Methoden moderner Röntgenphysik II: Streuung und Abbildung

Lecture22	Vorlesung zum Haupt- oder Masterstudiengang Physik, SoSe 2021		
	G. Grübel, O. Seeck, V. Markmann, F. Lehmkühler, A. Philippi-Kobs, M. Martins		
Location	online		
Date	Tuesdays	12:30 - 14:00	(starting 6.4.)
	Thursdays	8:30 - 10:00	(until 8.7.)

Outline

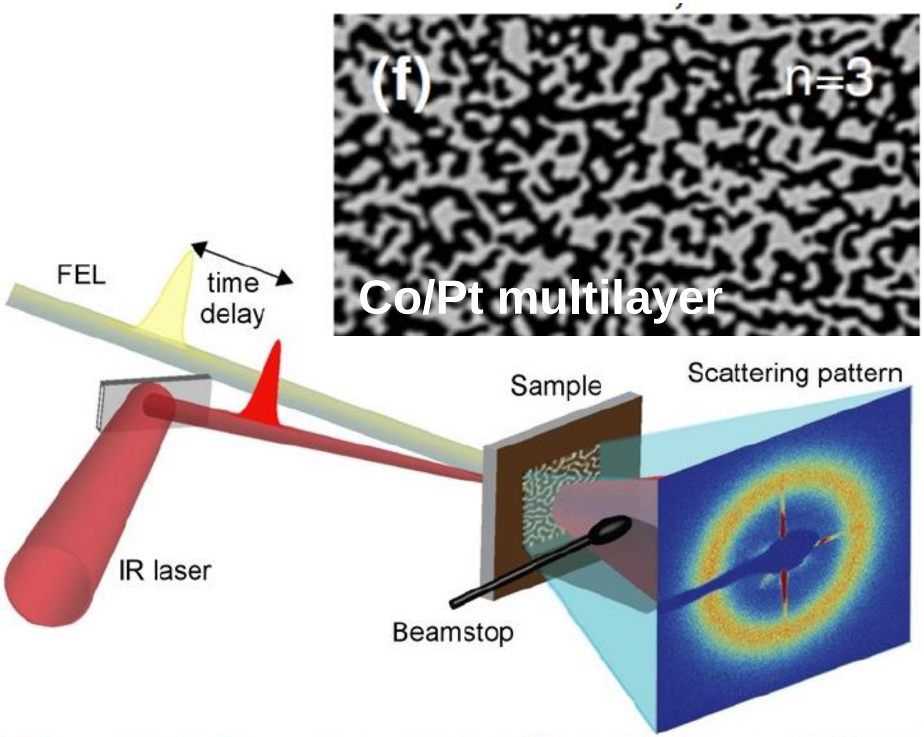
Part III/1:

Studies on Magnetic Nanostructures

by André Philippi-Kobs

[22.6.] **Ferromagnetism in a Nutshell**

- Introduction to Magnetic Materials
- Magnetic Phenomena
- Magnetic Free Energy
- Perpendicular Magnetic Anisotropy
- Magnetic Domains and Domain Walls



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)

[24.6.] **Interaction of Polarized Photons with Ferromagnetic Materials**

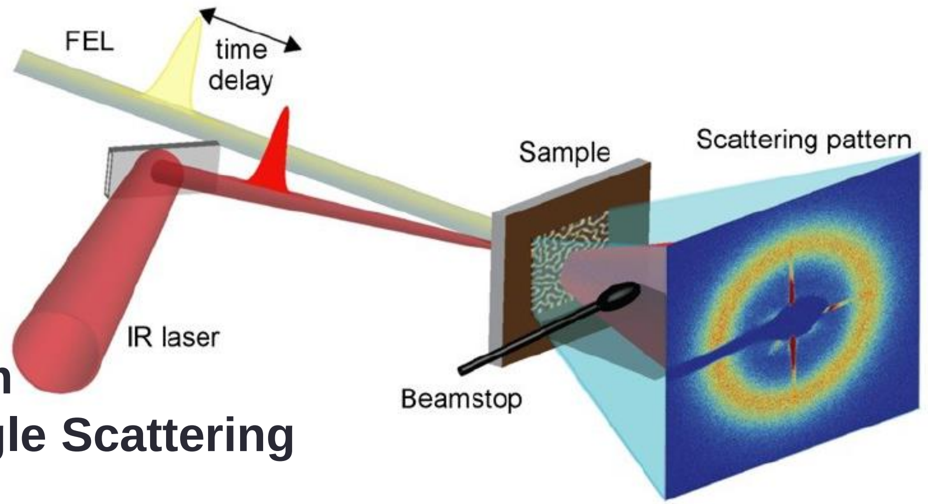
- Charge and Spin X-ray Scattering by a Single Electron
- Absorption and Resonant Scattering of Ferromagnets (Semi-Classical and Quantum-Mechanical Concepts)

Outline

Part III/2:

Studies on Magnetic Nanostructures

by André Philippi-Kobs

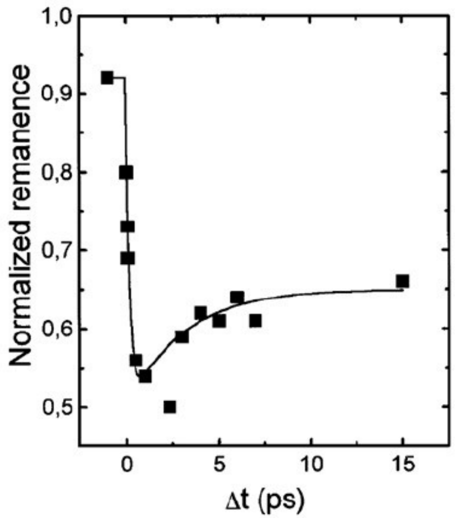


[29.6.] **X-ray Magnetic Circular Dichroism (XMCD) & Resonant Magnetic Small-Angle Scattering (mSAXS)**

- Role of Spin-Orbit Coupling and Exchange Splitting
- Sum Rules
- XMLD and Natural Dichroism
- mSAXS of Magnetic Domain Patterns

[1.7.] **Femtomagnetism**

- Introduction to Ultrafast Magnetization Dynamics Induced by Femtosecond Infrared Pulses
- Pump-Probe Experiments of Nano-Scale Magnetic Domain Patterns
- All-Optical Switching
- Manipulating Magnetism by XUV and THz Pulses



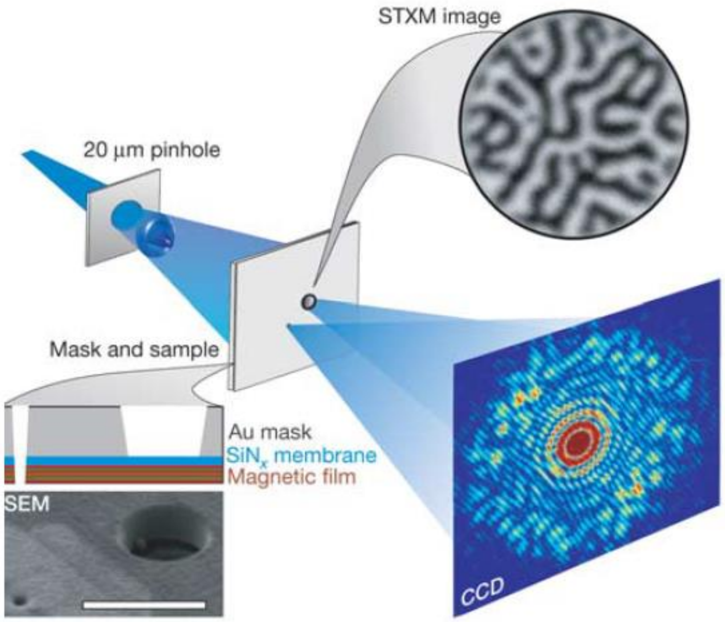
Part II/3:

Studies on Magnetic Nanostructures

by André Philippi-Kobs

[8.7.] **Imaging of Magnetic Domains**

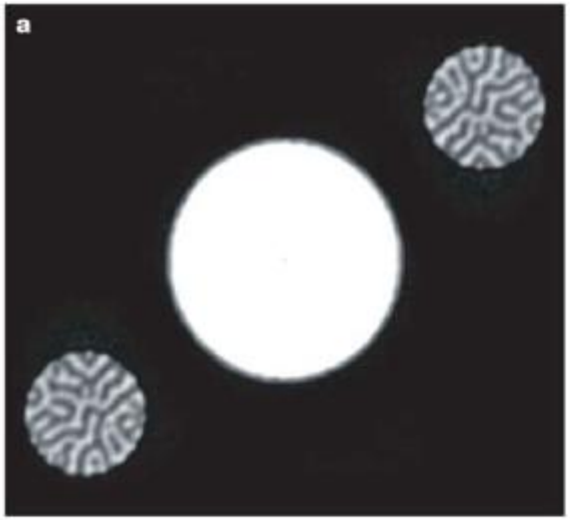
- **Fourier Transform Holography (FTH)**
- Scanning Transmission X-ray Microscopy (STXM)
- Coherent Diffraction Imaging (CDI)



Lensless imaging of magnetic nanostructures by X-ray spectro-holography

S. Eisebitt[1], J. Lüning[2], W. F. Schlotter[2,3], M. Lörgen[1], O. Hellwig[1,4], W. Eberhardt[1] & J. Stöhr[2]

NATURE | VOL 432 | 16 DECEMBER 2004 |

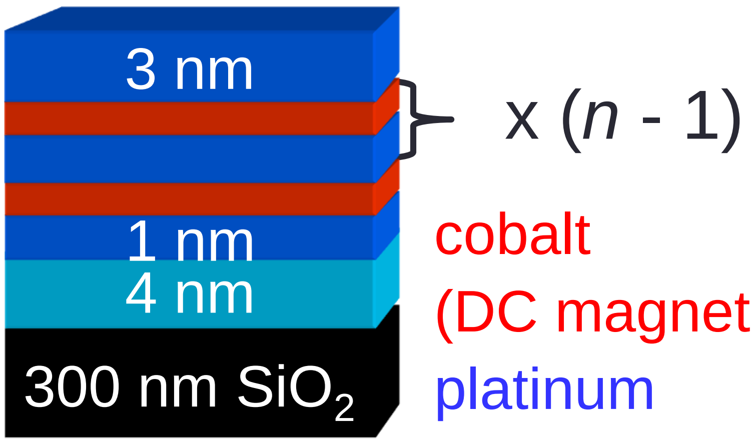


FTH

Co/Pt Multilayers

Layer Composition

Multilayer stack (n = 1 - 32)

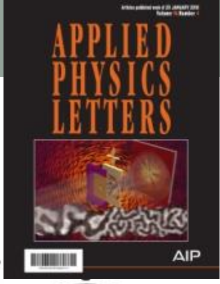


cobalt
(DC magnetron)
platinum
(DC magnetron)
platinum (ECR)

Perpendicular magnetic anisotropy in Co/Pt discovered in 1988

Carcia et al., J. Appl. Phys. **63**, 5066 (1988).

Magnetic Domains



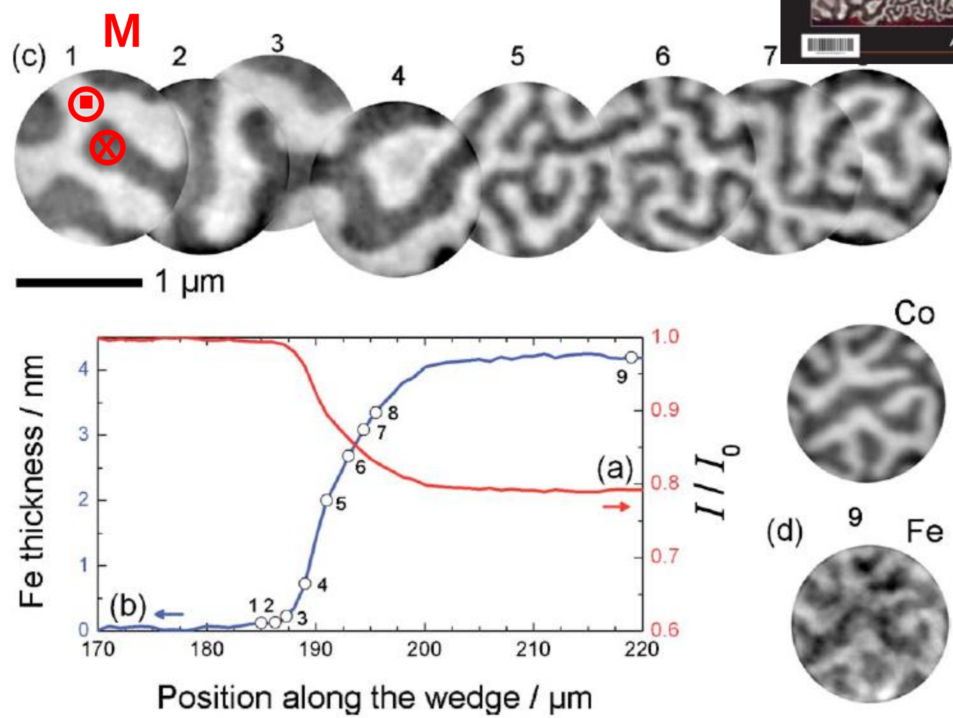
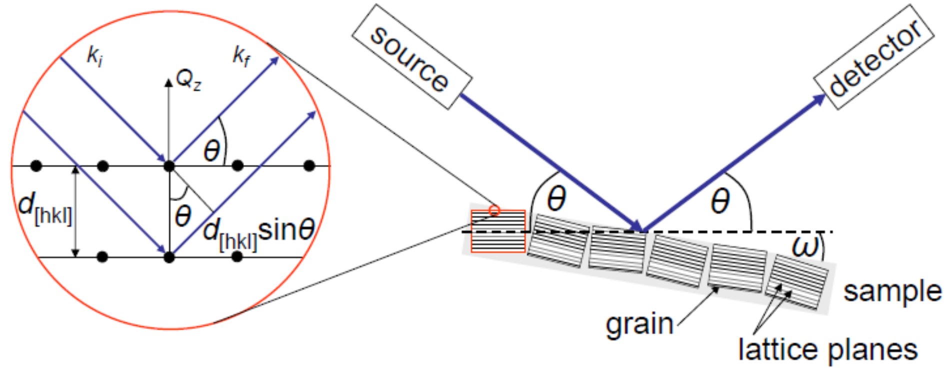


FIG. 3. (Color online) Domain size evolution of a Co/Pt multilayer film covered by an iron wedge. Plot (a) gives the absorption profile (normalized photodiode current) at the Fe L_3 absorption edge when scanning over the Fe wedge. The absorption is used to calculate the local iron overlayer thickness (b). A contiguous series of XMCD holograms at the Co L_3 absorption edge has been acquired and reconstructed (c) at the indexed positions along the iron wedge. Image (d) has been measured at the Fe L_3 absorption edge at the very same position as the last Co image (#9).

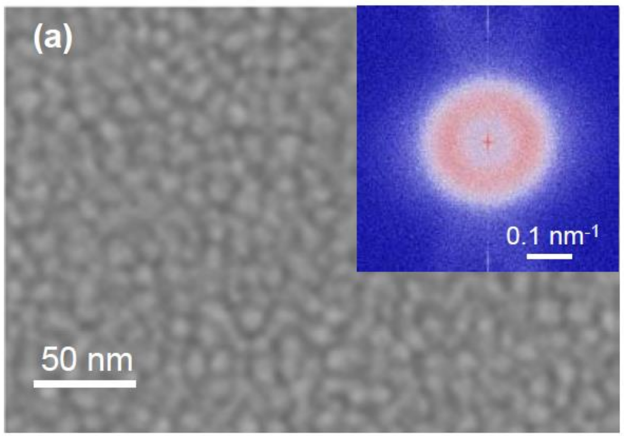
D. Stickler, G. Grübel, H. P. Oepen et al., Appl. Phys. Lett. **96**, 042501 (2010).

Co/Pt Multilayers



Structural analysis

X-ray diffraction (XRD) to determine crystallinity



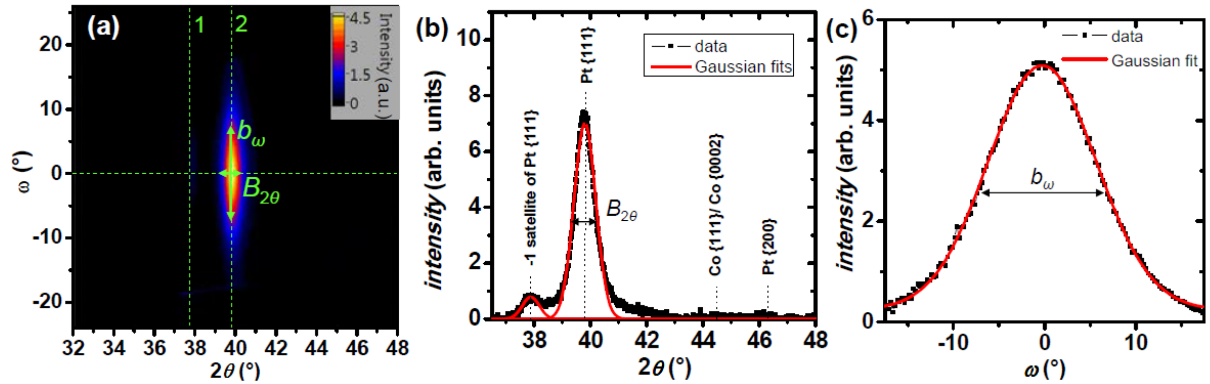


Figure 5.17: (a) Diffraction map $I(\omega, 2\theta)$ of a 5 nm Pt/ (0.8 nm Co/ 4 nm Pt)$_3$/ 0.8 nm Co/ 3 nm Pt multilayer grown on Si_3N_4. The intensity is color coded according to the given color bar. The positions of the -1 satellite reflex (1) and of the peak at the Pt(111) position (2) are indicated by vertical dashed lines. (b) shows the integrated intensity $I(2\theta) = \sum_\omega I(\omega, 2\theta)$ and (c) the cross-section $I(\omega)$ at the peak position $2\theta_{\mathrm{fcc\ Pt(111)}} = 39.8°$. Both curves are fitted to a normal distribution (red lines) with a FWHM of $B_{2\theta}$ and b_ω, respectively.

