Micro-428
Nanomagnetism

Marcos Penedo

Nanomagnetism

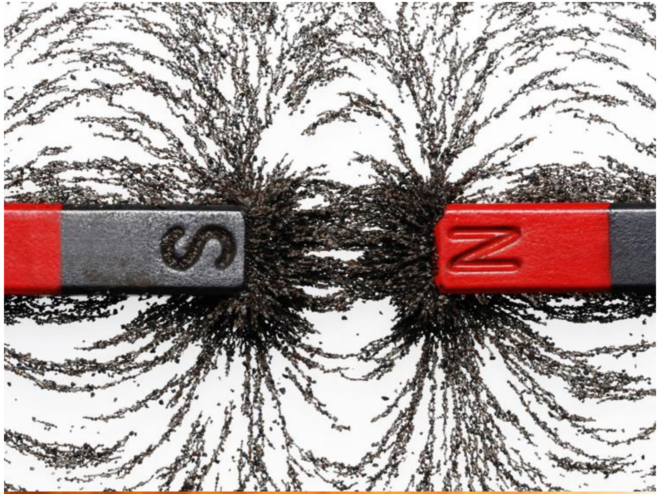
École
polytechnique
fédérale
de Lausanne

Magnetism

- Magnetism is the force exerted between objects when they attract or repel each other, through magnetic fields.

- All substances exhibit some type of magnetism.

- Magnetic field sources: ***electric currents*** and the ***magnetic moments*** of elementary particles.



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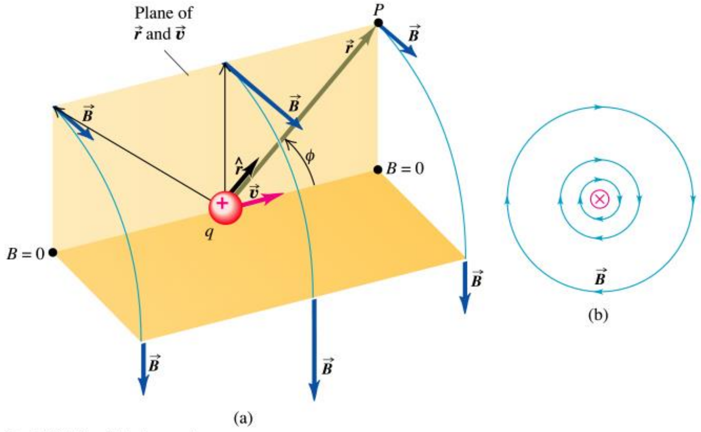
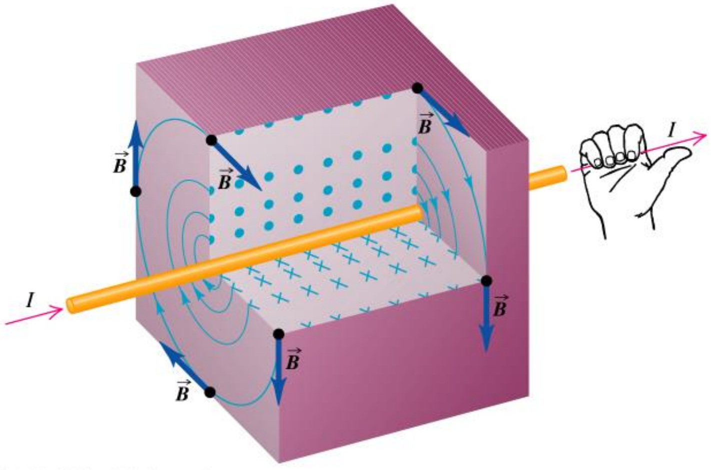
Magnetic sources: moving charges (currents) Biot–Savart law

Field created by a moving charge: $\vec{B} = r\frac{\mu_0}{4\pi}\frac{q\vec{v}\times\hat{r}}{r^2}$

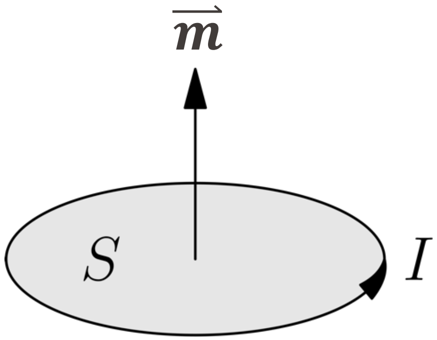


$\vec{B}$ field lines around long straight conductor (right hand)

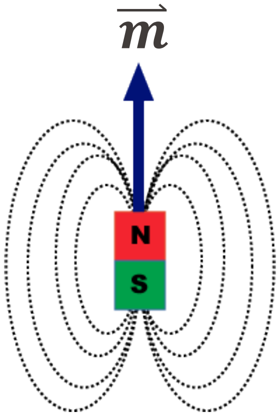


Magnetic sources: moving charges (currents)

- Magnetic moment is the magnetic strength and orientation of a magnet that produces a magnetic field: loops of electric current, permanent magnets, etc.
- It refers to a system's ***magnetic dipole moment***, the component of the magnetic moment that can be represented by an equivalent magnetic dipole: a magnetic north and south pole separated by a very small distance.



$$\vec{m} = I\vec{S}$$



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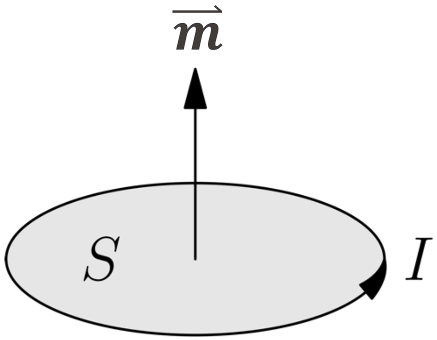
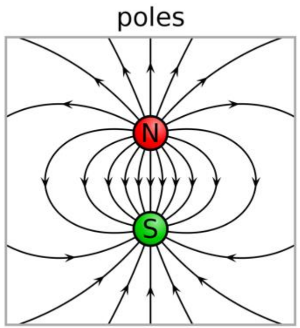


$$\vec{m} = I\vec{S}$$



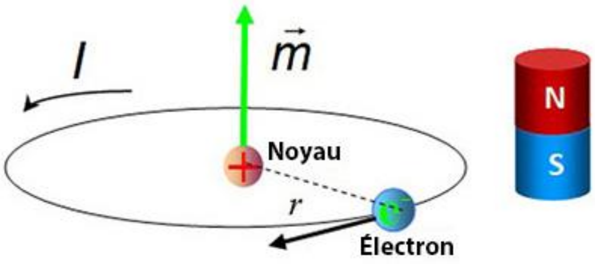
$$\vec{m} = q_m \vec{l}$$

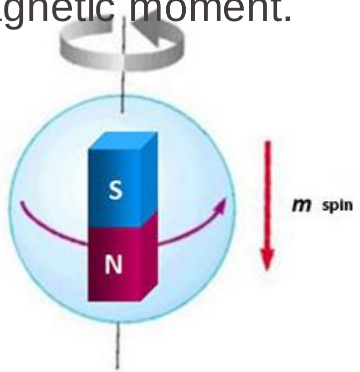
Magnetic sources: orbital and spin magnetic moments

- Electrons circular movement around the atom can be equated with the circular current, leading to an orbital magnetic dipole moment.

