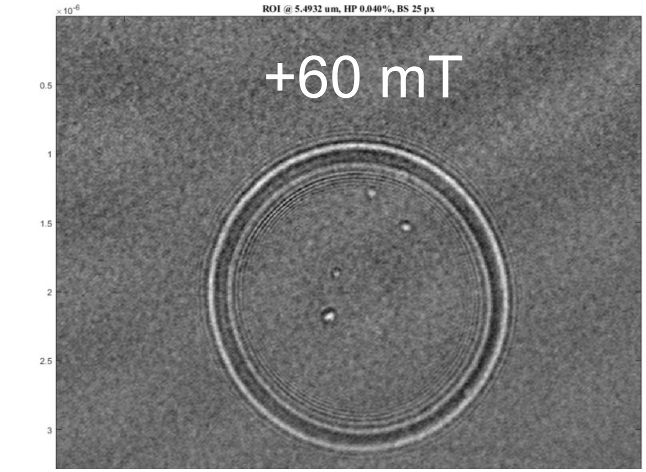
Pt/Co/Ir Multilayers

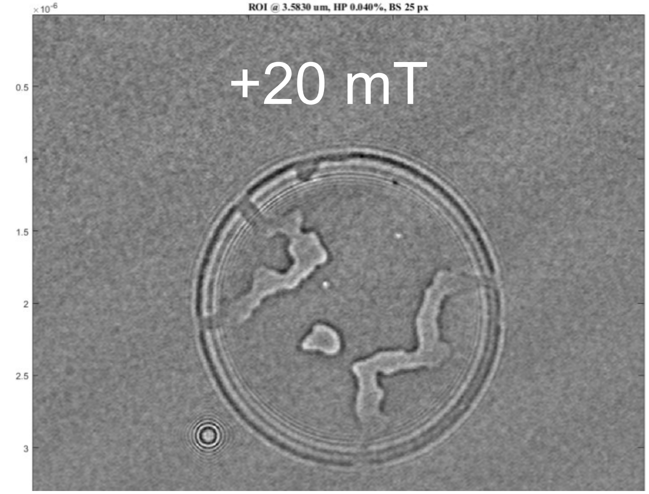


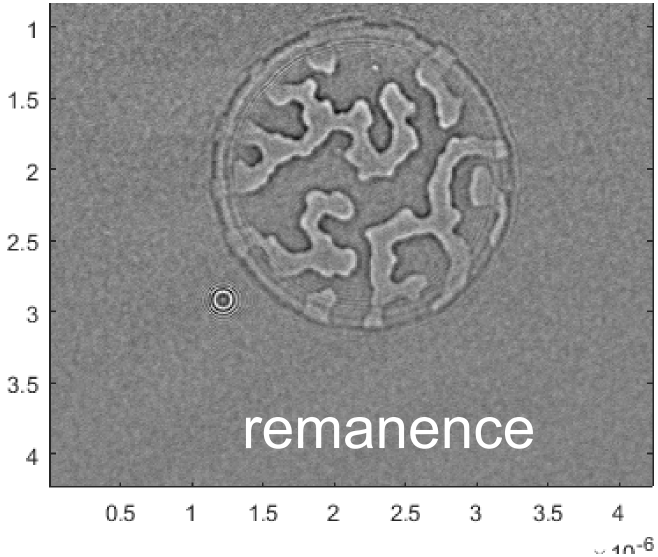


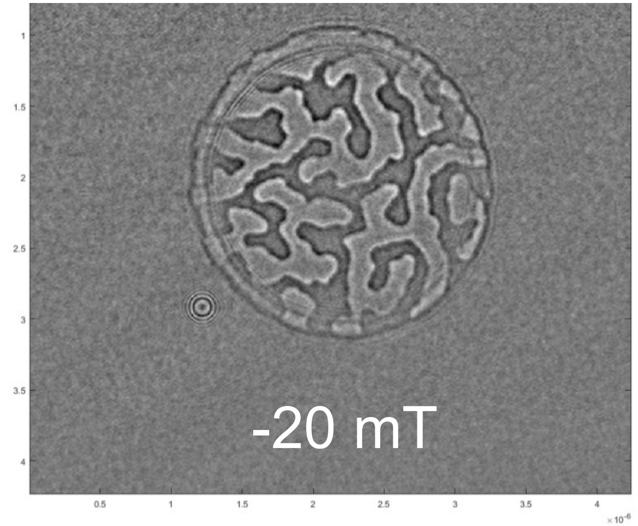
Ferromagnetism in thin films

- Out-of-plane field sweep









Ferromagnetism in thin films

- Current induced Skyrmion motion