- Co and Pt layers have fcc lattice
- polycrystalline,
  grain size of (11 ± 2) nm
- out-of-plane textured,
  tilting of grains (FWHM):(23 ± 2)°

More details, see G. Winkler, A. Kobs, A. Chuvilin, D. Lott, A. Schreyer, H. P. Oepen, J. Appl. Phys. **117**, 105306 (2015).

Co/Pt Multilayers

Structural analysis

X-ray reflectometry (XRR) to determine quality of layered structure

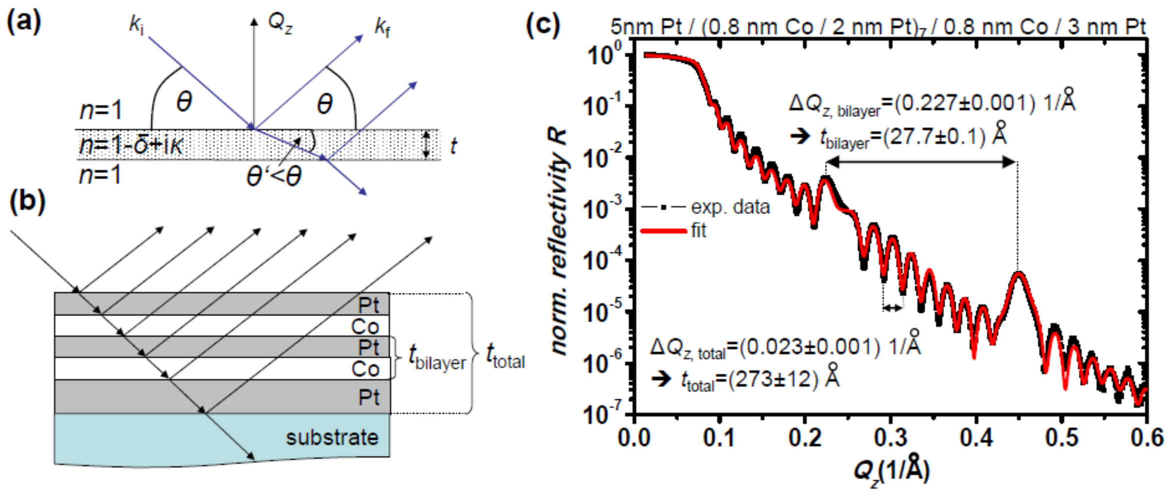


Figure 5.27: (a) Refraction and reflection of an x-ray beam hitting a thin layer with thickness t. The interference of the partial waves refracted from the two interfaces generates oscillations (Kiessig fringes) in the reflectivity profile $R(\theta)$. (b) In a periodically layered structure the interferences of the reflected partial waves additionally yield beating waves in $R(\theta)$. (c) Reflectivity R in dependence of the scattering vector Q_z for a multilayer with $n = 8$ and a Pt interlayer thickness of $t_{\mathrm{Pt}} = 2$ nm. From the oscillation and beating wave period the total thickness of the stacking and the bilayer thickness was verified utilizing Eq. 5.64 and Eq. 5.65, respectively. The red solid line is a fit utilizing the software PARRAT32 [715], which is used in particular to determine the thickness of the roughness/interdiffusion regions.

A. Kobs, PhD thesis, Universität Hamburg (2013).

$$\Delta Q_{z,\,\mathrm{total}} = \frac{2\pi}{t_{\mathrm{total}}}$$

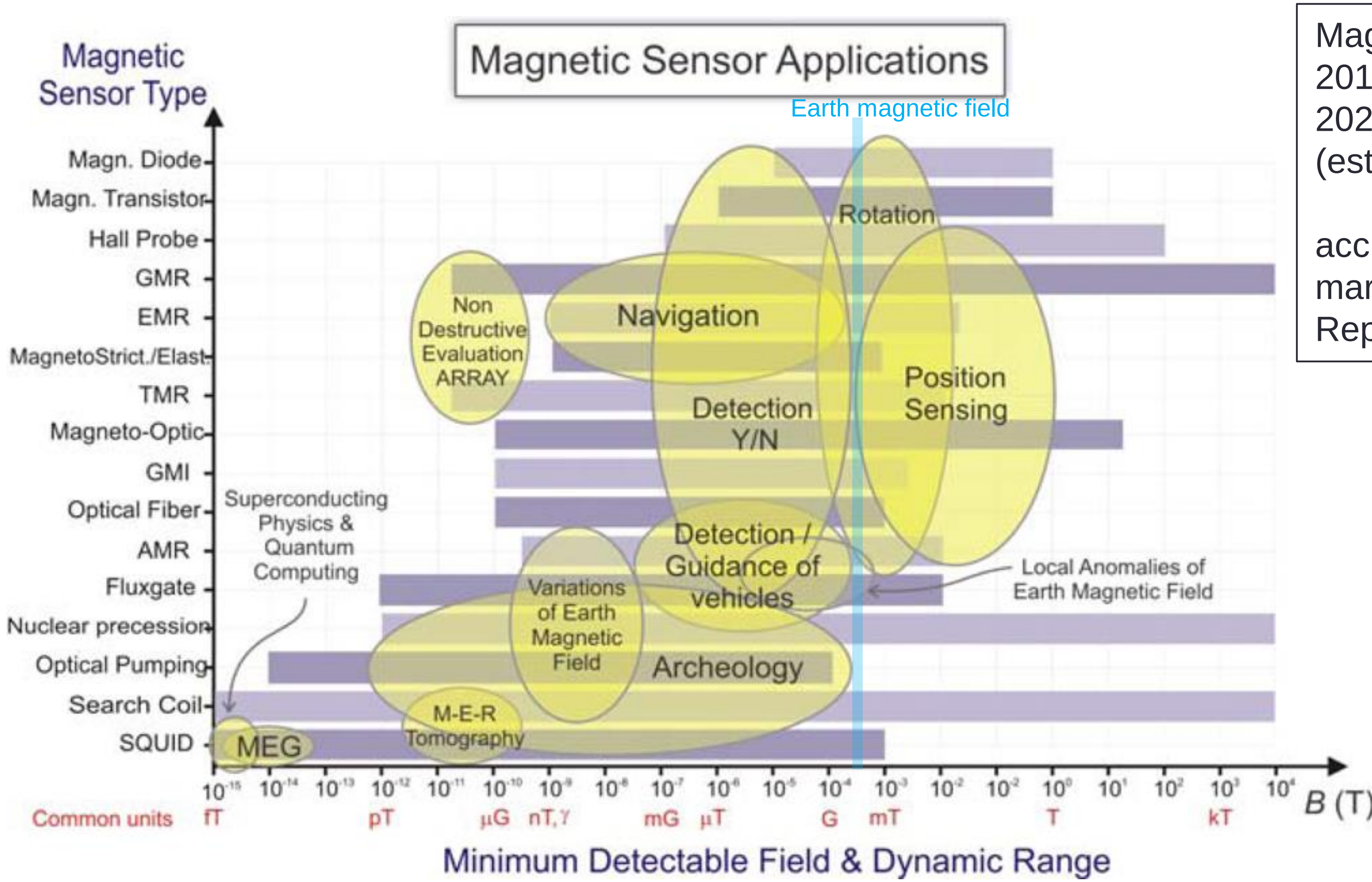
$$\Delta Q_{z,\,\mathrm{bilayer}} = \frac{2\pi}{t_{\mathrm{bilayer}}}$$

- roughness: (0.2 ± 0.1) nm
- interdiffusion of Co & Pt: (0.5 ± 0.2) nm

disentangling of both from off-specular scans

Introduction to Magnetic Materials

Magnetic Materials in Sensor Applications



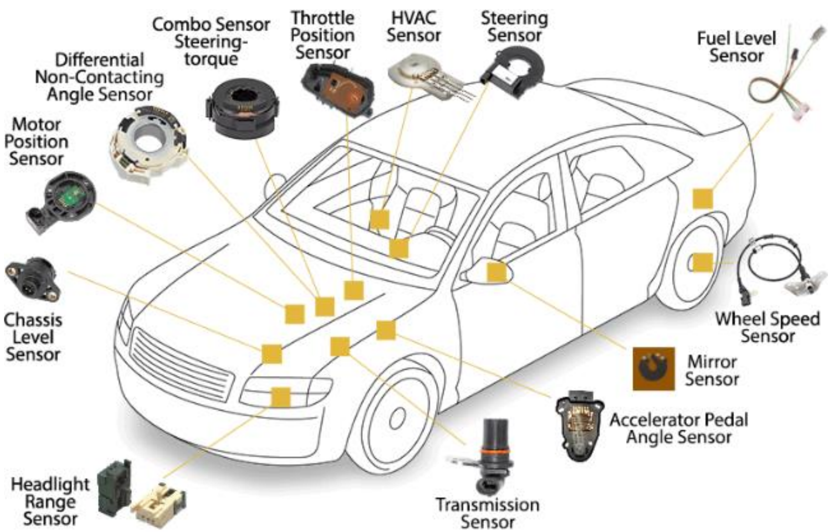
Magnetic Sensor Market:
2016: USD 2.96 Billion
2023 : USD 5.37 Billion
(estimated before Corona)

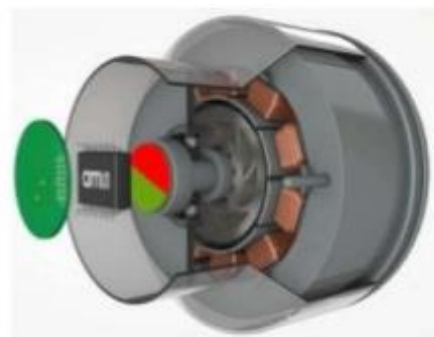
acc. to marketsandmarkets.com, Report Code: SE 2688

M. Díaz-Michelena, Sensors 9, 2271 (2009)

Introduction to Magnetic Materials

Magnetic Materials in Sensor Applications

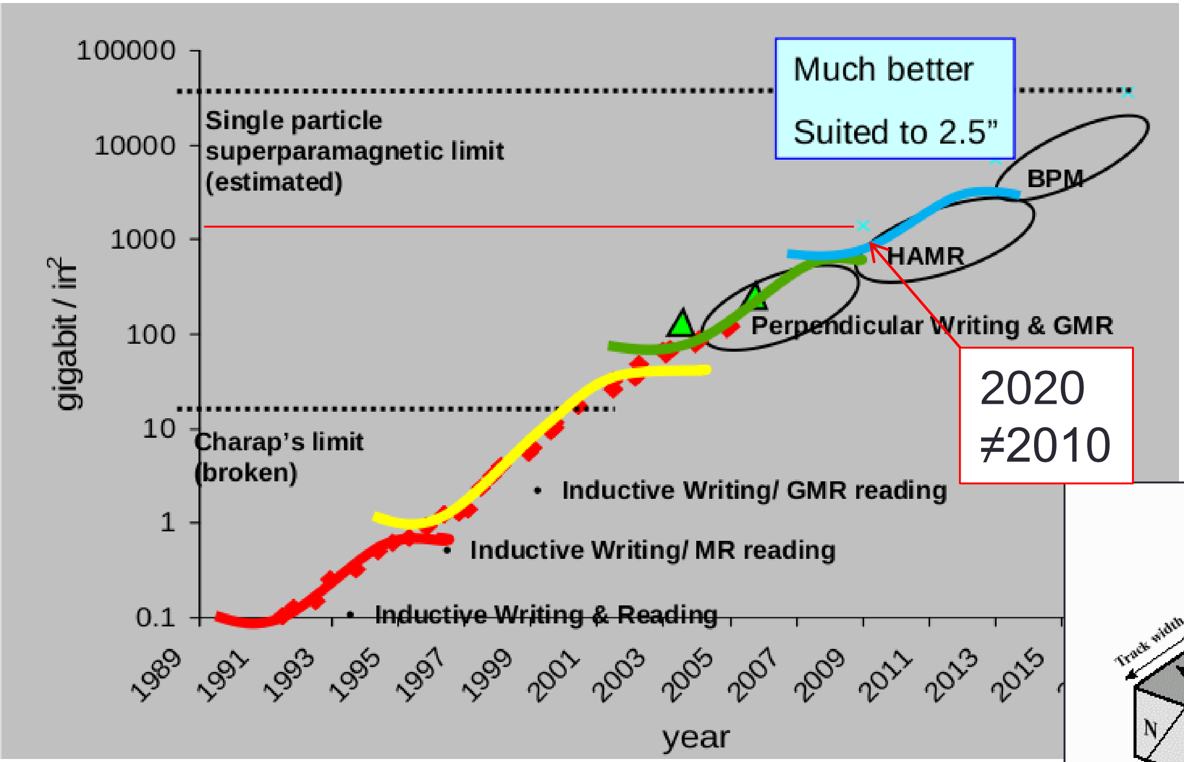


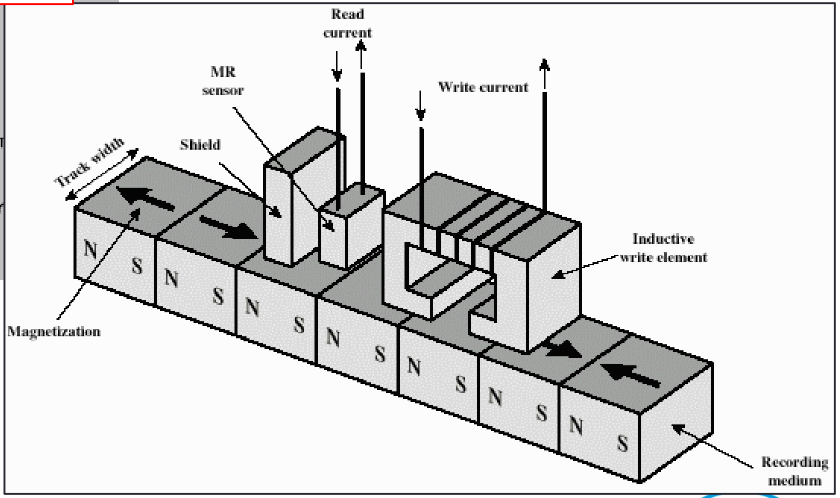


https://ams.com/ http://www.vectormagnets.com

Introduction to Magnetic Materials

Temporal Evolution of Storage Density in HDD

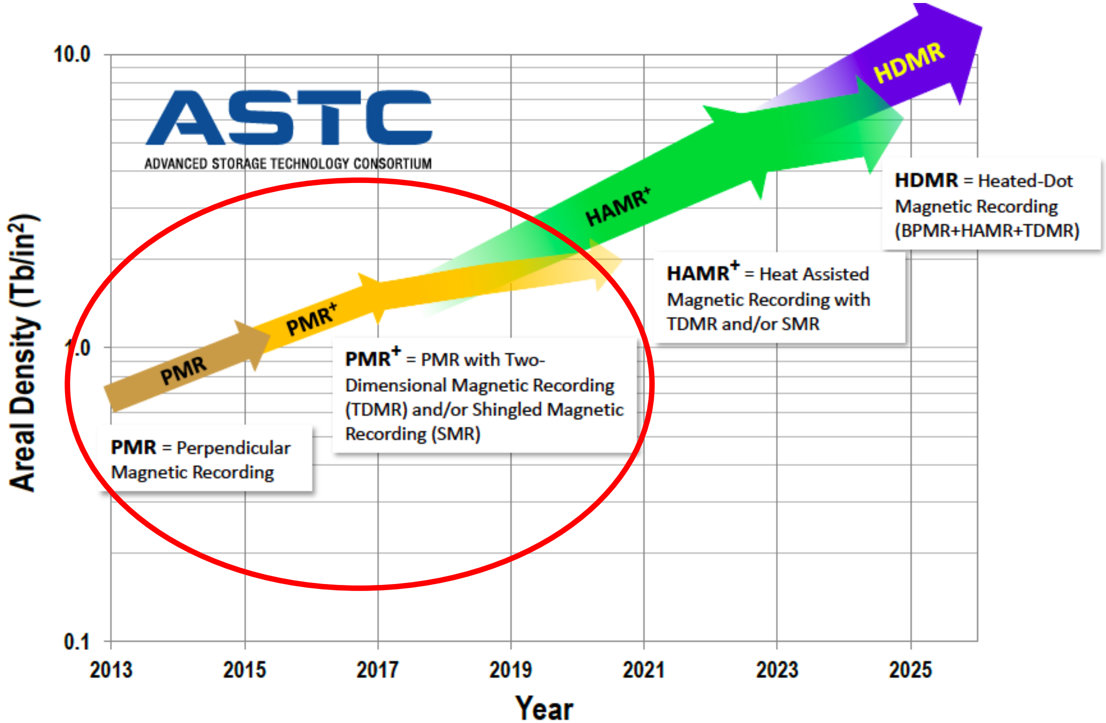




→ Demanding from a technological point of view

Introduction to Magnetic Materials

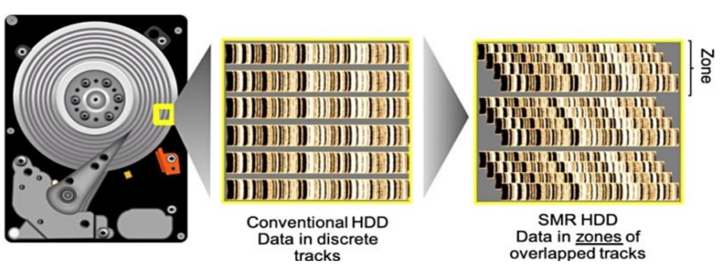
Temporal Evolution of Storage Density in HDD