- Electrons possess their own angular momentum, the spin. It is the origin of the spin magnetic moment.

- If the atoms have an even number of electrons, it will be cancelled each other, otherwise the atom will have a net magnetic moment.



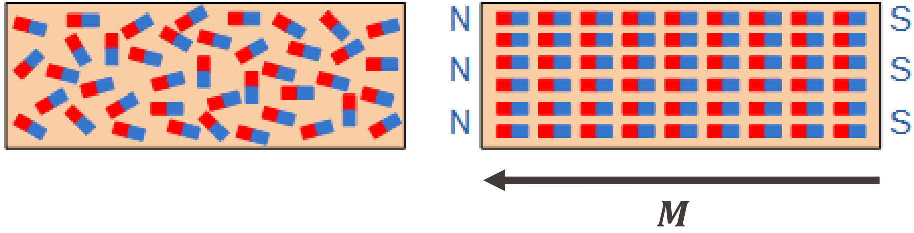


$$\vec{m} = I\vec{S}$$

Magnetic fields

- Magnetization $\boldsymbol{M}$ is the vector field that expresses the density of permanent or induced magnetic dipole moments in a magnetic material.

$$\boldsymbol{M} = \frac{d\boldsymbol{m}}{dV}$$



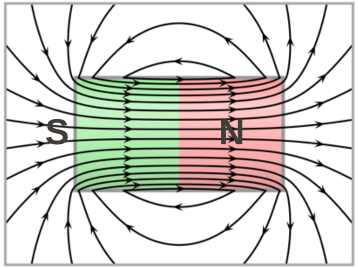
In the *magnetic pole model*, magnetization begins at and ends at magnetic poles, leading to a net positive "magnetic pole strength" in certain areas.

- Magnetic field is a vector field that describes the magnetic influence on moving electric charges, electric currents.

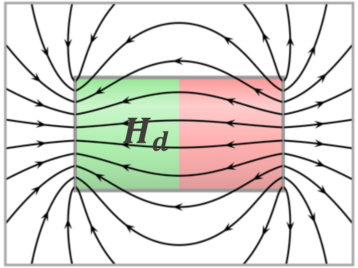
$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$$

H: magnetic field strength [A/m]
B: magnetic flux density [T]

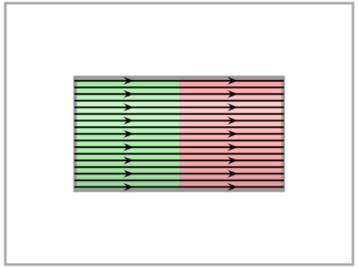
In a magnetized magnet, the magnetic field generated on the surface goes from the N pole to the S pole while in the magnet, the magnetic field called $\boldsymbol{H_d}$ is generated moving against magnetization. It strictly depends on the shape of the magnet, leading to different demagnetization factors.



$\vec{B}$



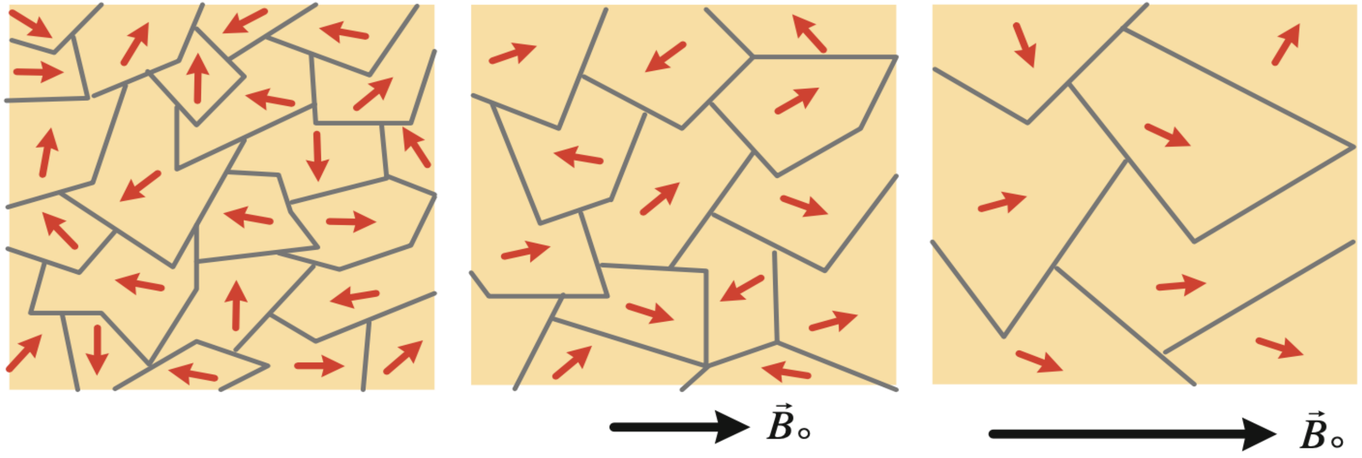
$\vec{H}$



$\vec{M}$

Magnetic domains

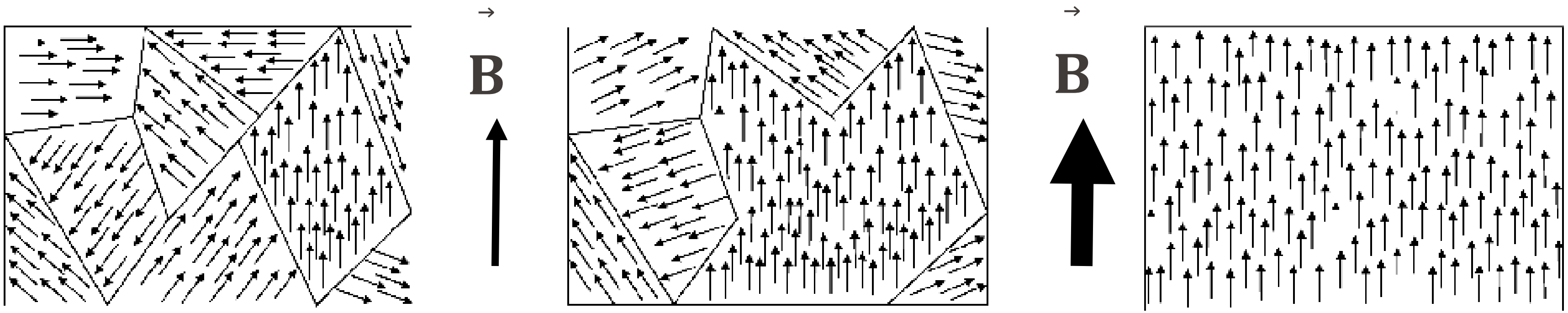
Magnetic materials are formed by microscopic magnetic domains



Hafez A. Radi et al. Principles of Physics, Springer

Magnetic domains

A **magnetic domain** is a region within a magnetic material in which the magnetization is in a uniform direction. This means that the **individual magnetic moments of the atoms (spins) are aligned with one another and they point in the same direction**

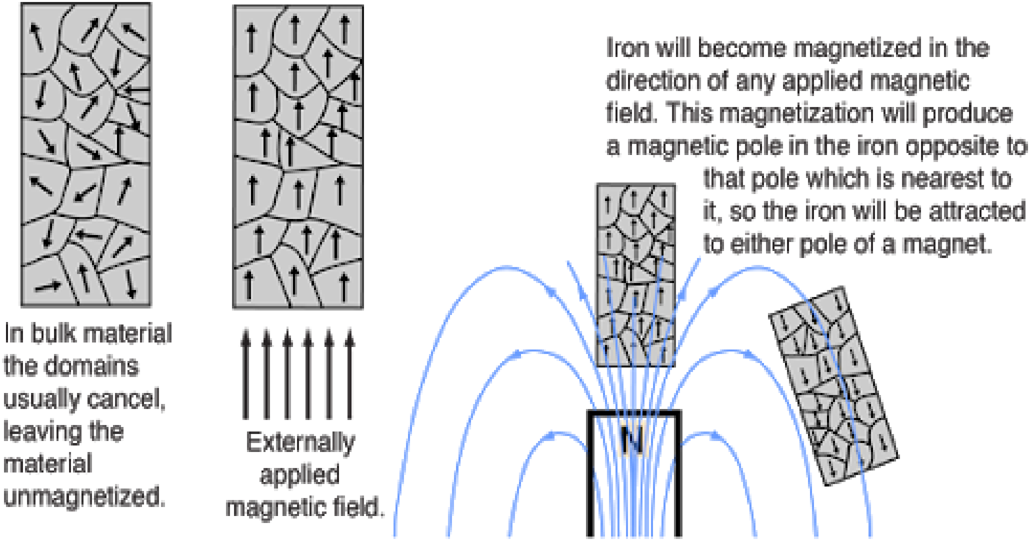


weak magnetic field is applied

strong magnetic field is applied

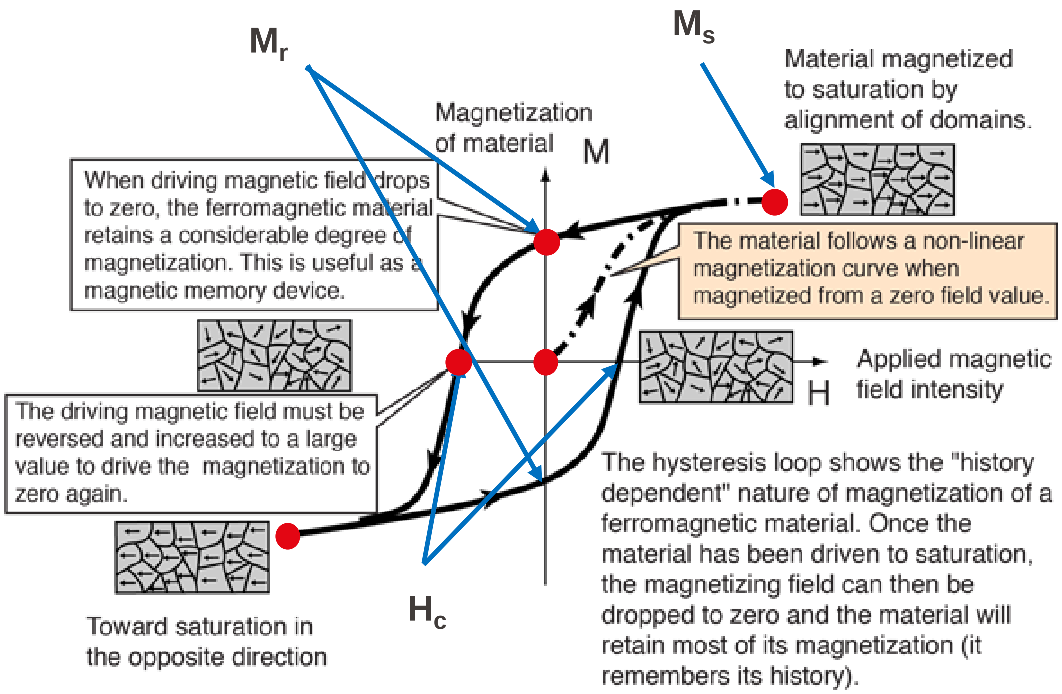
Magnetic hysteresis loops

Magnetic domains align when an external magnetic field is applied



http://hyperphysics.phy-astr.gsu.edu/

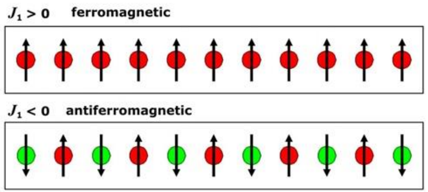
Magnetic hysteresis loops



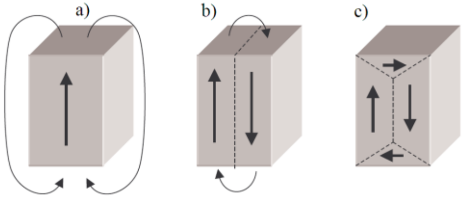
M_r magnetic remanence
M_s magnetic saturation
H_c coercivity field

Energy contributions

- Magnetic exchange energy: $E_H = -\frac{1}{2}\sum_{ij} J_{ij}\mathbf{S}_i \cdot \mathbf{S}_j$ favors $\mathbf{S}_i \| \mathbf{S}_j$



- Magnetic anisotropy energy: $E_a = -\sum_i K_u(\hat{\mathbf{z}} \cdot \mathbf{S}_i)^2$ favors $\mathbf{S}_i \| \hat{\mathbf{z}}$

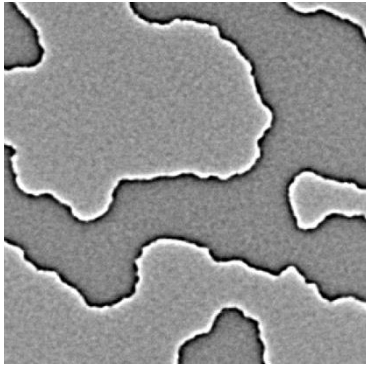


- Magnetostatic energy: $E_M = \frac{1}{2}\mu_0 \mathbf{M}_s^2$

- Zeeman energy: interaction between **M** and **H**

$$\mathcal{H} = \int d^3r \left[-\mathbf{B}\cdot\mathbf{m} + \frac{1}{2} J \left(\nabla \mathbf{m}\right)^2 - K_u \left(\hat{\mathbf{z}}\cdot\mathbf{m}\right)^2 \right]$$

Stable solutions are magnetic domains: finite areas of uniform magnetization



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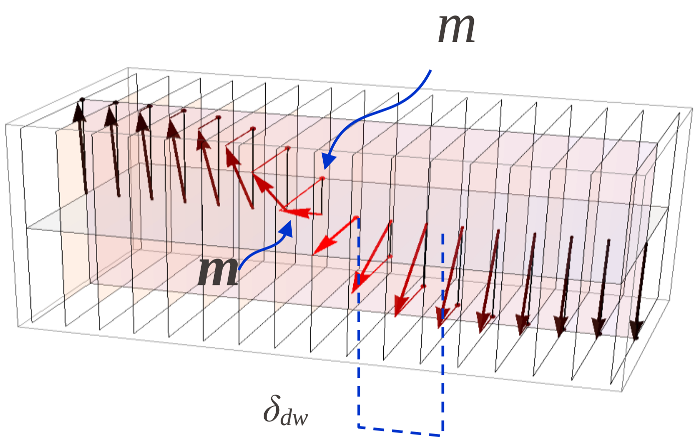
Domain walls