ASTC Proprietary

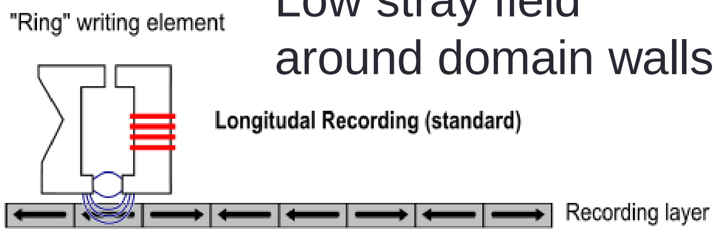
IDEMA

PMR+: Shingled MR



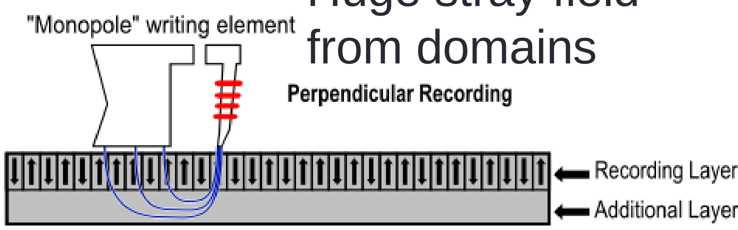
LMR

Low stray field around domain walls



PMR

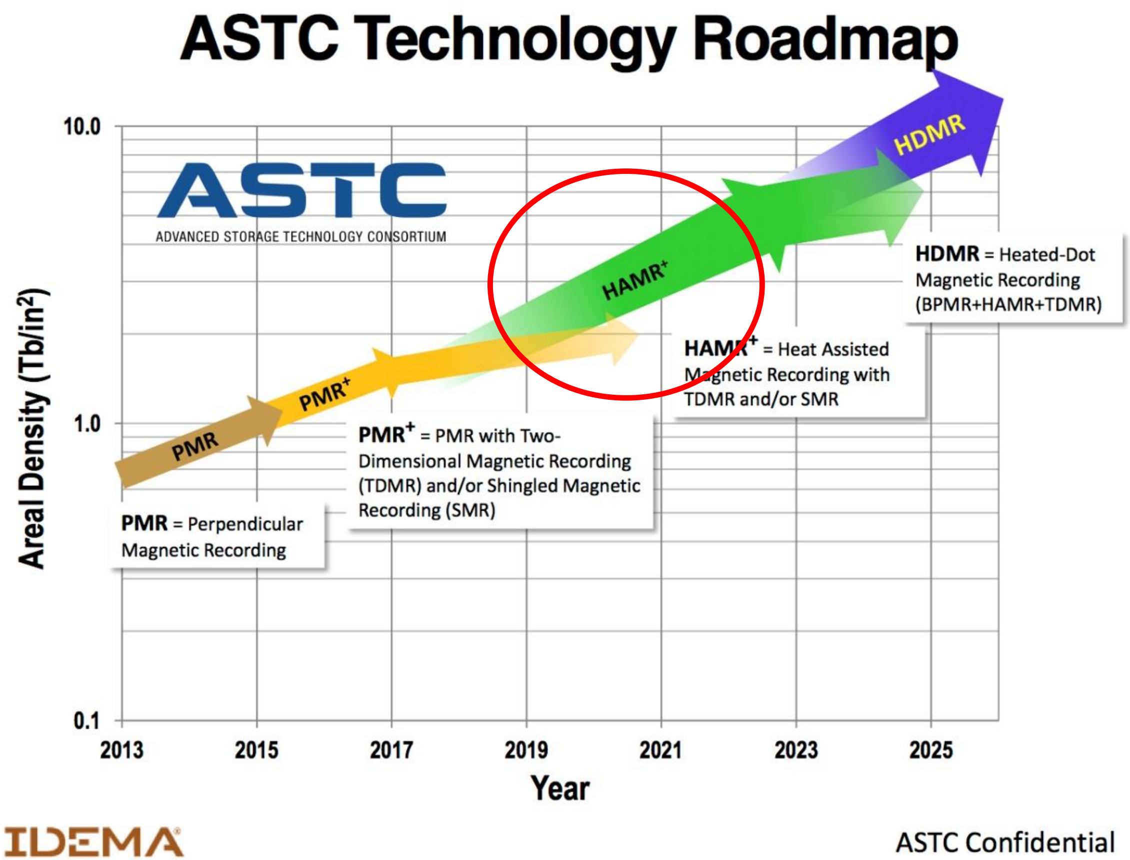
Huge stray field from domains



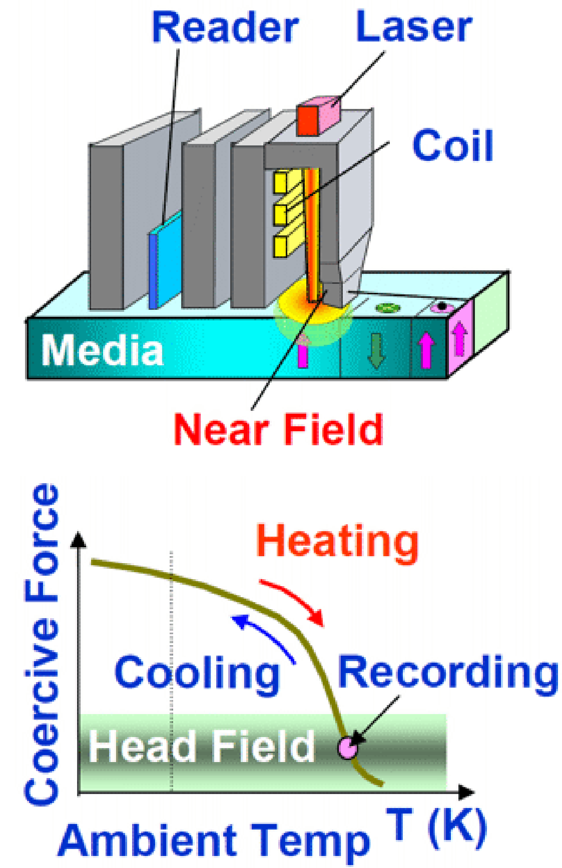
DESY.

Introduction to Magnetic Materials

Temporal Evolution of Storage Density in HDD



HAMR



Introduction to Magnetic Materials

Temporal Evolution of Storage Density in HDD

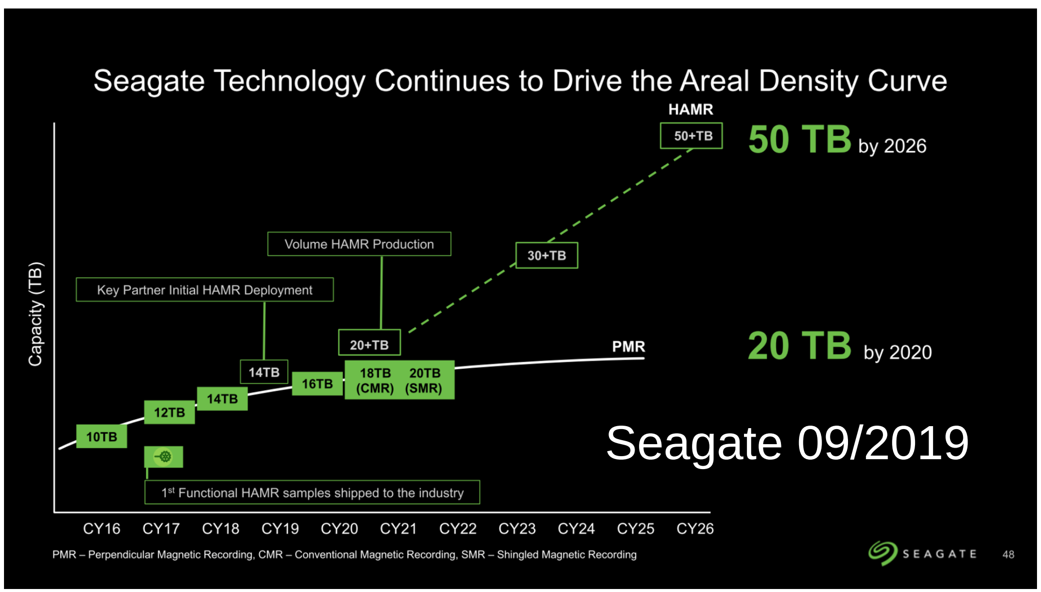
COMPUTERBASE › STORAGE

Seagate-Festplatten: HAMR-HDDs ab 2020 und Mach.2 in der Musterung

24.9.2019 10:56 Uhr | Michael Günsch 26 Kommentare

HAMR startet 2020 spät

Während sich der Marktstart der ersten HAMR-Festplatten immer weiter verschoben hatte, will Seagate dennoch ein altes Versprechen erfüllen: Im Herbst 2013 hatte Chief Technology Officer Mark Re 20-Terabyte-HDDs bis zum Jahr 2020 dank HAMR prognostiziert. Und genau diese Hürde soll die erste kommerzielle Generation der HAMR-Festplatten im kommenden Jahr nehmen. Allerdings sollen zum Jahresende 2020 vorerst Partner mit den 20-TB-HAMR-Laufwerken versorgt werden, um diese zu qualifizieren, der eigentliche Marktstart dürfte daher erst 2021 erfolgen.

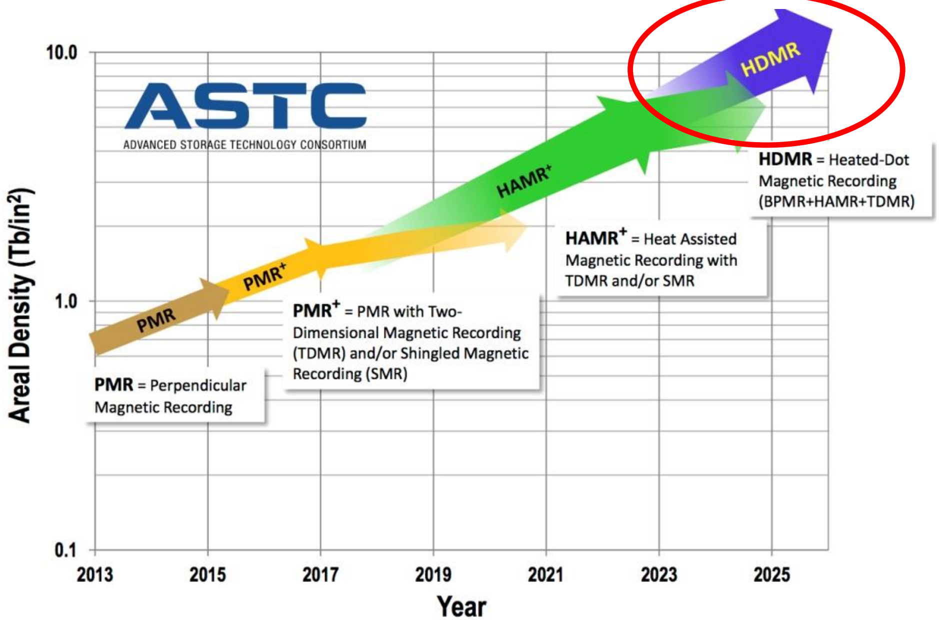


Fully functional pre-series ready now with 16 TB

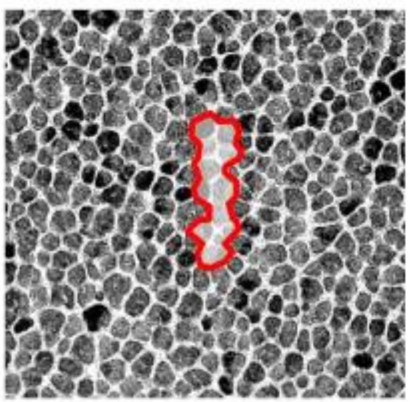
20 TB-HAMR-HDDs probably enter the market in 2021

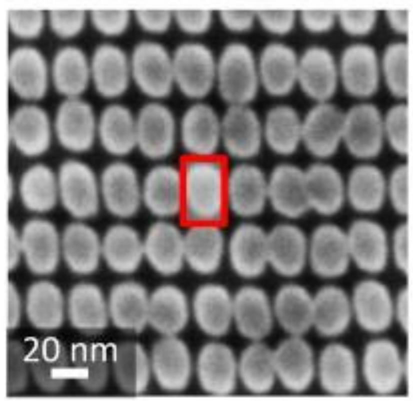
Introduction to Magnetic Materials

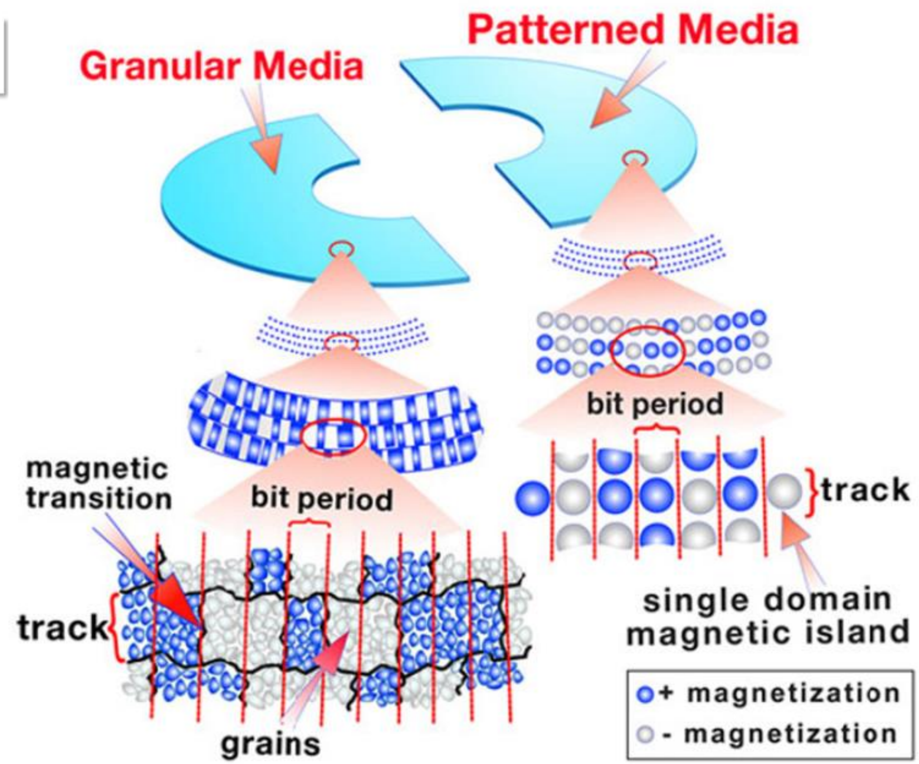
Temporal Evolution of Storage Density in HDD



Bit-patterned Media Recording (BPMR)







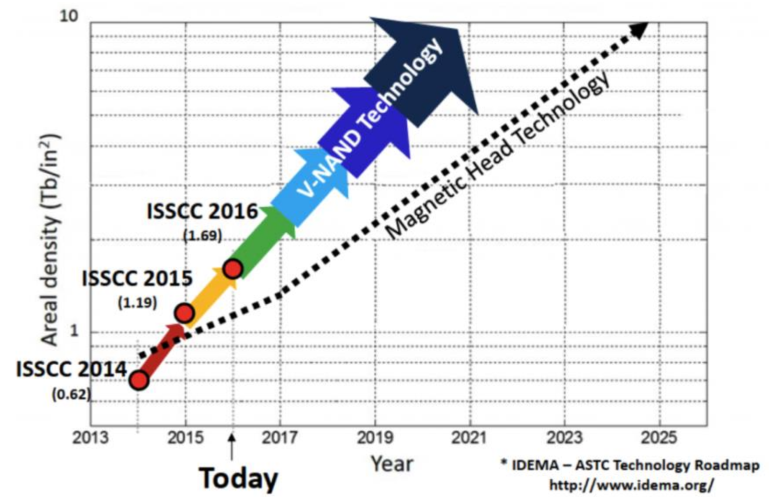
Griffith et al., J. Phys. D: Appl. Phys. 46, 503001 (2013)

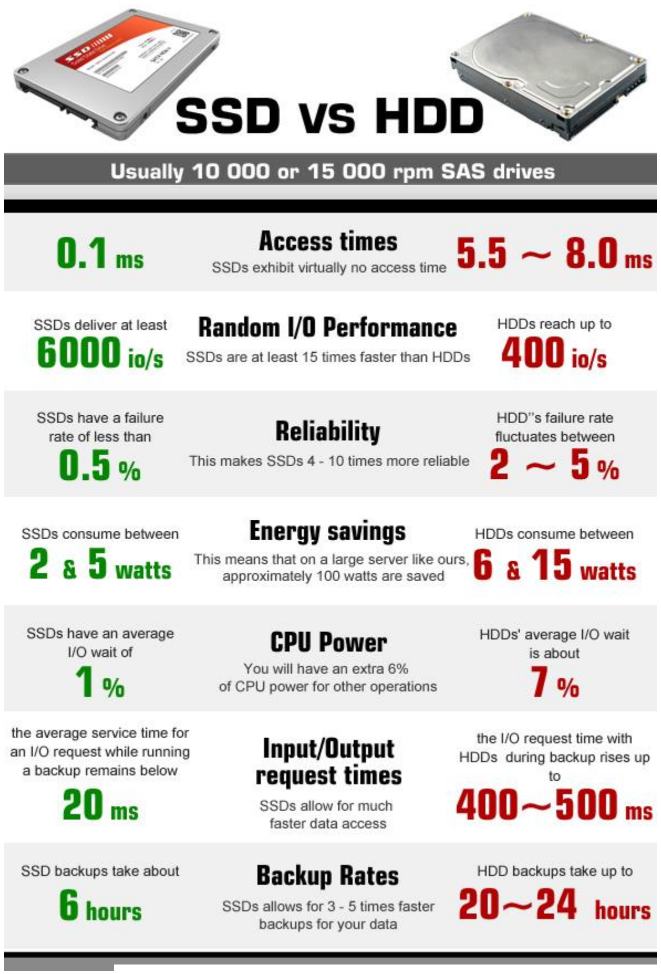
Introduction to Magnetic Materials

Temporal Evolution of Storage Density in HDD

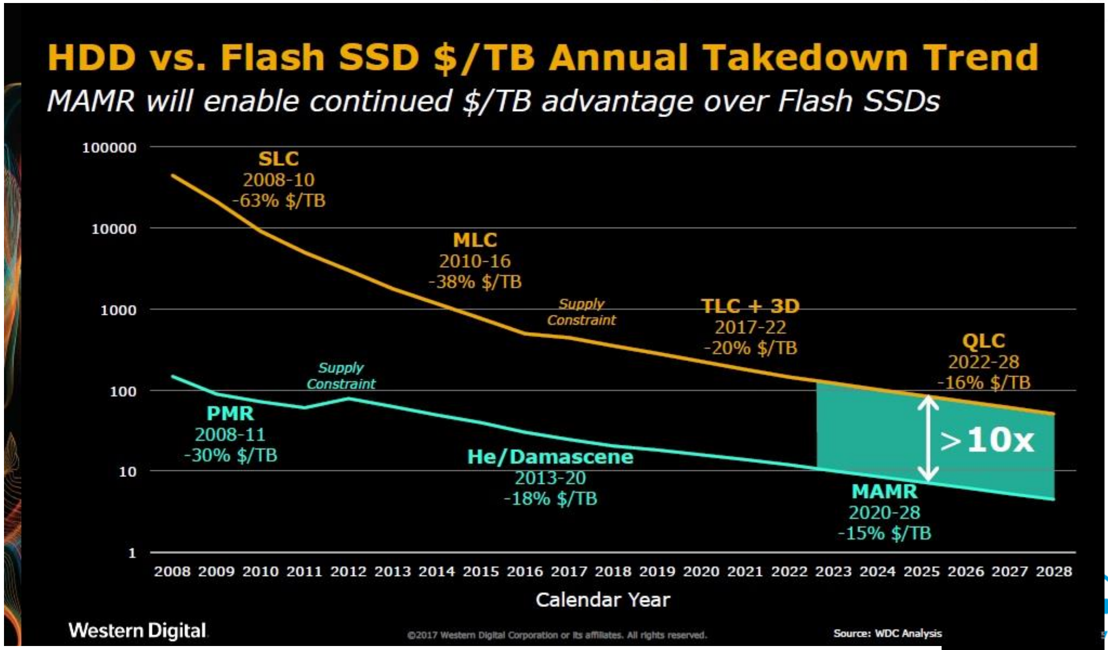
HDD vs FLASH (SSD) memory

SSD





Is magnetism out of the game?