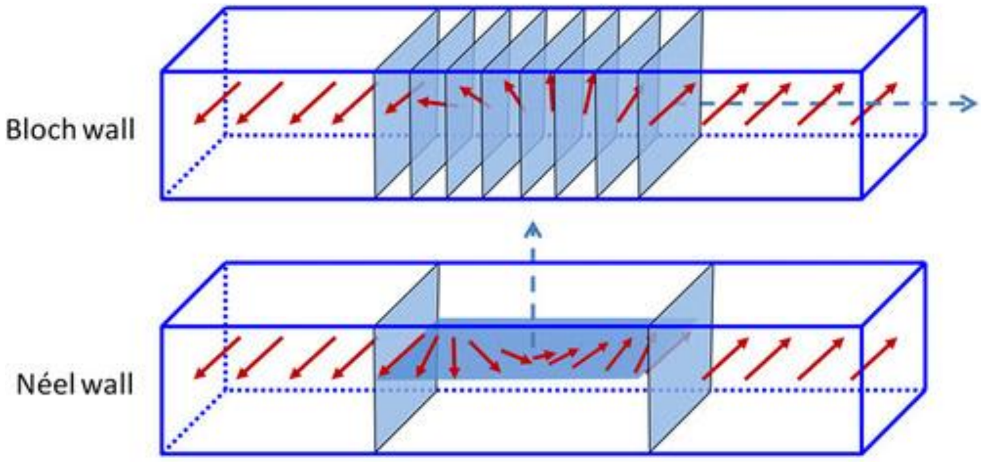
- A domain wall is an interface separating magnetic domains. It helps to minimize the total energy.



$$\delta_{dw} = \pi\sqrt{\frac{A}{K_{eff}}}$$

- In a ***Bloch wall***, the magnetization rotates about the normal of the domain wall.

- In a ***Néel wall***, the magnetization smoothly rotates from the direction of magnetization within the first domain to the direction of magnetization within the second.



Magnetic orderings

- Magnetization is the vector field that expresses the density of permanent or induced magnetic dipole moments in a magnetic material

- Depending on the ordering of spins, we have different types of magnetic orderings

Ferromagnetic ↑ ↑ ↑ ↑ ↑ ↑ ↑	Below T_C, spins are aligned parallel in magnetic domains
Antiferromagnetic ↑ ↓ ↑ ↓ ↑ ↓ ↑	Below T_N, spins are aligned antiparallel in magnetic domains
Ferrimagnetic ↑ ↓ ↑ ↓ ↑ ↓ ↑	Below T_C, spins are aligned antiparallel but do not cancel
Paramagnetic ↑ ↓ ↑ ↑ ↓ ↑ ↓	Spins are randomly oriented (any of the others above T_C or T_N)

Types of magnetism: diamagnetism

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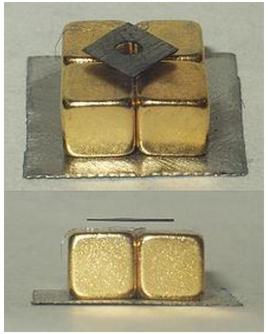
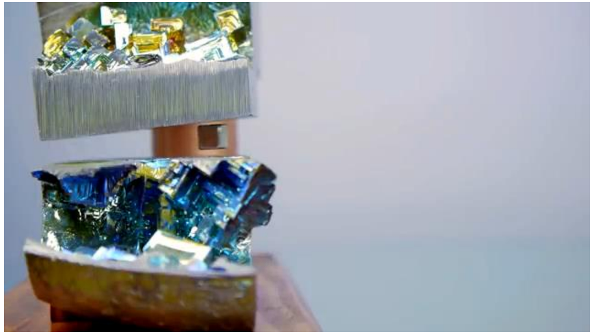
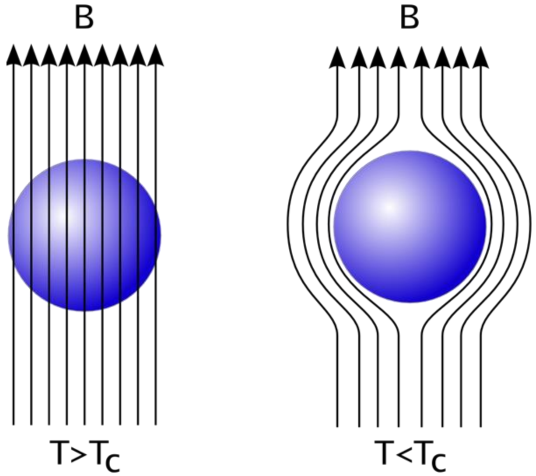
- Diamagnetic materials are repelled by a magnetic field; an applied magnetic field creates an induced magnetic field in them in the opposite direction, causing a repulsive force.
- It is a weak property of all materials.
- Superconductors are perfect diamagnets and when placed in an external magnetic field expel the field lines from their interiors.

Diamagnetic levitation of pyrolytic carbon and a bismuth crystal





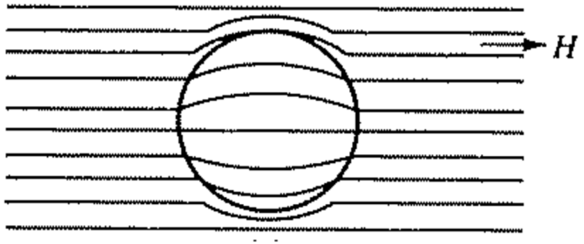


Types of magnetism: paramagnetism

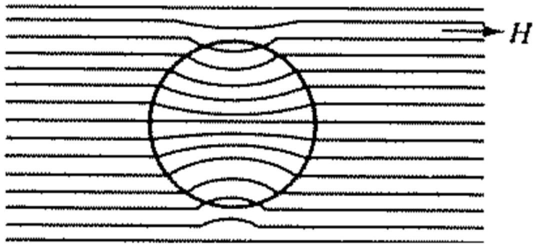
- Alignment of the atomic magnetic dipoles in a material that is otherwise non-magnetic to align with an external magnetic field, resulting in a relative magnetic permeability greater than one and in a net magnetization of the material.
- If there is an unpaired electron on an atom, it is free to align its magnetic moment to an applied external field.

$$M = \chi H$$

χ is the volume magnetic susceptibility



Diamagnetic materials: reduce the density of the lines of force (flux density).

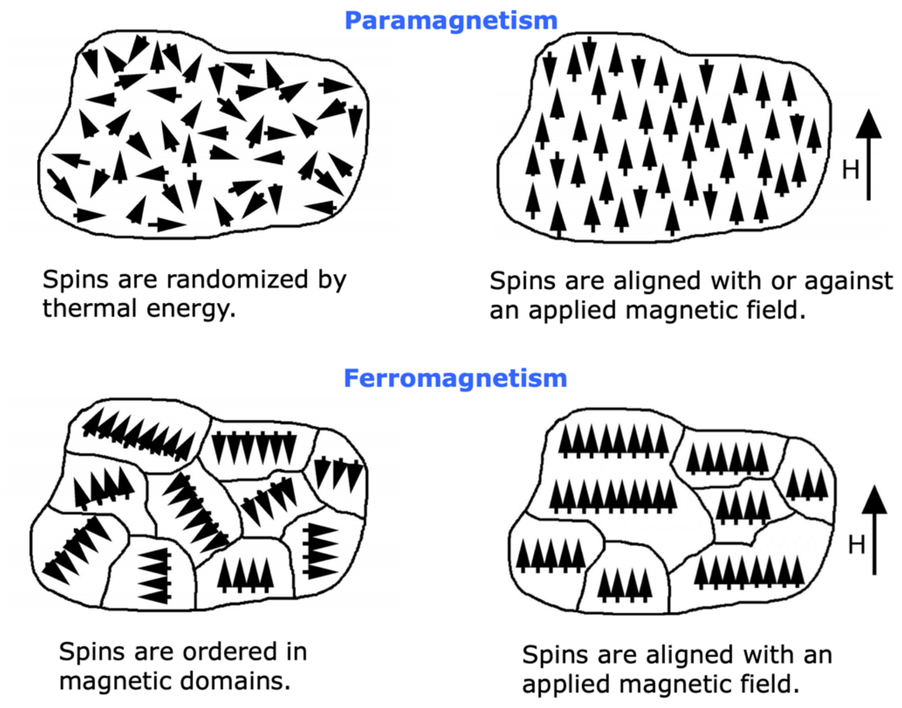


Paramagnetic materials: increase the density of the lines of force (flux density).

https://www.magcraft.com/magnetism

Types of magnetism: ferromagnetism

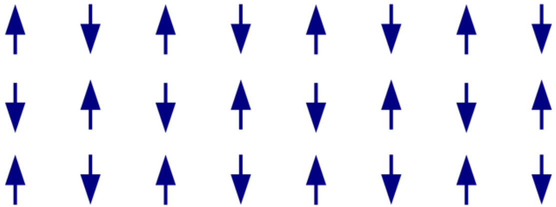
- Ferromagnetism is one of the strongest forms of magnetism, responsible for most common permanent magnets in everyday life (iron, cobalt, nickel, and gadolinium).
- It has unpaired electron on an atom like in paramagnetism, leading to a net magnetic moment. In a ferromagnet coupling interactions cause the magnetic moments of adjacent atoms to align with one another (e.g. magnetic exchange).

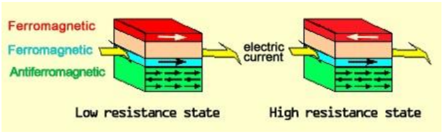


Types of magnetism: antiferromagnetism and ferrimagnetism

Antiferromagnetism

- Magnetic moments of neighbouring electrons point in opposite directions.
- Zero net magnetic moment.

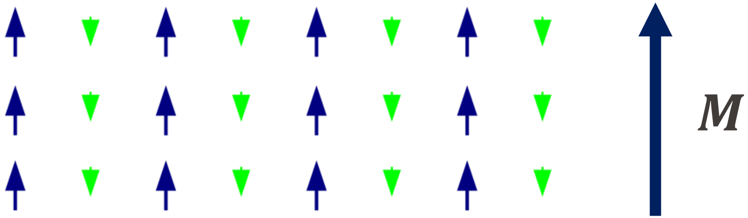




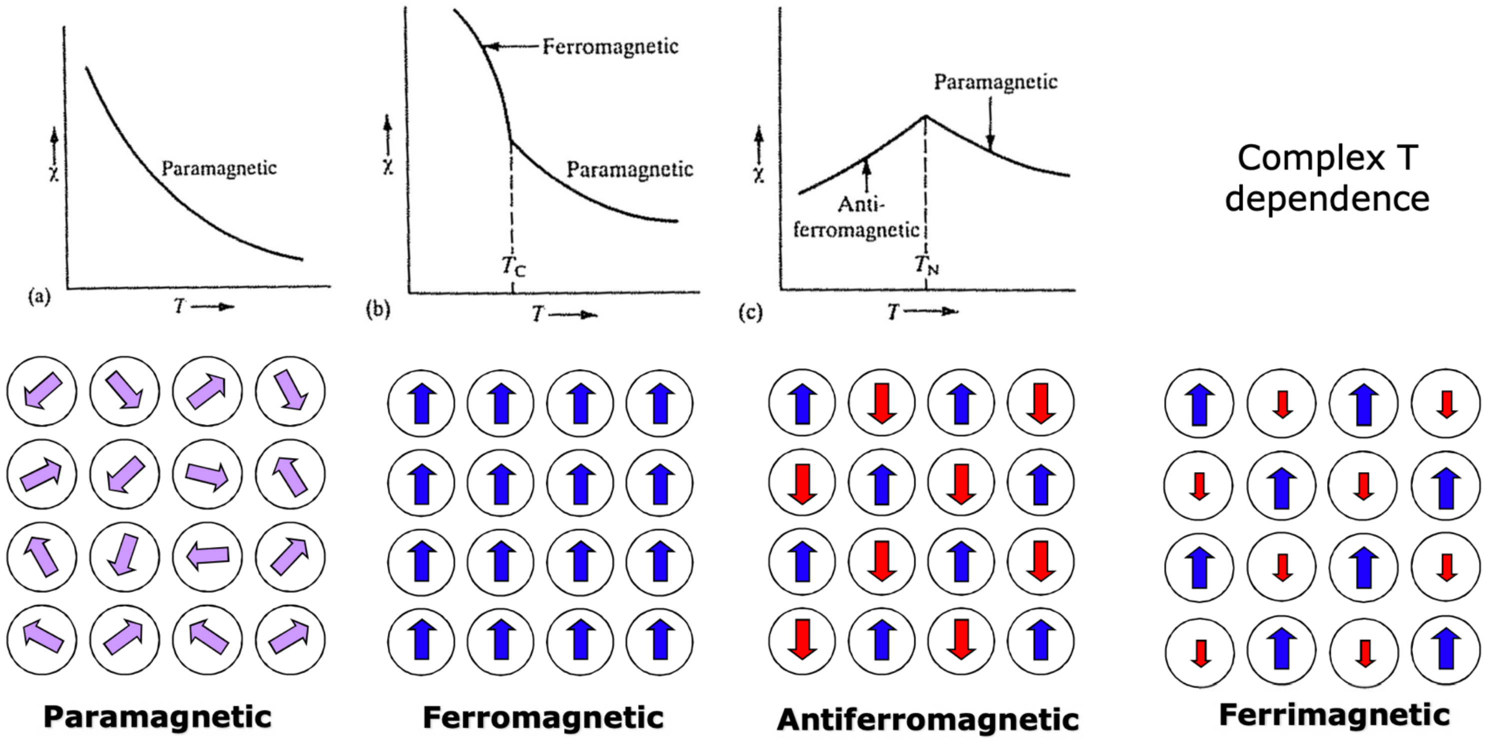
Spin valve

Ferrimagnetism

- Magnetic moments of neighbouring electrons point in opposite directions, but unbalanced.
- Possess net magnetic moment when no magnetic field is applied.