Introduction to Magnetic Materials

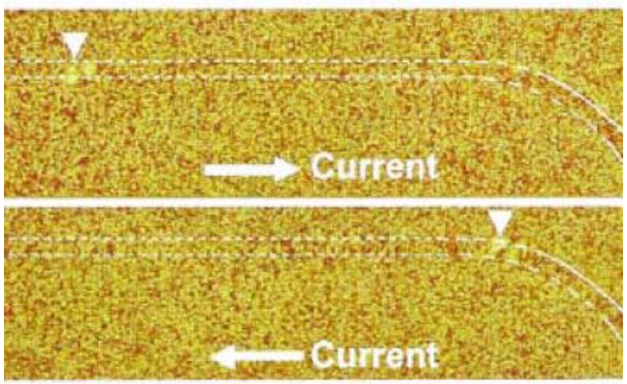
New Concepts Triggered by Novel Phenomena

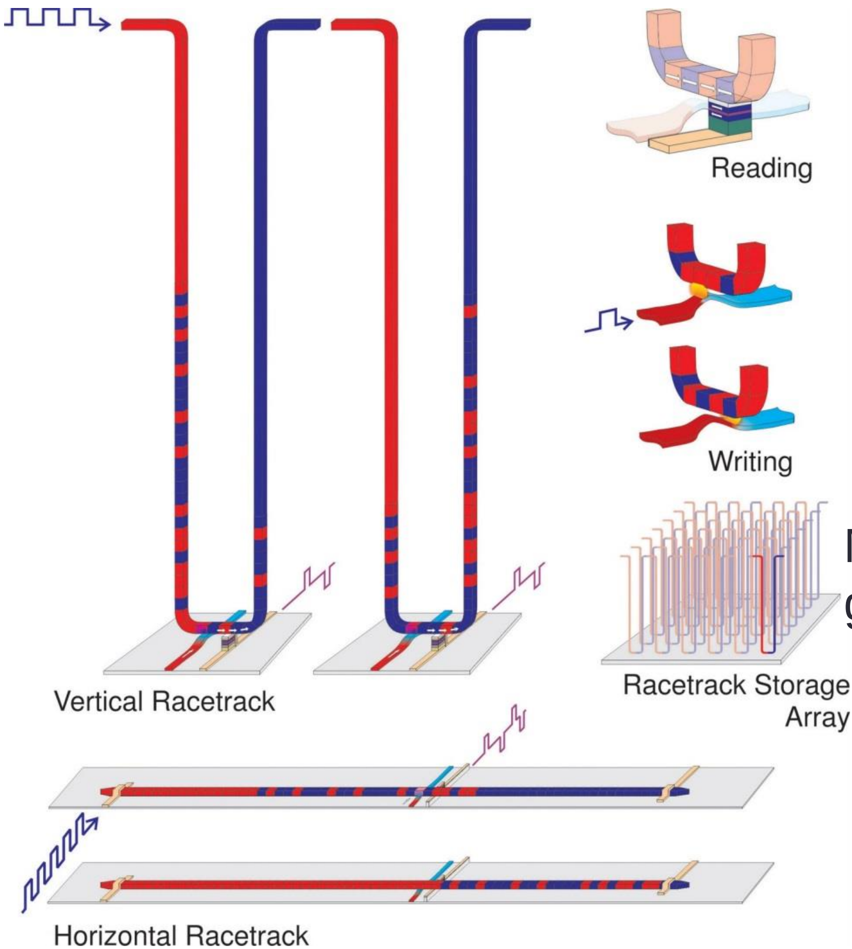
3,000,000 x faster than disk acc. to IBM – and cheap

Racetrack Memory (2008)

Electrical currents can manipulate magnetism!

- Oersted fields (1820)
- Current Driven Domain Wall Motion due to Spin-Torque Phenomena (2004)





Magnetic storage goes 3D

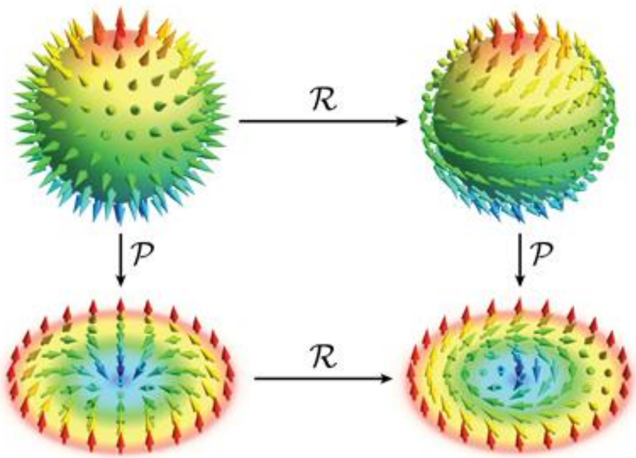
A. Yamaguchi et al., Phys. Rev. Lett. **92**, 077205 (2004)

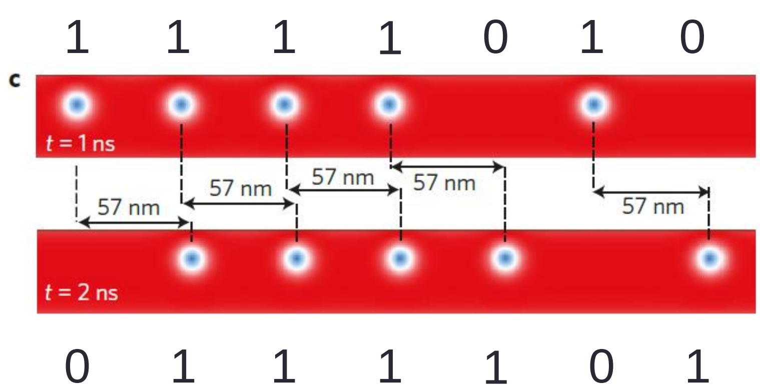
S.S.P. Parkin et al., Science **320**, 5873 (2008)

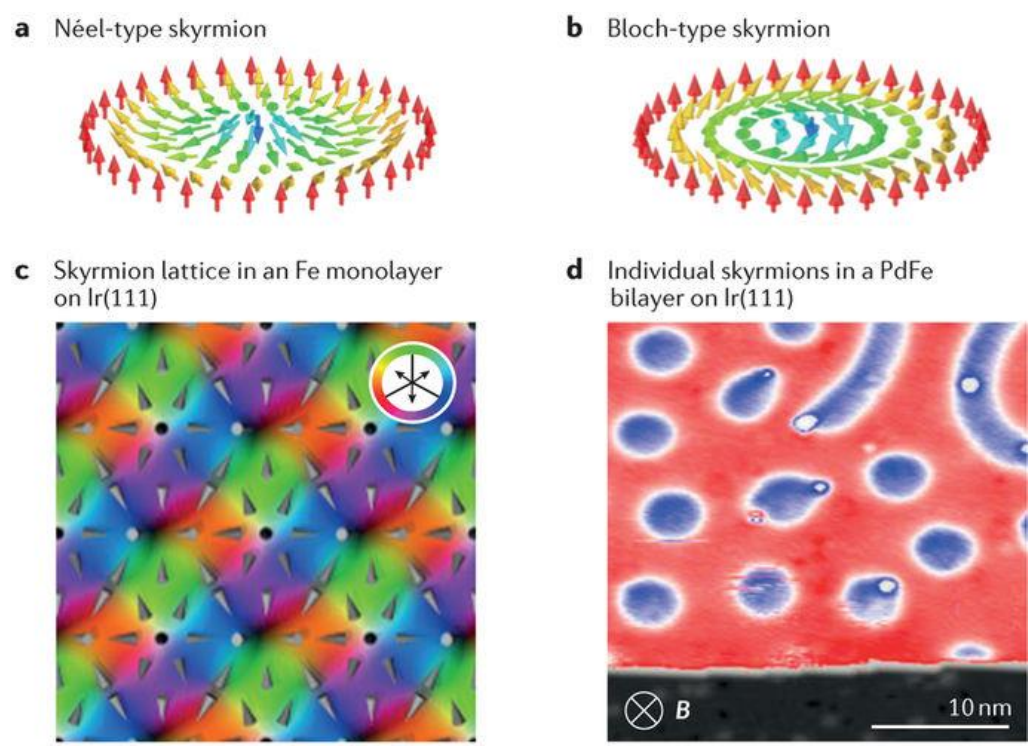
Introduction to Magnetic Materials

New Concepts Triggered by Novel Phenomena

Skyrmion Racetrack Memory (2013)







Nature Reviews | Materials

A. Fert et al., Nat. Nanotech. **8**, 152 (2013).
A. Fert et al., Nature Rev. Mat. **2**, 17031 (2017).

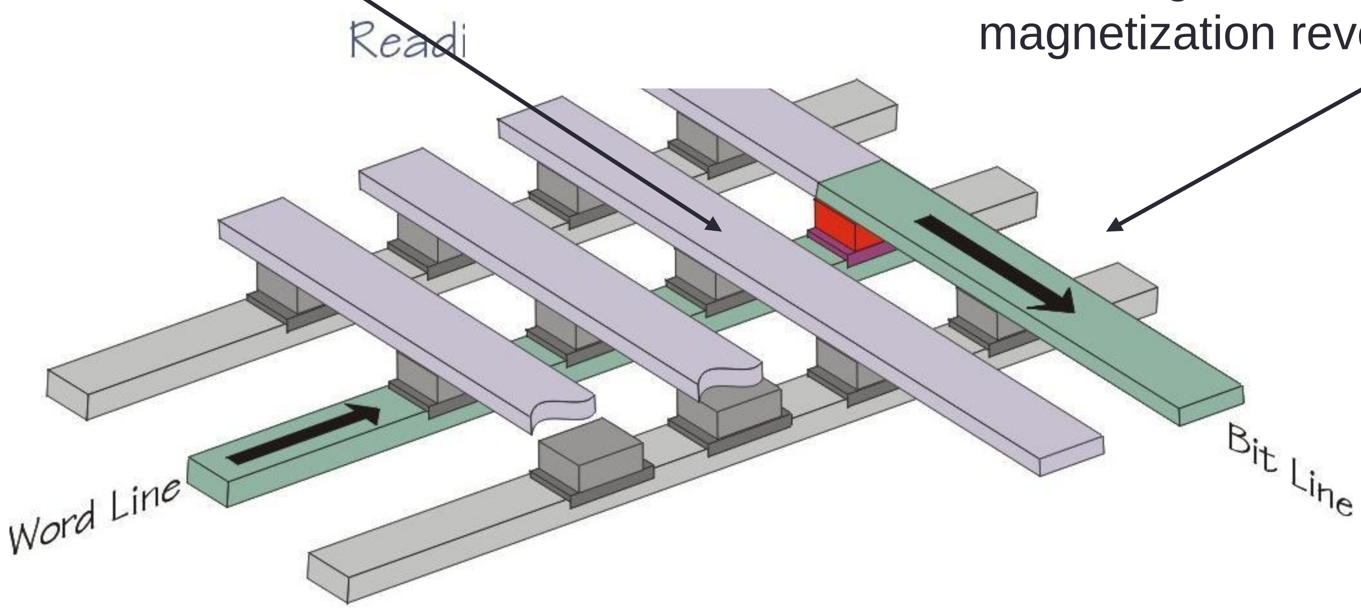
Introduction to Magnetic Materials

New Concepts triggered by novel Phenomena

(Non-Volatile) Magnetic Random Access Memory (MRAM)

Nanoscale:
1dot = 1bit

Read by means of
low voltage without
magnetization reversal

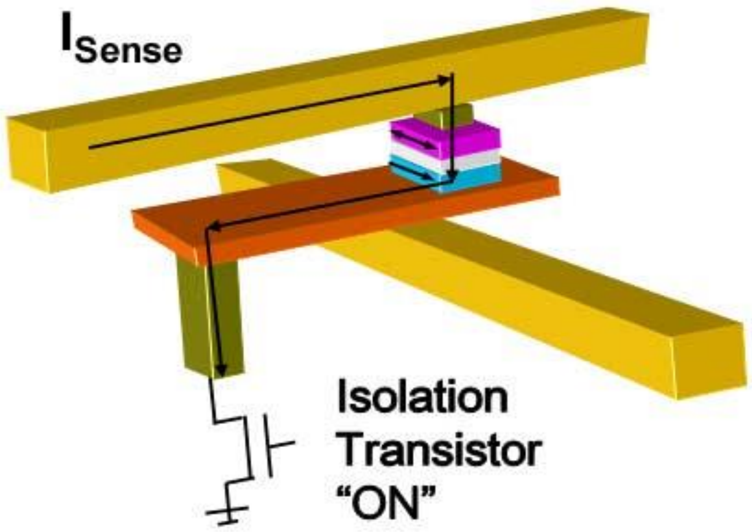


Dot size 20x20nm², distance 20nm: 4 Tbit/in²

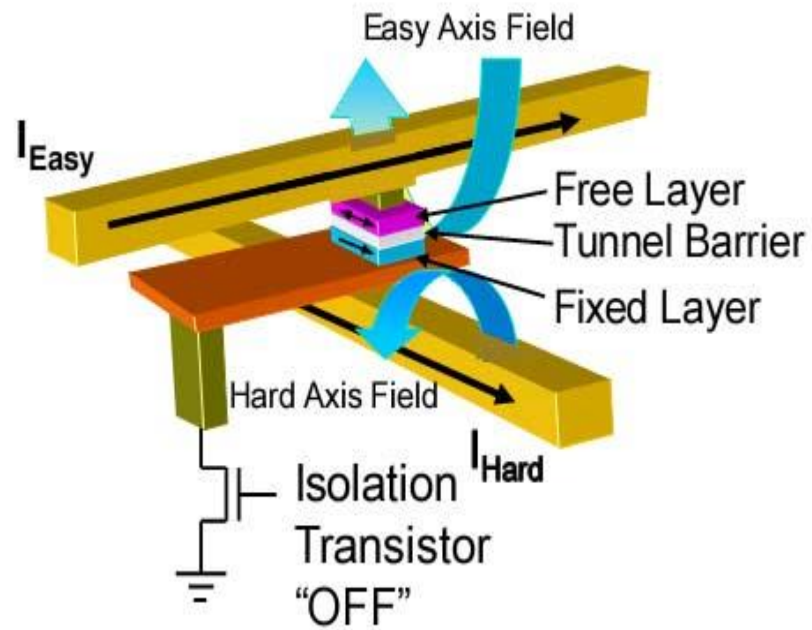
Introduction to Magnetic Materials

New Concepts triggered by novel Phenomena

(Non-Volatile) Magnetic Random Access Memory (MRAM)



"Read" mode



"Write" mode

images: „Freescale"

Introduction to Magnetic Materials

New Concepts triggered by novel Phenomena

(Non-Volatile) Magnetic Random Access Memory (MRAM)

EVERSPIN® TECHNOLOGIES

About Everspin | Investors | Careers | Press

PRODUCTS | APPLICATIONS & CASE STUDIES | TECHNOLOGY & RELIABILITY | BUY OR SAMPLE | SUPPORT

Home > DDR4 ST-MRAM Products

DDR4 ST-MRAM Products

“soon“

DDR4 Compatible Spin Torque MRAM

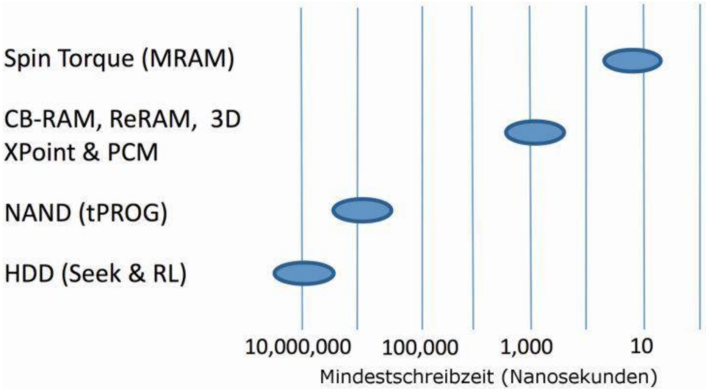
Everspin's newest Spin-Torque MRAM product is designed to comply with all JEDEC DDR4 DRAM commands and physical levels but with some timing differences that are unique to ST-MRAM.

- DDR4 protocol and physical layer compliant interface memories
- Non-volatile, high endurance persistent memory
- Capable of operation at rates of up to 2133MT/sec/pin
- Refresh is not required with Spin-Torque MRAM technology, which greatly simplifies design and reduces system overhead
- Some unique timing and page size limits

Everspin 1Gb DDR4 Spin-Torque MRAM

The EMD4E001G is a 1 Gigabit ST-MRAM organized as a 128Mb x 8 or 64Mb x 16 and capable of DDR4 operation at rates of up to 2133MT/sec/pin. Product availability will be announced soon.

Request more information about Everspin's 1Gb ST-MRAM >



STT-MRAM Products

“now“

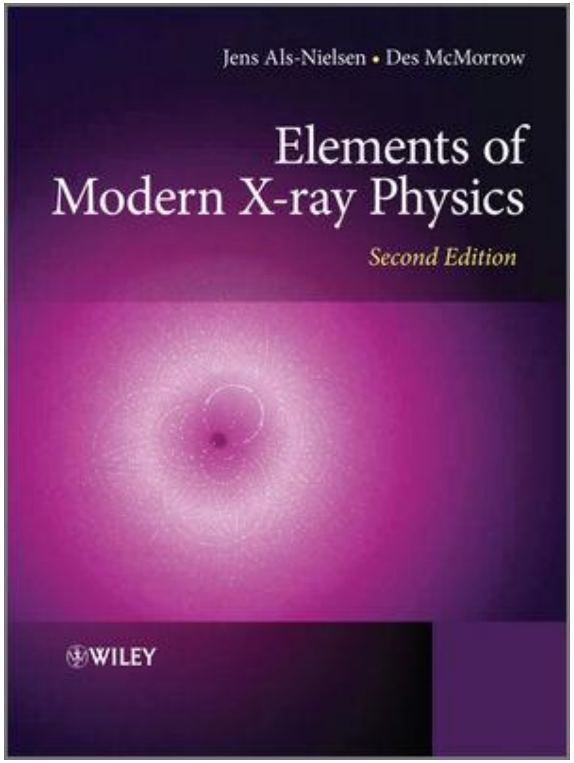
ST-DDR3 STT-MRAM

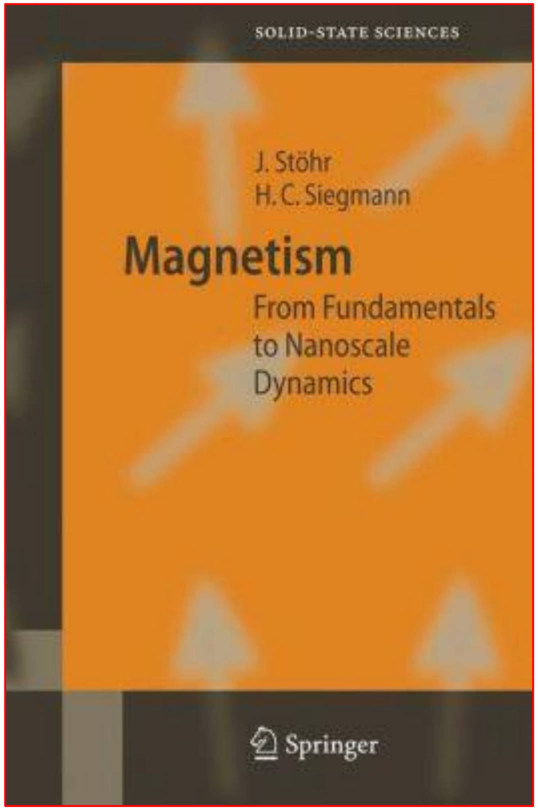
Everspin ST-DDR3 STT-MRAM is designed for enterprise-style applicaitons like SSD buffers, RAID buffers or synchronous logging applications where performance is critical and endurance is a must. The persistence of STT-MRAM protects data and enables systems to dramatically reduce latency, by up to 90%, boosting performance and driving both efficiency and cost savings.

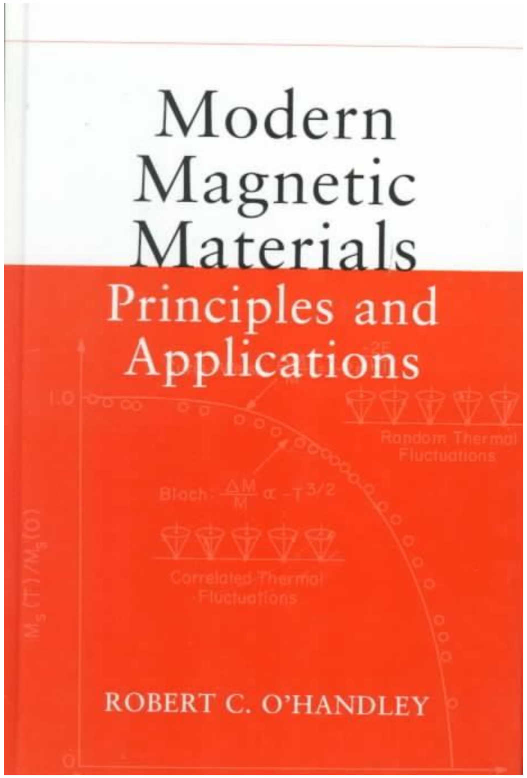
256Mb STT-MRAM

Size	Speed / Frequency	Configuration	
256Mb	667MHz	16 x 16Mb or 8 x 32Mb	EMD3D256M>

Literature:







http://magnetism.eu

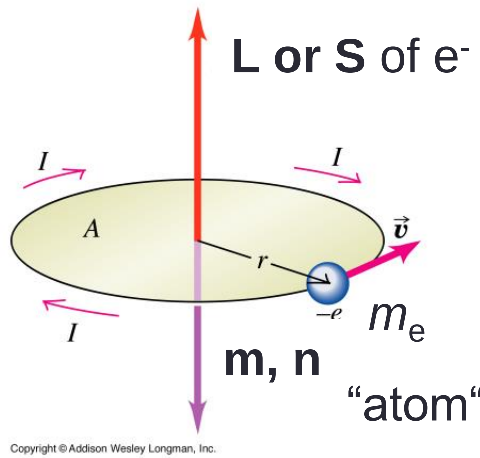
Introduction to Magnetic Materials

1.) Ferromagnetism in a nutshell

- Forms of Magnetic Phenomena
- Contributions to Magnetic Free Energy
- Focus on Systems with Perpendicular Magnetic Anisotropy (Co/Pt multilayers)
- Magnetic Domains and Domain Walls

Ferromagnetism in a nutshell – Forms of magnetism

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

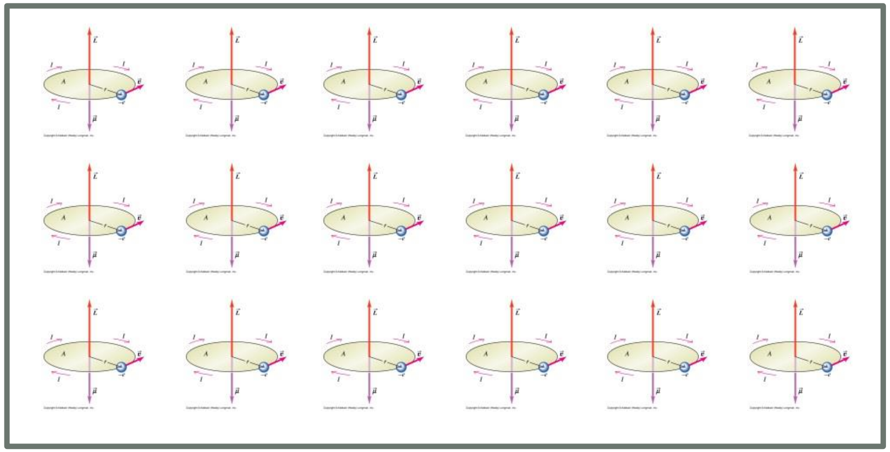


Definition: $\mathbf{m} = I \cdot A \cdot \mathbf{n}$
Unit: $[m] = \mathrm{Am}^2$

n = surface normal of A

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

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



Saturation magnetization ("length" of **M**):

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

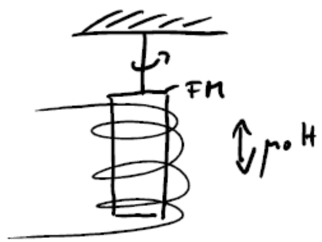
Volume V

Ferromagnetism in a nutshell – Forms of magnetism

- Connection of magnetic moment **m** 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

Durch alle Messungen konnte übereinstimmend der „Einsteineffekt" nachgewiesen werden, aber in einer Größe, die nicht der zugrunde gelegten Theorie entspricht, nach welcher nur *negative* Elektronen mit dem Wert $m/e = 0{,}565 \cdot 10^{-7}$ in den magnetischen Molekülen kreisen. Während Einstein und de Haas auch quantitativ eine sehr gute Bestätigung der Theorie finden, ergeben meine Messungen einen bei Eisen um 47 Proz., bei Nickel um 43 Proz. zu kleinen Einsteineffekt.

E. Beck, Ann. Phys. **18**, 1919 (1915).

Gyromagnetic ratio γ :

$$|\vec{m}| = I \cdot A, \qquad A = \text{area encirceled by current}$$

$$|\vec{L}| = Nrmv, \qquad N = \#\,\text{particles}, v = \frac{2\pi r}{T}, I = \frac{qN}{T}, \qquad T = \text{revolving time}$$

$$\frac{|\vec{m}|}{|\vec{L}|} = \frac{IA}{Nrmv} = \frac{qN \cdot \pi r^2 \cdot T}{T \cdot Nrm \cdot 2\pi r} = \frac{q}{2m}$$

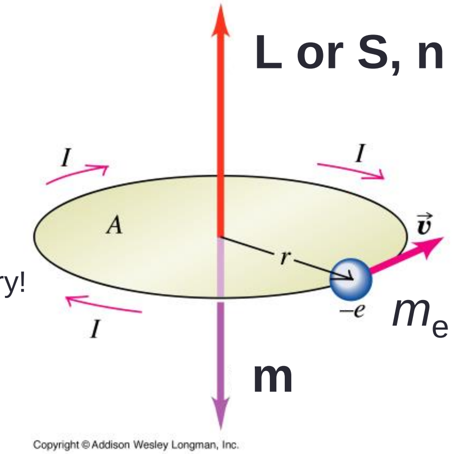
Only valid for classical ring current!

Ferromagnetism in a nutshell – Forms of magnetism

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

$$
\begin{aligned}
g &= 1\text{: classical description, angular momentum (orbital)}\\
g &= 2.00231930436182(52)\text{ for electron spin (exp.)}\\
g_p &= 5.585694702(17)\text{ for protons}\\
g_n &= -3.82608545(90)\text{ for neutrons}\\
g_{^{14}\mathrm{C}} &= 0\text{ for carbon 14}
\end{aligned}
$$

In accordance with theory!



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

$$|\vec{m}| = \gamma\hbar = \frac{q\hbar}{2m}, \text{for } q = |e|: \qquad \mu_B = 9.274 \cdot 10^{-24}\,\mathrm{Am}^2$$

Note that $\gamma < 0$ for electrons $\vec{L} \uparrow\downarrow \vec{m}$

Ferromagnetism in a nutshell – 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”): $$H' = \overbrace{\frac{q}{2m_e}\mathbf{L}}^{-\mathbf{m}} \cdot \mathbf{B} + \frac{q^2}{8m_e}(\mathbf{B} \times \mathbf{r})^2$$

electron-orbit 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 a nutshell – Forms of magnetism

- Different types of magnetic phenomena in solid states

Paramagnetism and Diamagnetism

- Ratio of both corrections:

$$\frac{\frac{q}{2m}\vec{L}\cdot\vec{B}}{\frac{q^2}{8m}\left|\overrightarrow{(\vec{B}\times\vec{r})}^2\right|} \geq \frac{\overbrace{\frac{q}{2m}\hbar}^{\mu_B} B}{\frac{q^2}{8m}B^2 r^2} = \frac{4\hbar}{qBr^2} = 10^4 \qquad \text{for } B = 10\text{ T and } r = 0.15\text{nm}$$

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

$$E_{\text{therm}} = k_{\text{B}}T = 25\text{ meV}$$
$$E_{\text{para}} = 0.58\text{ meV}$$

$$E_{\text{para}} \ll E_{\text{therm}}$$

- Thermodynamic description:

$$\frac{< m >}{\mu_B} = \tanh\frac{\mu_B B}{k_B T} \approx \frac{\mu_B B}{k_B T} = \frac{E_{\text{para}}}{E_{\text{therm}}} = 0.023 \text{ at } 10\text{ T}$$

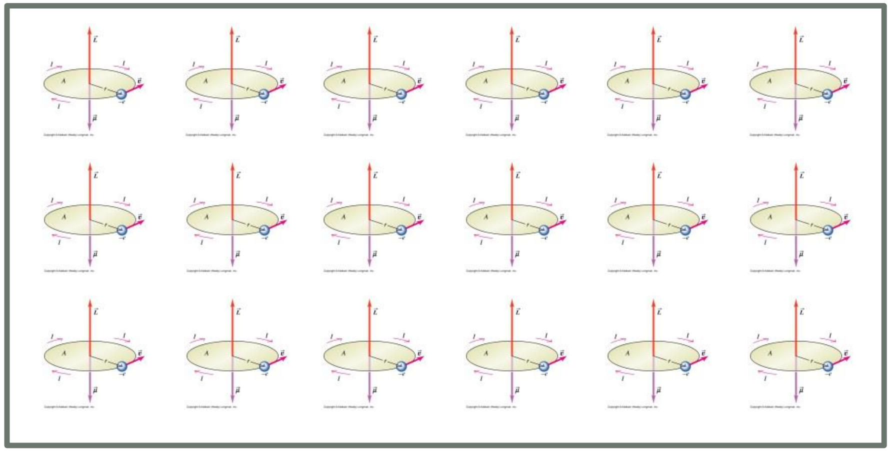
Ferromagnetism in a nutshell – Forms of magnetism

- Different types of magnetic phenomena in solid states

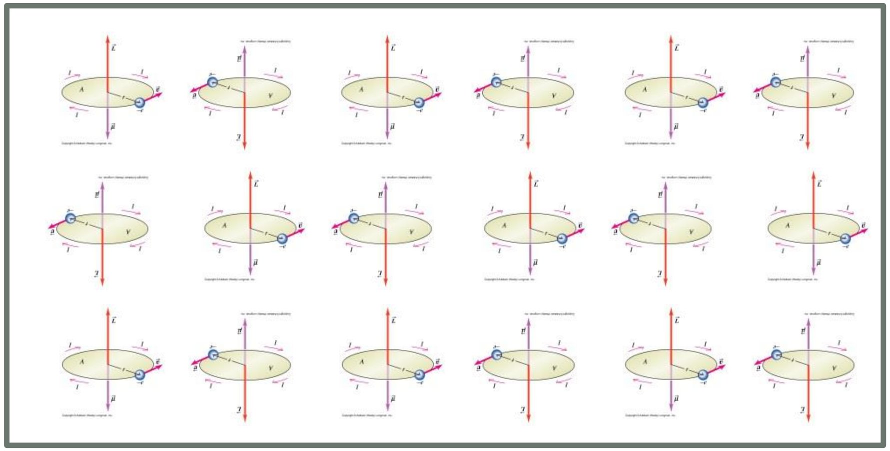
<u>Materials with long-range magnetic order</u> (without external magnetic field)

due to strong interaction between electrons' magnetic moments

Ferromagnetism (FM)



Antiferromagnetism (AFM)



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

Ferromagnetism in a nutshell – Forms of magnetism

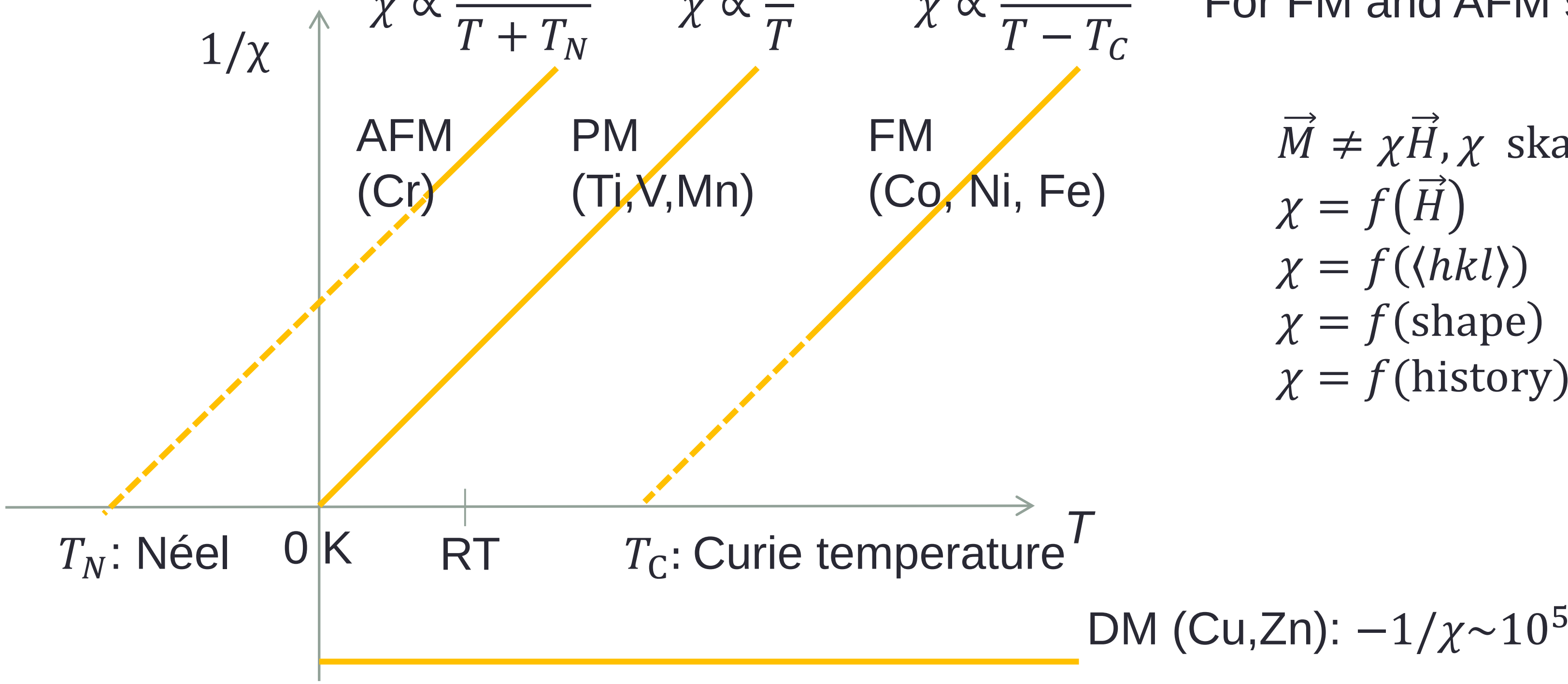
- Different types of magnetic phenomena $M = \left(\frac{\partial E}{\partial B}\right)$, $\chi = -\mu_0 \frac{\partial^2 E}{\partial B^2}$, E =free Energy