Types of magnetism: T dependence



https://www.unf.edu/~michael.lufaso/chem4627/ch8_solid_state.pdf

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Types of magnetism

Characteristic Magnetic Properties

Type	Sign of χ	Typical χ	Dependence of χ on H (field dependence)	Change of χ w/inc. temp.	Origin
Diamagnetism	-	$-(1\text{-}600)\times10^{-5}$	Independent	None	Electron charge
Paramagnetism	+	0.001-0.1	Independent	Dec.	Spin and orbital motion of electrons on atoms.
Ferromagnetism	+	$0.1\text{-}5\times10^{3}$	Dependent	Dec.	Cooperative interaction between magnetic moments of individual atoms.
Antiferromagnetism	+	0-0.1	May be dependent	Inc.	

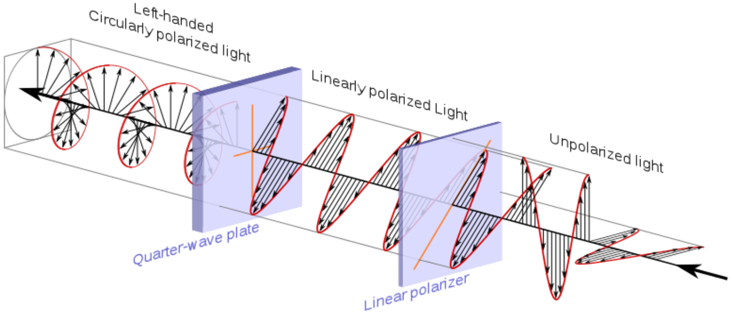
https://www.unf.edu/~michael.lufaso/chem4627/ch8_solid_state.pdf

Techniques to investigate magnetic structures at the nanoscale

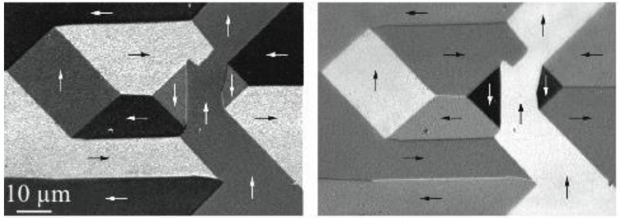
- Magneto-optical Kerr effect (MOKE).
- Lorentz transmission electron microscopy (LTEM).
- Nitrogen-vacancy (NV) centre microscope
- Spin polarized scanning tunneling microscopy (SP-STM).
- Magnetic force microscopy (MFM).

Magneto-optical Kerr effect (MOKE)

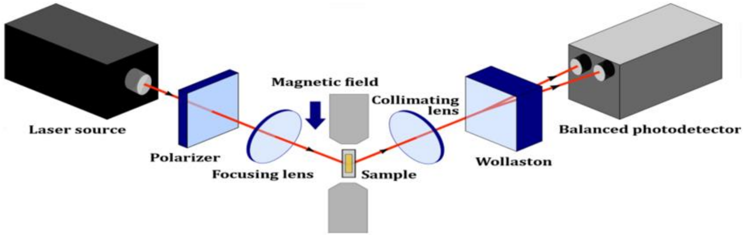
- It is based on the effect first observed by John Kerr in 1876, where the change of the polarization of light upon reflection on the surface of a magnetic material depending on the material's magnetization intensity and direction.



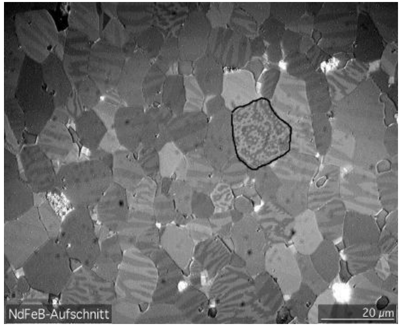
Domain pattern on iron-silicon [100] sheet



Nanomaterials **2020**, *10*(2), 256



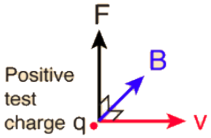
Grains of NdFeB



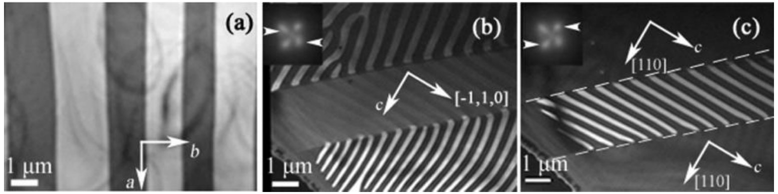
The spatial resolution of MOKE microscopy using a microscope objective lens is determined by the optical diffraction limit.

Lorentz transmission electron microscopy (LTEM)

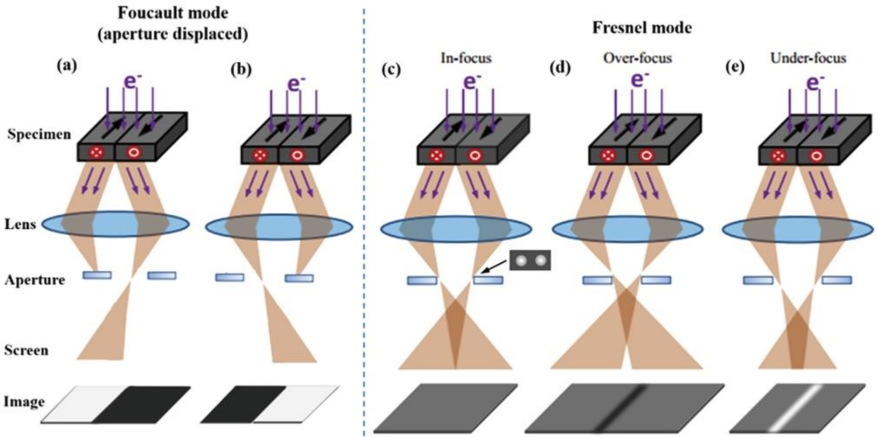
$$\vec{F} = q\vec{v} \times \vec{B}$$



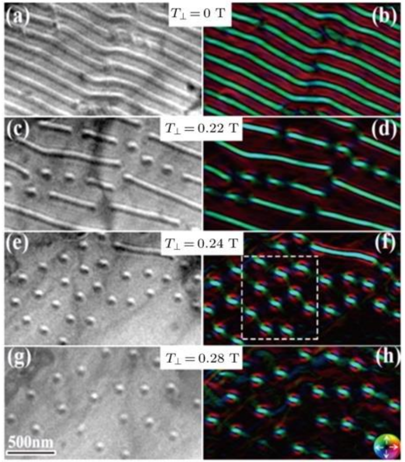
Lorentz TEM images of (001) and {110} $La_{0.69}Ca_{0.31}Mn_{O3}La_{0.69}Ca_{0.31}MnO_3$



Appl. Phys. Lett. **95**, 092504 (2009)