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

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

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

$\chi \propto \frac{1}{T + T_N}$ $\chi \propto \frac{1}{T}$ $\chi \propto \frac{1}{T - T_C}$



Note:
For FM and AFM state (low T)

$\vec{M} \neq \chi \vec{H}, \chi$ skalar
$\chi = f(\vec{H})$
$\chi = f(\langle hkl \rangle)$
$\chi = f(\text{shape})$
$\chi = f(\text{history})$

Ferromagnetism in a nutshell – Magnetic energies

- Magnetic free energy

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

Exchange energy

Magnetocrystalline Anisotropy

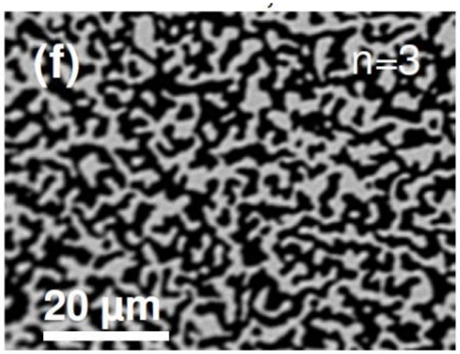
Demagnetization or stray field energy

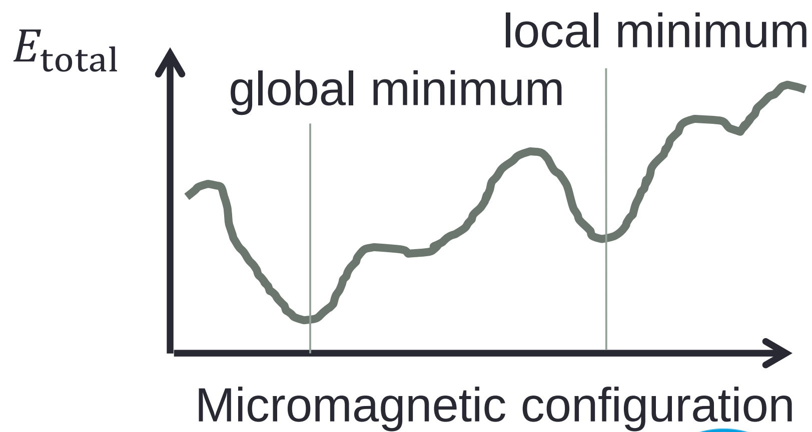
Zeeman energy

Dzyaloshinskii-Moriya interaction

in equilibrium:

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





Ferromagnetism in a nutshell – Magnetic energies

> 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

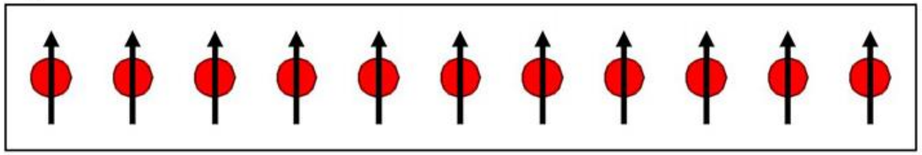
$$J \propto <\Psi_{\text{symmetric}}|H_{\text{Coulomb}}|\Psi_{\text{symmetric}}> - <\Psi_{\text{antisymmetric}}|H_{\text{Coulomb}}|\Psi_{\text{antisymmetric}}>$$

Exchange constant (or integral)

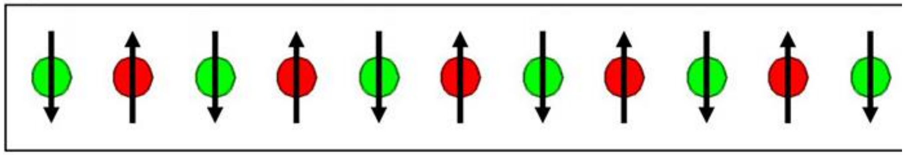
➔ Heisenberg exchange (effective spin-spin interaction)
(generally, only next neighbor interaction)

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

$J_1 > 0$ ferromagnetic



$J_1 < 0$ antiferromagnetic



Ferromagnetism in a nutshell – Magnetic energies

- Micromagnetic approximation

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

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

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

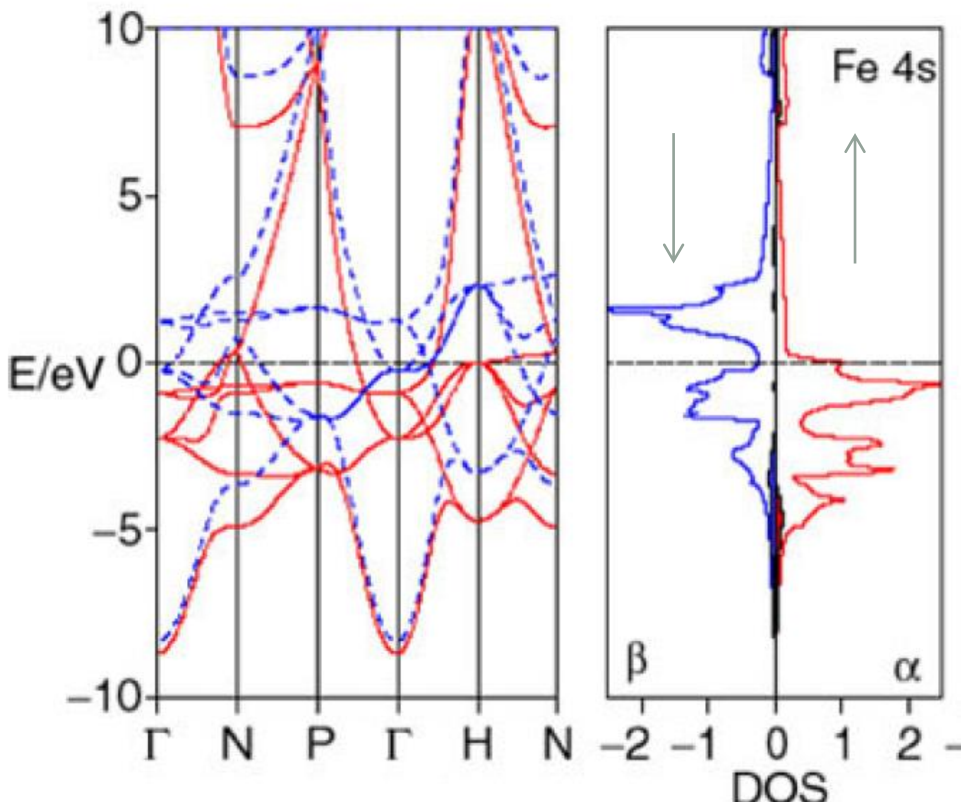
➔ $\Delta E_{xc}/V \approx (E_{\uparrow\downarrow} - E_{\uparrow\uparrow})/V = 1$ GJ/m³ (0.1 eV/atom ≈ 4 times thermal energy at RT)

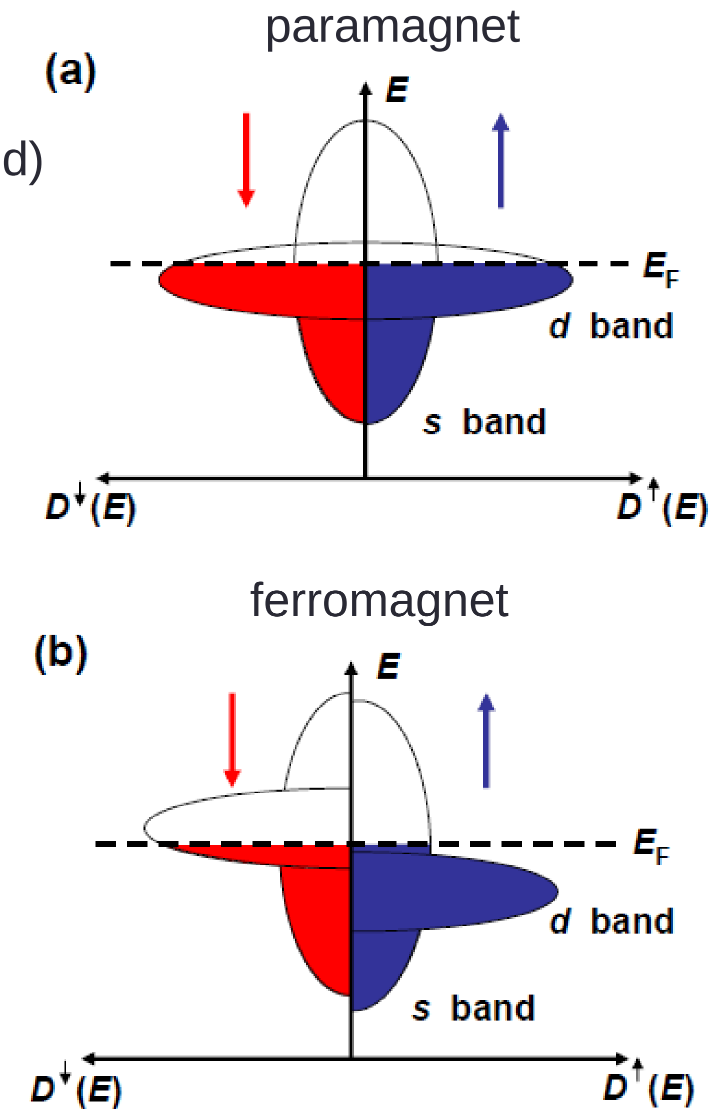
➔ FM at room temperature!

Ferromagnetism in a nutshell – Magnetic energies

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

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





- Saturation magnetization: $M_S = \mu_B(n_\uparrow - n_\downarrow)$

Ferromagnetism in a nutshell – Magnetic energies

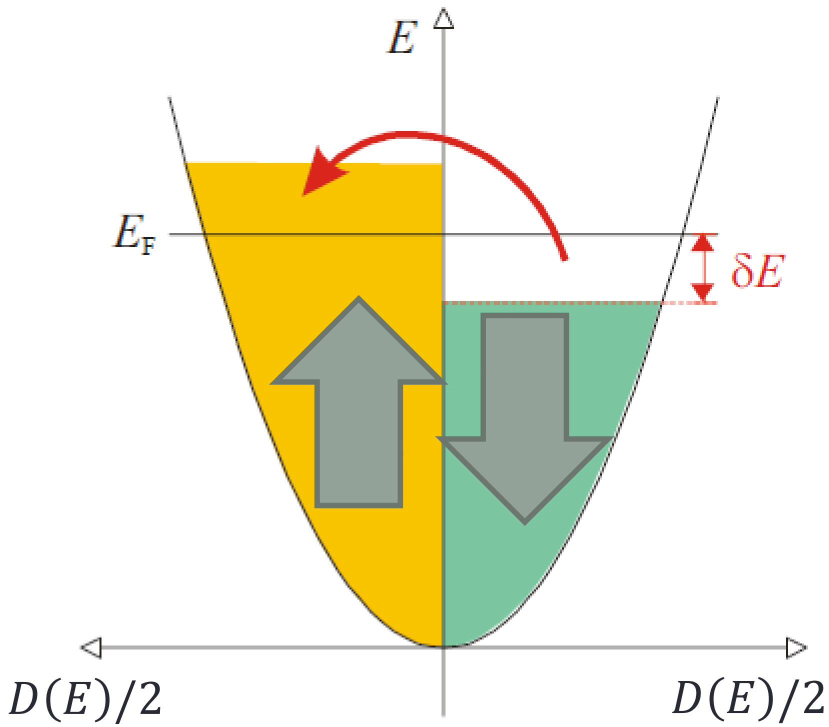
- Itinerant (band) Ferromagnetism for Ni, Fe, Co

  (assume quasi-free electron gas)

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

  Derivation:

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



Ferromagnetism in a nutshell – Magnetic energies

> Itinerant (band) Ferromagnetism

Stoner criterion (1939): $I \cdot D(E_\mathrm{F}) > 1$

I : Stoner parameter

	$n^o(E_F)[eV^{-1}]$	$I[eV]$	$I\,n^o(E_F)$
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

- Derivation: Comparison of ferromagnet and paramagnet

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

Number of electrons

shift

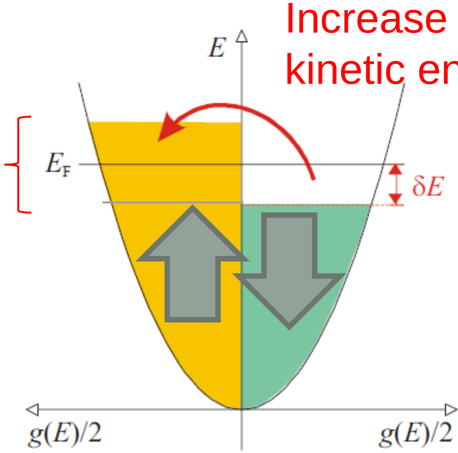
2.) Decrease of static energy: $dE = -\mu_0 M dH_\mathrm{xc} = -\mu_0 M\lambda(J)dM$

$$\Delta E_\mathrm{pot} = -\int_0^{M_S} M\mu_0\lambda(J)\,\mathrm{d}M = -\frac{\mu_0}{2}\lambda(J){M^2}_S$$

$$= -\frac{1}{2}\underbrace{\lambda(J)\mu_0{\mu_\mathrm{B}}^2}_{I}(D(E_\mathrm{F})\delta E)^2$$

Increase of kinetic energy

e$^-$ without repulsive Coulomb interaciton



3.) Total energy balance:

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

Ferromagnet, if $\Delta E < 0 \Rightarrow \boxed{I \cdot D(E_\mathrm{F}) > 1}$

Ferromagnetism in a nutshell – Magnetic energies

> Magnetocrystalline anisotropy

- Gedankenexperiment:
  Assume an infinite amorphous material (a)/ crystal (b), 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 a nutshell – Magnetic energies

> Magnetocrystalline anisotropy

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

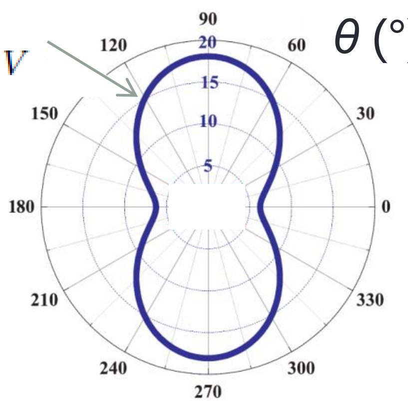
$$(E/V)_{\text{mca, }V} = K_{1V}\sin^2\theta + \underline{K_{2V}\sin^4\theta} + \mathcal{O}(\sin^6\theta)$$

Higher order is also considered in excercise next week

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

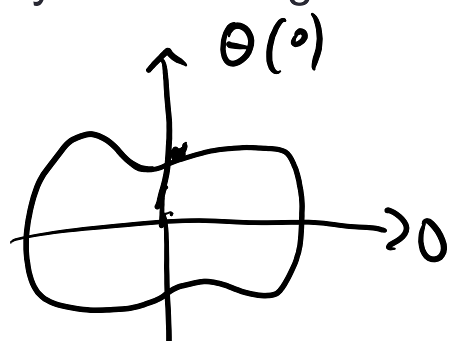
➔ The (0001) axis is the „easy axis of magnetization“ for Co

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

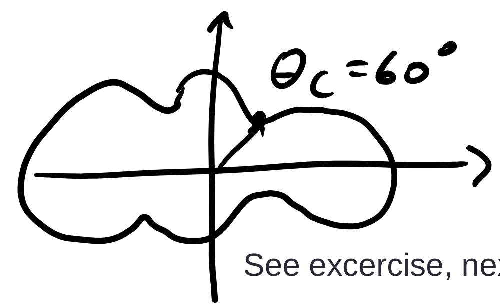


θ (°)

$K_1 > 0$
$K_2 = 0$



$K_1 < 0, K_2 = 0$



See excercise, next week

$-2K_2 < K_1 < 0, K_2 > 0$

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

Ferromagnetism in a nutshell – Magnetic energies

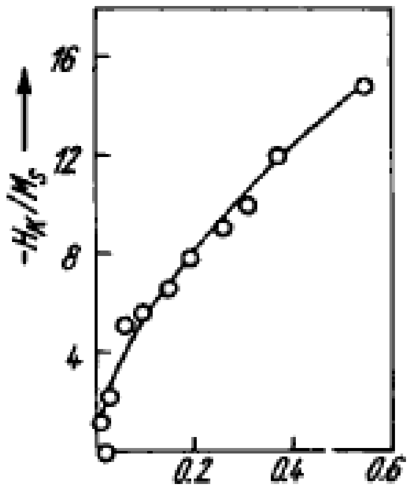
> (Magnetocrystalline) **interface anisotropy** (Néel's pair interaction model 1959)

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

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

t: film thickness

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



$1/t$ (monolayers^{-1})

- 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 by Carcia:

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

when considering half atomic layer (1Å)

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

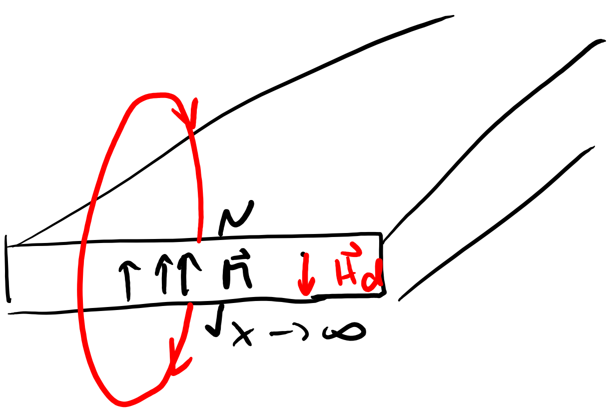
Ferromagnetism in a nutshell – Magnetic energies

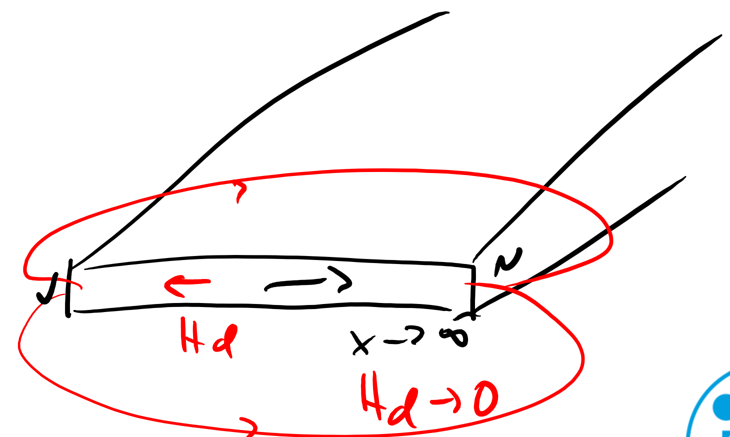
> **Demagnetization energy E_d (shape anisotropy)**

- Gedankenexperiment II:
  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 a nutshell – Magnetic energies

- **Demagnetization energy E_d**

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

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

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:

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

Isotropy
➔ No shape anisotropy

cylindrical wire ~ “cigar“

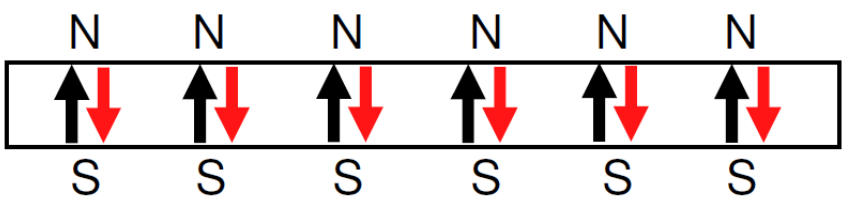
pancake

Ferromagnetism in a nutshell – Magnetic energies

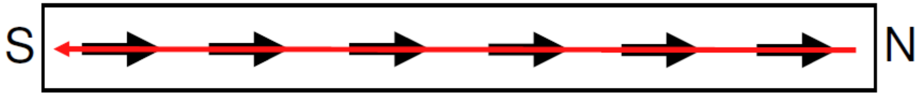
> **Demagnetization energy E_d**

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

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



$E_{\text{demag}} \approx 0$



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

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

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

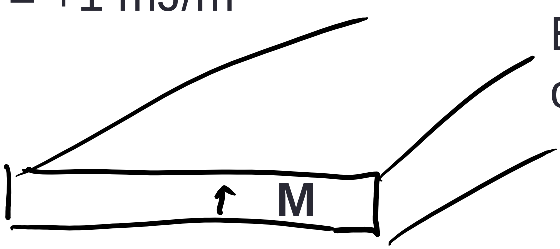
Ferromagnetism in a nutshell – Magnetic energies

> **Effective anisotropy constant for uniaxial thin films:**

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

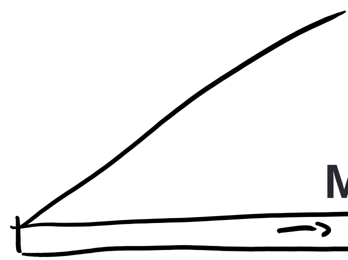
For Co(0001)/Pt(111) system:

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 !!!

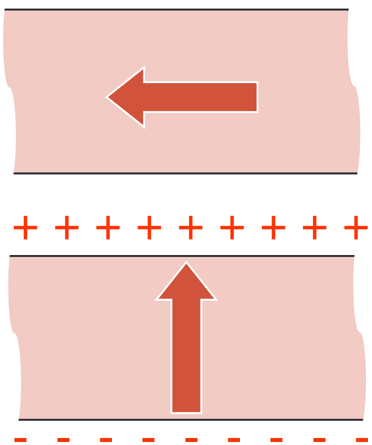
$K_{1,\mathrm{eff}} < 0$ for $t > 2$ nm

Ferromagnetism in a nutshell – Magnetic energies

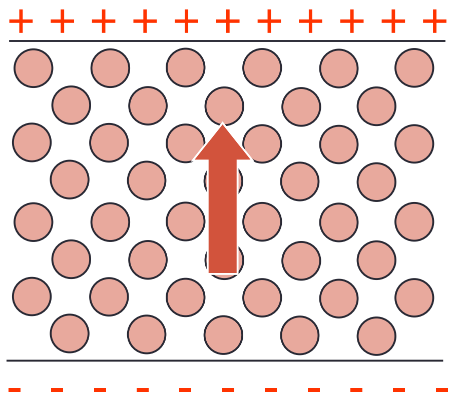
How to realize a perpendicular magnetic anisotropy in a thin film (Summary)?

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

Shape anisotropy



MCA (volume)



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

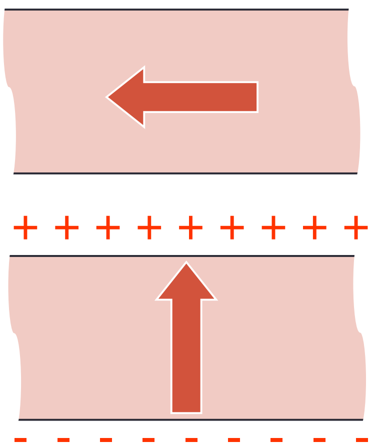
>0, e.g. for FePt $L1_0$ alloys

Ferromagnetism in a nutshell – Magnetic energies

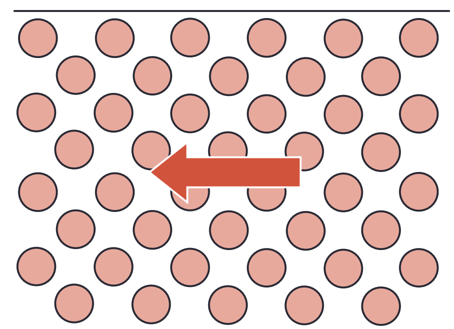
How to realize a perpendicular magnetic anisotropy in a thin film (Summary)?

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

Shape anisotropy



MCA (volume)



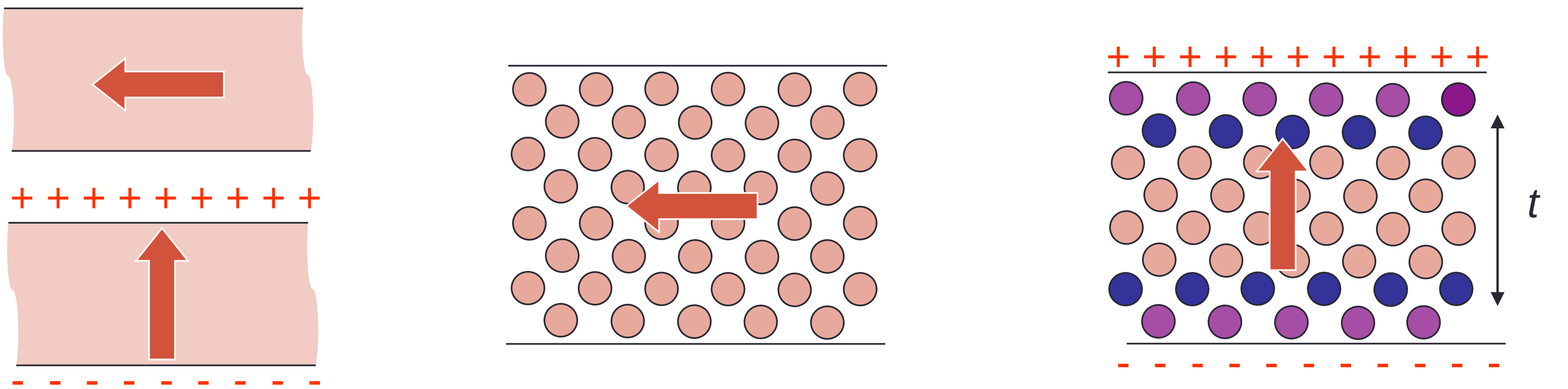
$$K_{eff} = \underbrace{-\frac{\mu_0}{2} M_S^2 \qquad + K_V}_{<0\text{, e.g. for Co}}$$

Ferromagnetism in a nutshell – Magnetic energies

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)

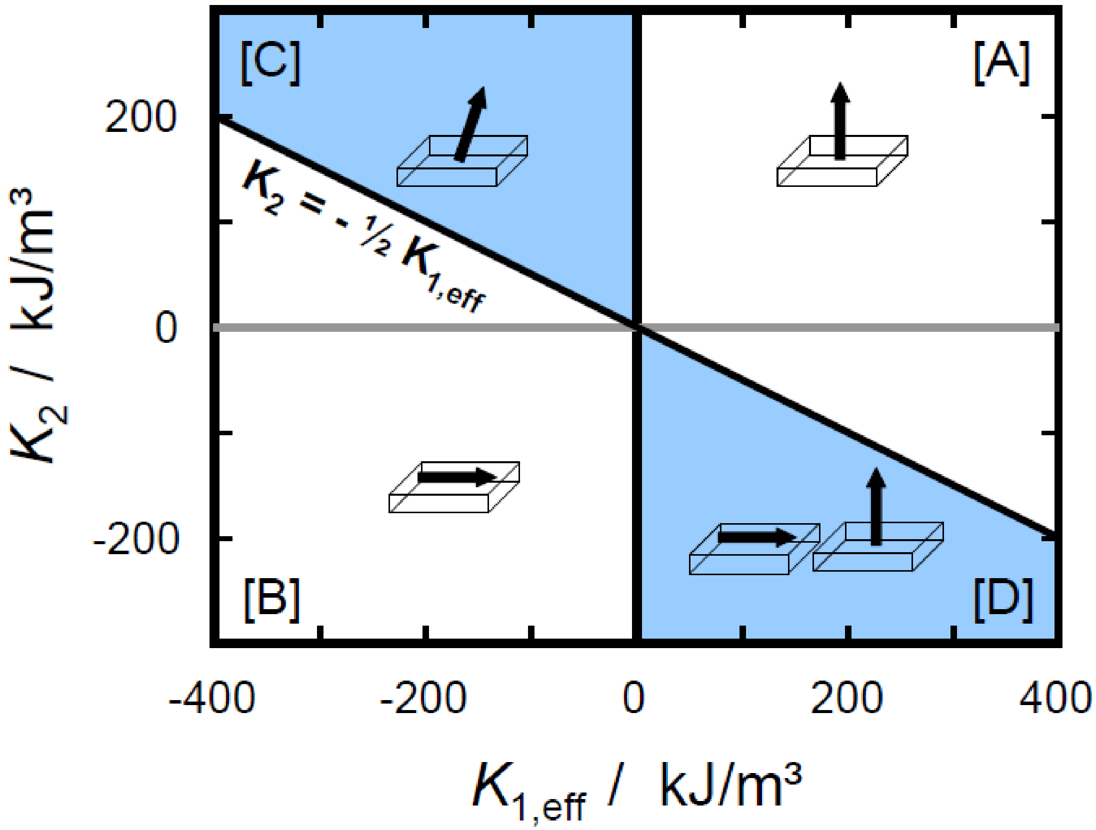


$$\underbrace{K_{eff} = -\frac{\mu_0}{2}M_S^2 + K_V + \frac{2K_S}{t}}$$

>0, e.g. for **Co/Pt,** if t < 2 nm

Ferromagnetism in a nutshell – Magnetic energies

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



Ferromagnetism in a nutshell – Magnetic energies

- Zeeman energy

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

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

- Total energy of single-domain system (excercise today):

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

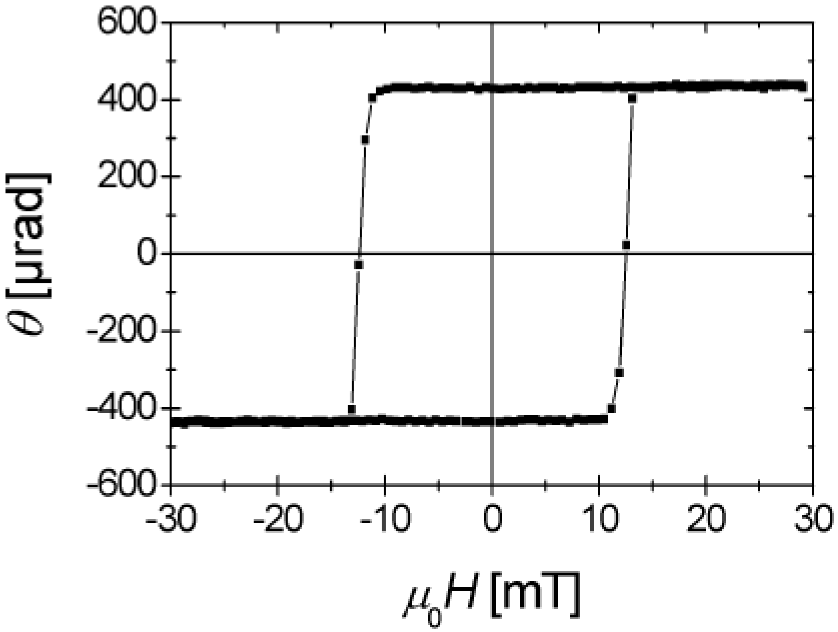
Zeeman term

➔ Experimental determination of $K_{1,\mathrm{eff}}$ and K_2

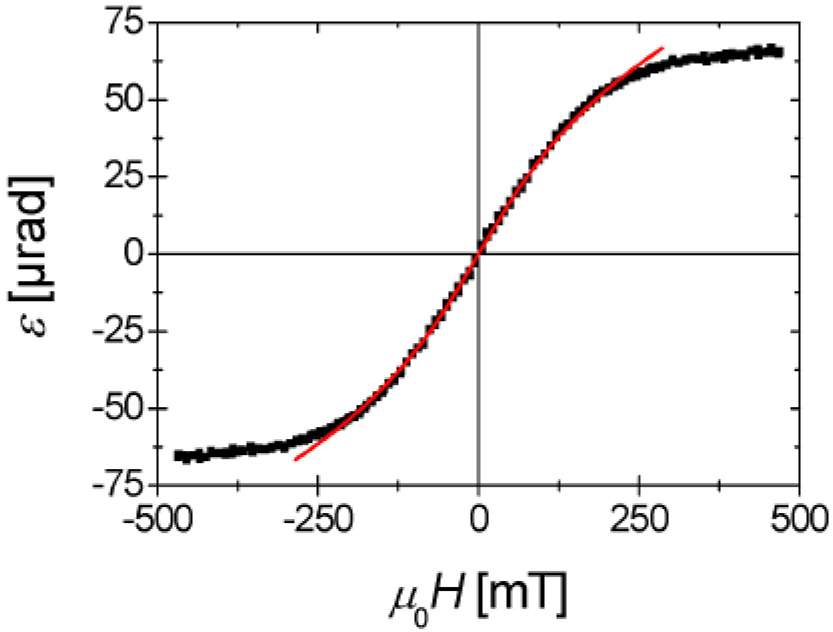
Ferromagnetism in a nutshell – Magnetic energies

> Magnetic hysteresis curves (to obtain magnetic anisotropy constants)

a)



b)

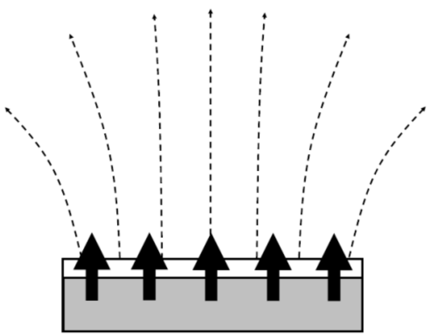


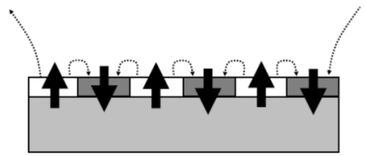
Easy axis
(domain nucleation and domain wall motion)

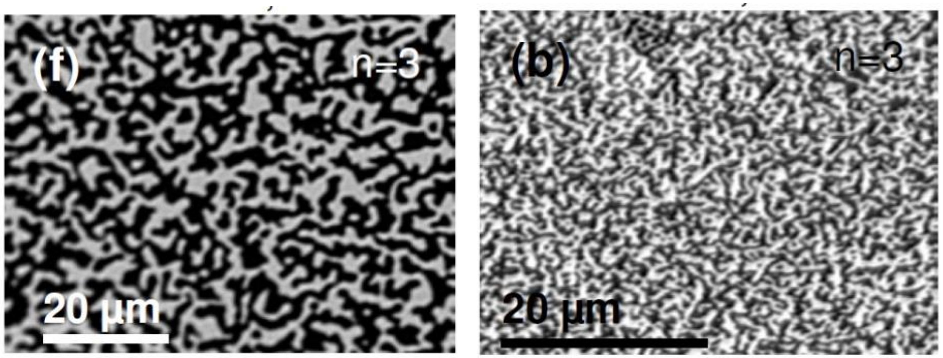
Hard axis
(coherent rotation of magnetization,
 excercise next week)