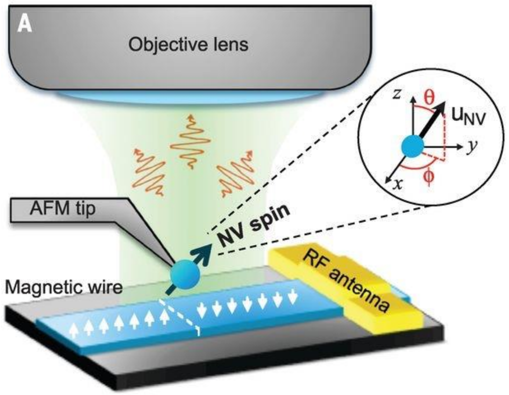
Magnetic field dependence of biskyrmions



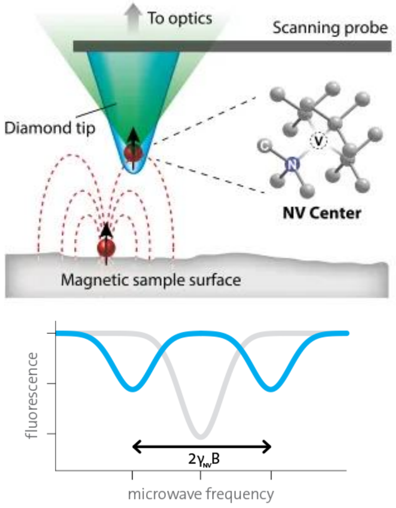
Nano Lett. **17** 7075 (2017)

Nitrogen-vacancy (NV) center microscopy

- The NV center is a lattice defect in diamond whose magnetic orientation can be measured by optical fluorescence.
- A single NV defect hosted in a diamond nanocrystal, which is attached to the tip of an atomic force microscope and used as a magnetic field sensor.

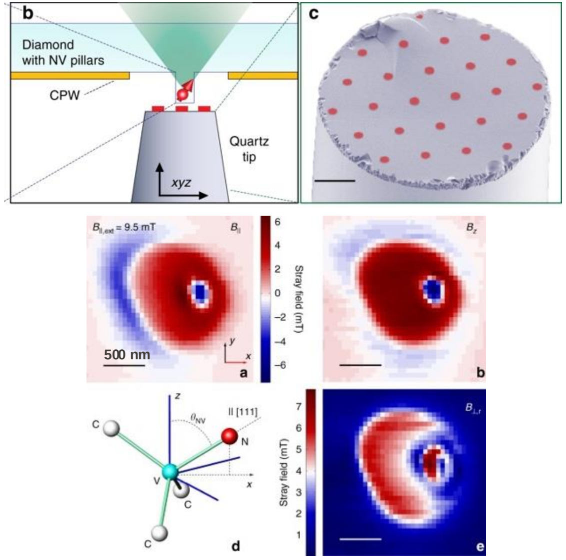


Science **344**, 1366–1369 (2014)



Annu. Rev. Phys. Chem. 2014. 65:83–105

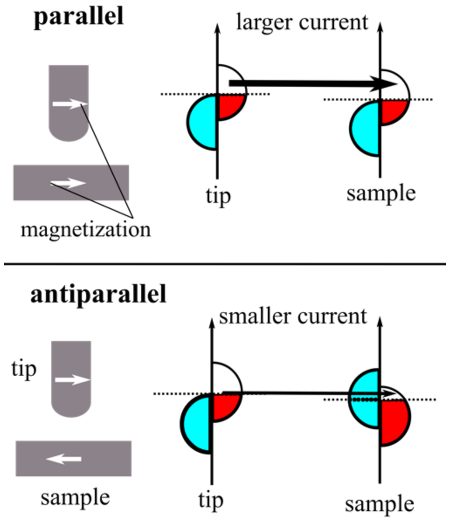
[Pt (3 nm)/Co (1.1 nm)/Ta (4 nm)] × 10 stack



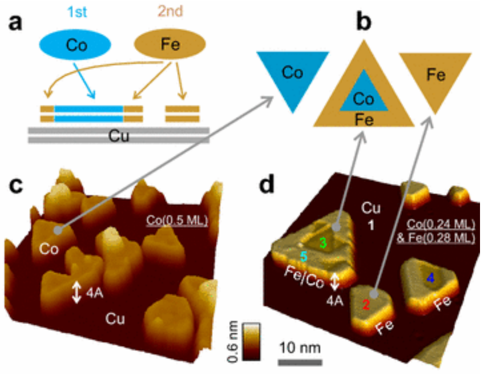
Nat. Comm. 9, 2712 (2018)

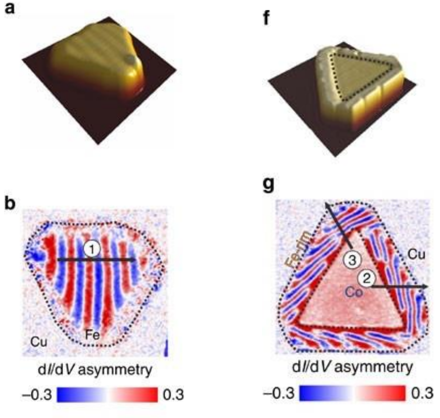
Spin polarized scanning tunneling microscopy (SP-STM)

When the STM tip and sample are magnetized, electrons with spins matching the tip's (sample's) magnetization will have higher probability of tunnelling.



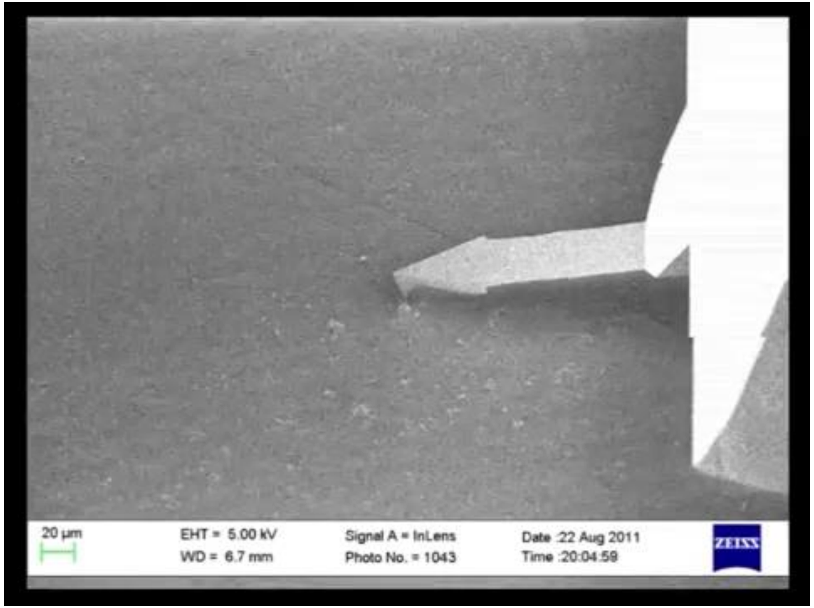
Biatomic-layer-high Co and Fe nanoislands on Cu(111