Ferromagnetism in a nutshell – Domains and Walls

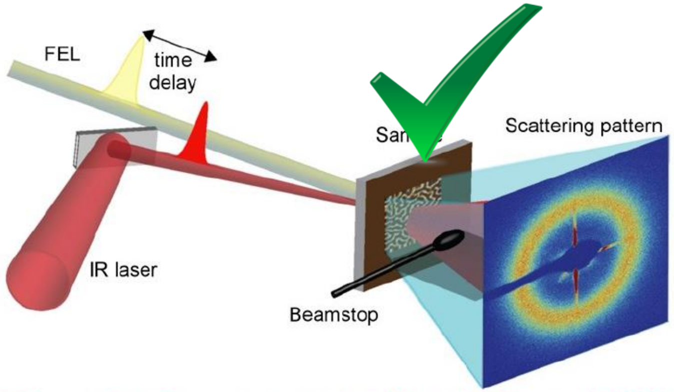
> Magnetic domains and domain walls







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

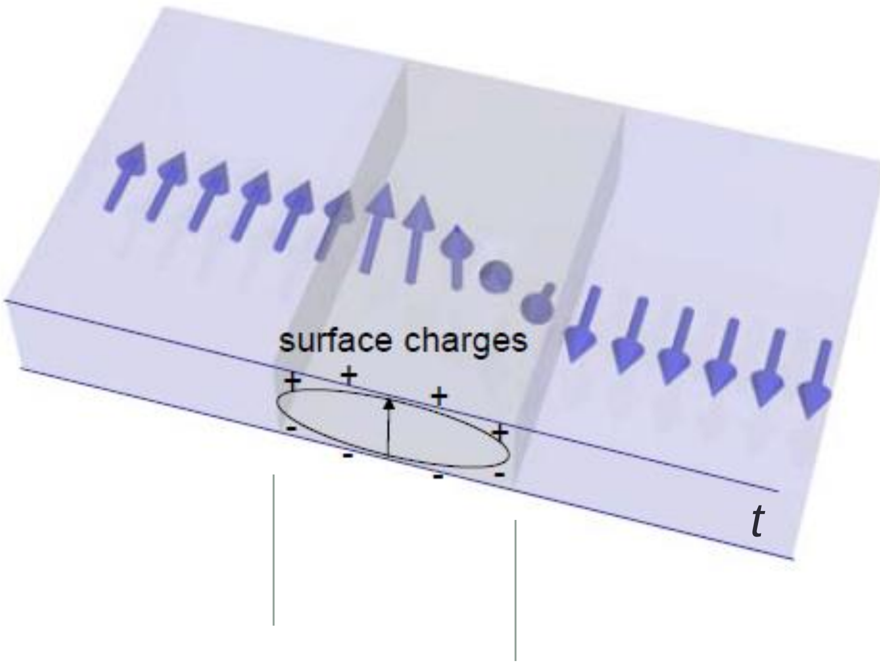


B. Pfau et al., Nature Communications, Vol. 3, 11; DOI:doi:10.1038/ncomms2108 (2012)
L.Müller et al., Rev. Sci. Instrum. 84, 013906 (2013)

Ferromagnetism in a nutshell – Domains and Walls

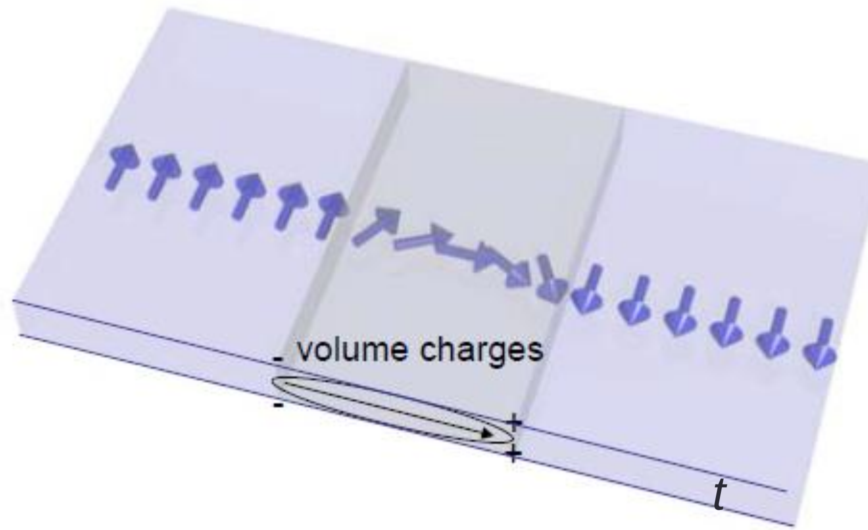
- Néel and Bloch domain walls for in-plane magnetized systems

Bloch wall



Domain wall width $d_w < t$

Néel wall

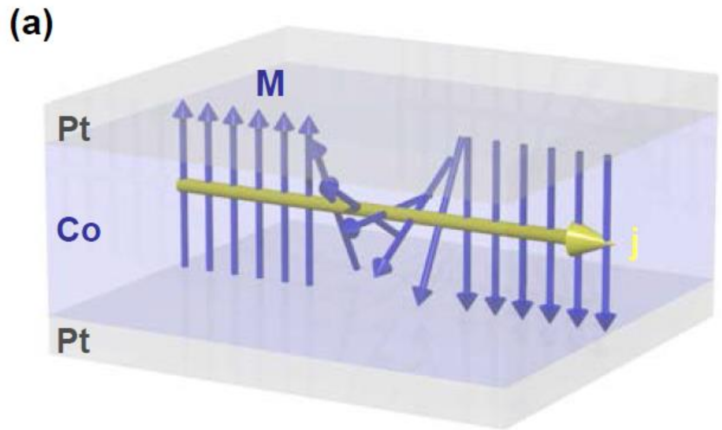


Domain wall width $d_w > t$

Ferromagnetism in a nutshell – Domains and Walls

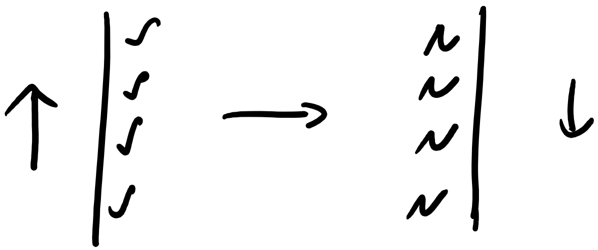
> Néel and Bloch domain walls for films with perpendicular anisotropy

Bloch wall



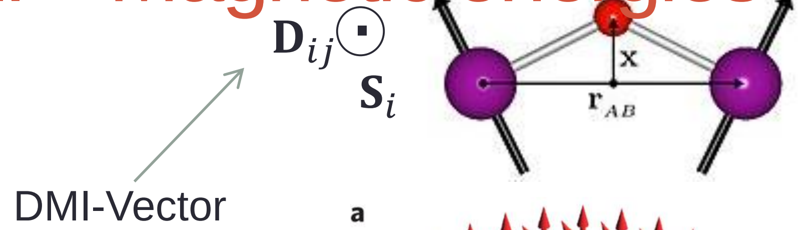
- No magnetic charges in wall!

Néel wall



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

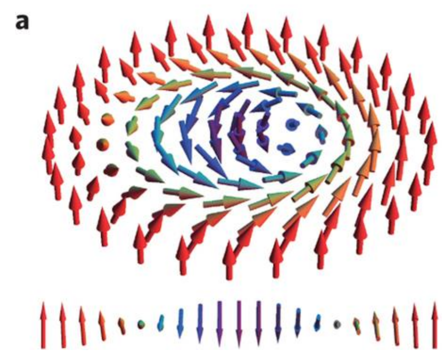
Ferromagnetism in a nutshell – Magnetic energies



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

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

➔ Minimization of total energy yields to formation of chiral structures = ‘skyrmions’



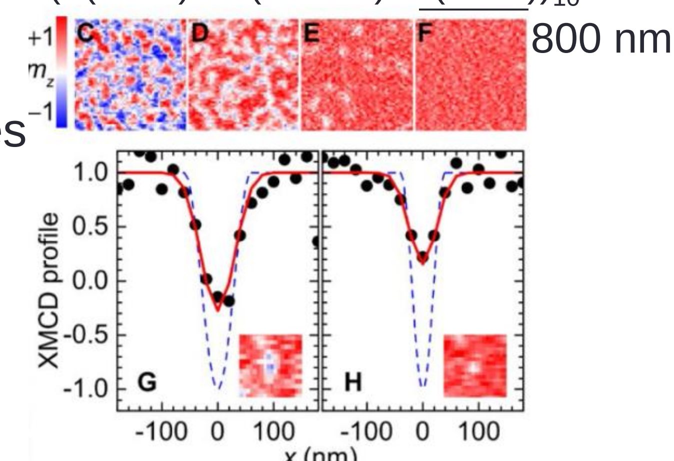
- **Asymmetric magnetic multilayers like Pt/Co/Ir**

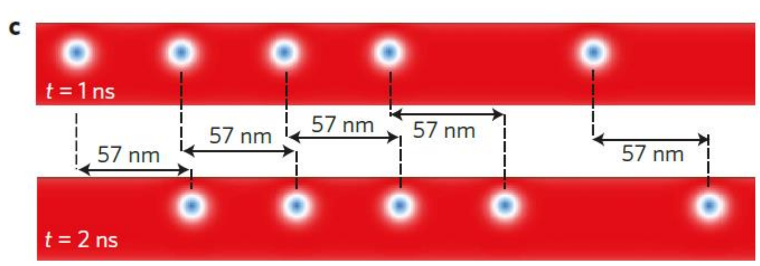
  Different sign of $\mathbf{D}_{ij}$ for Co/Pt and Co/Ir interface

  ➔ additive, large effective DMI

- Future Skyrmion-based memory & data storage devices

(Ir(1 nm)/Co(0.6 nm)/Pt(1 nm))$_{10}$





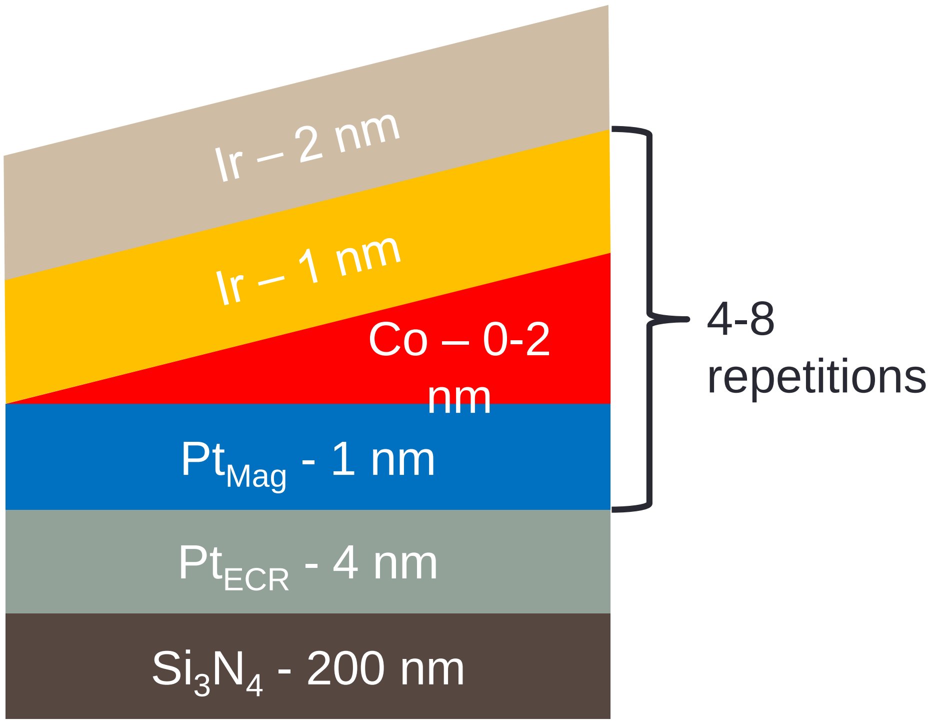
J. Sampaio, A. Fert et al., Nat. Nanotech. 8, 839 (2013)

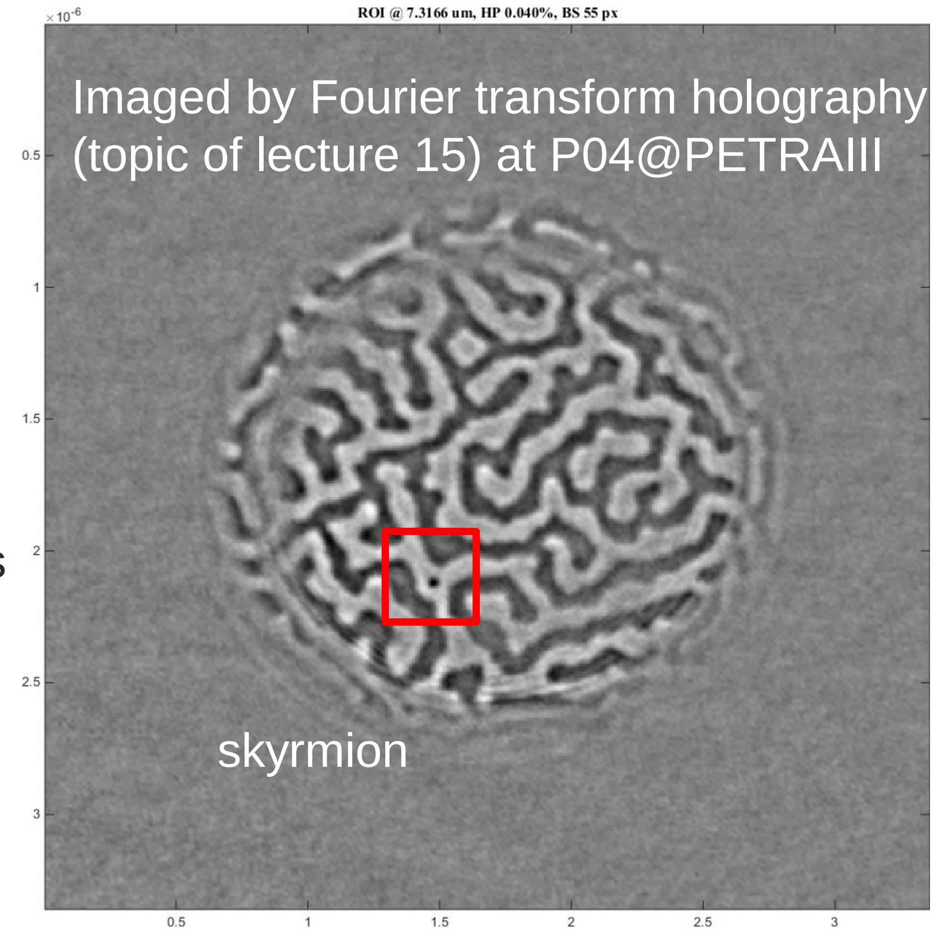
C. Moreau-Luchaire, A. Fert et al., arXiv:1502.07853v1 (2015)

Ferromagnetism in a nutshell – Domains and Walls

- What we are doing?

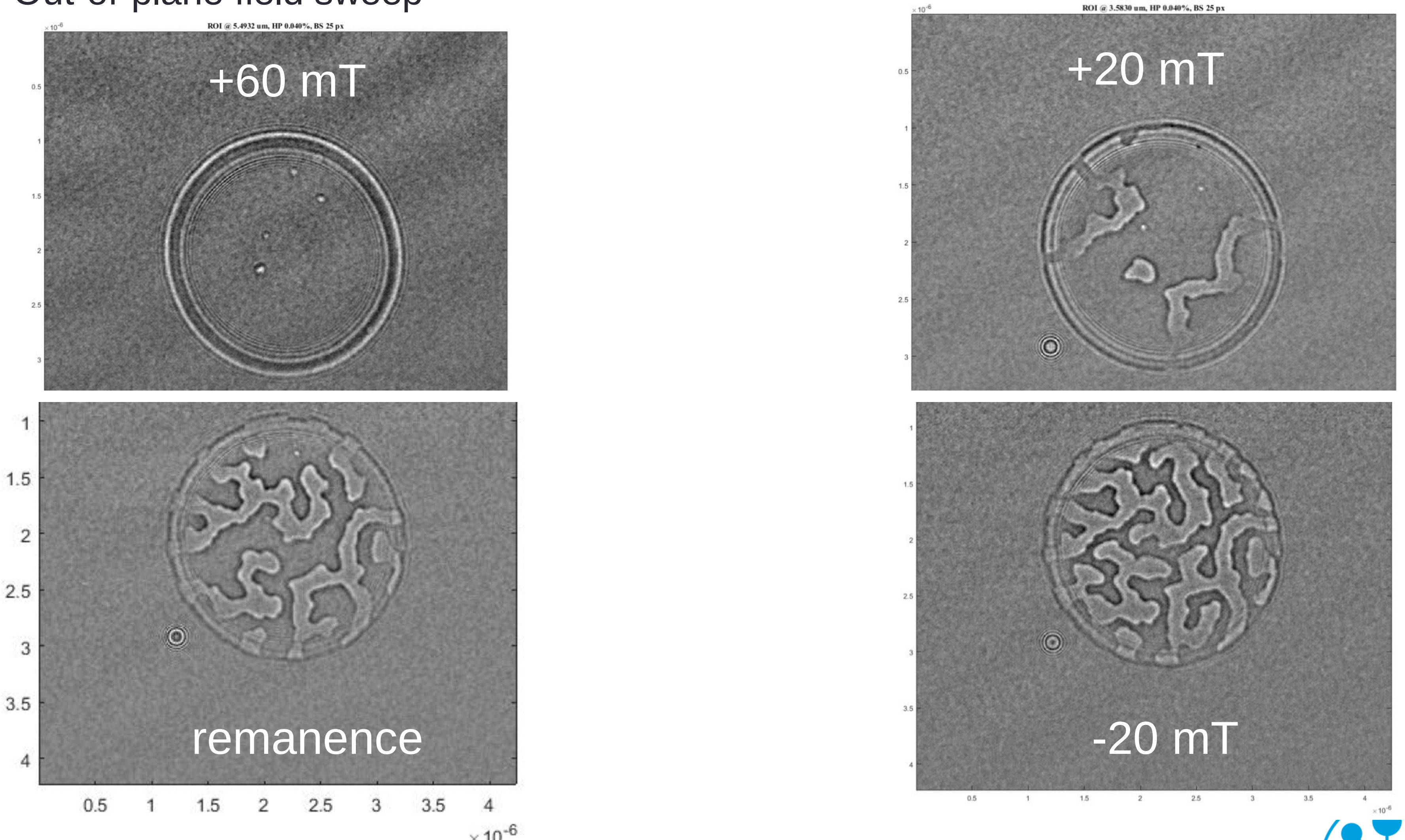
Pt/Co/Ir Multilayers





Ferromagnetism in a nutshell – Domains and Walls

- Out-of-plane field sweep



Ferromagnetism in a nutshell – Domains and Walls

- Current induced Skyrmion motion