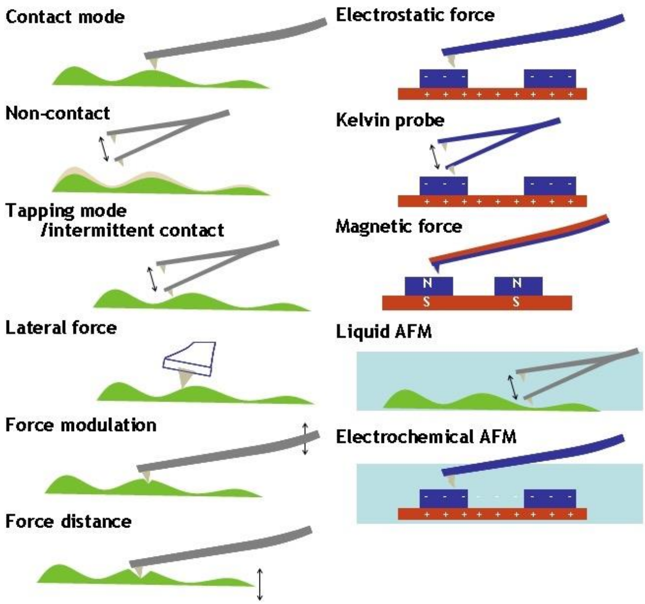


Nano Convergence **4**, 8 (2017)

Atomic force microscopy (AFM)



From www.zeiss.com

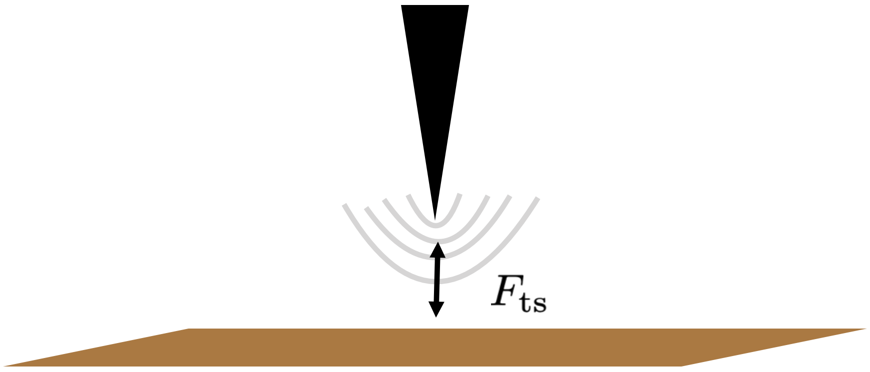


Surface properties are sensed by "feeling" or "touching" the surface with a mechanical probe, consisting in a micro cantilever with a sharp tip which scans the surface feeling the different tip-sample forces involved.

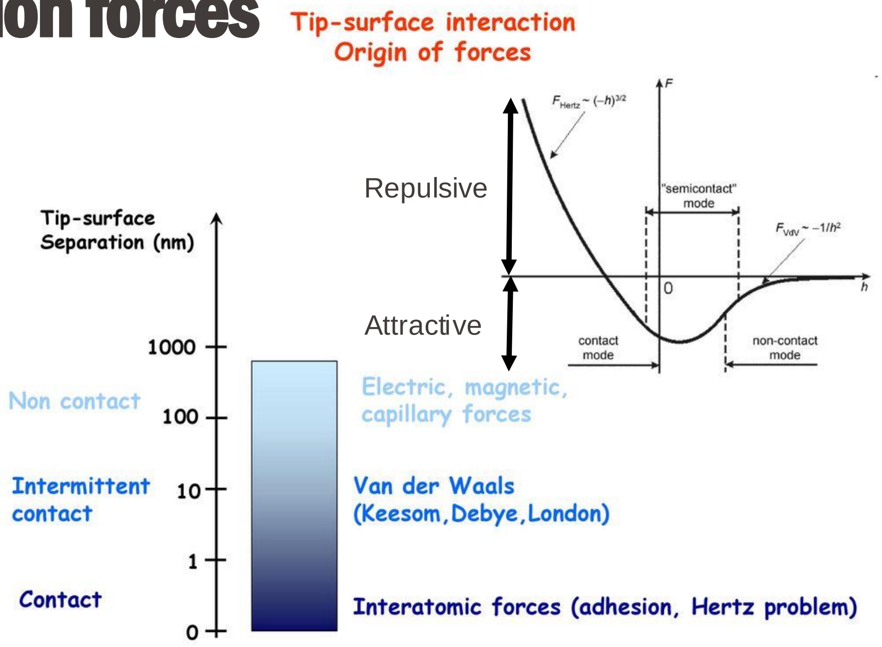
GOAL →

Separate and differentiate the different origins of the tip-sample interactions.

AFM: tip/sample interaction forces



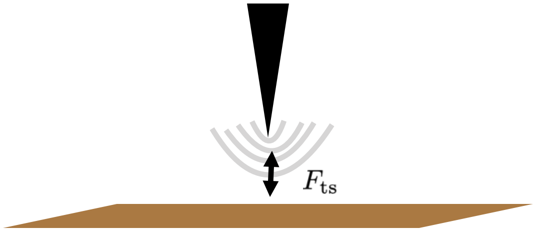
$$F_{ts} = F_{atom} + F_{vdW} + F_{capill} + F_{elec} + F_{mag}$$



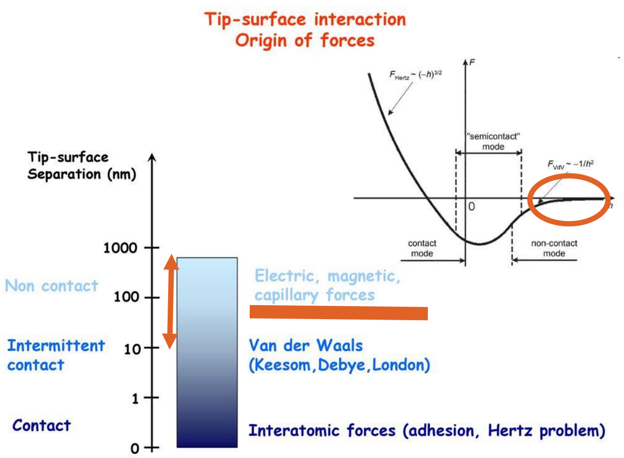
https://slideplayer.com/slide/12509410/

- The cantilever tip 'feels' all the forces together.
- Consequently, 'artifacts' are produced in the different AFM image types: topography, electric, magnetic maps, etc.
- The main goal is to disentangle and separate all the forces, so we can generate a separate map for every force involved.

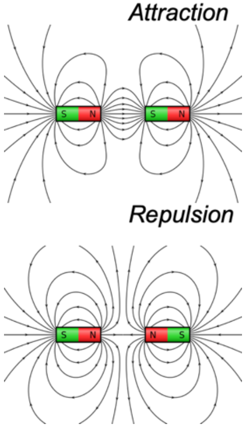
Magnetic forces



$$F_{ts} = F_{atom} + F_{vdW} + F_{capill} + F_{elec} + F_{mag}$$

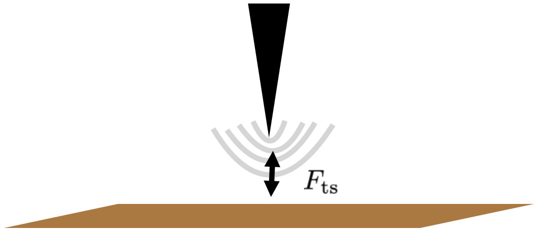


F_{mag} are due to microscopic currents of electrically charged electrons orbiting nuclei and the intrinsic magnetism of fundamental particles (such as electrons) that make up the material.

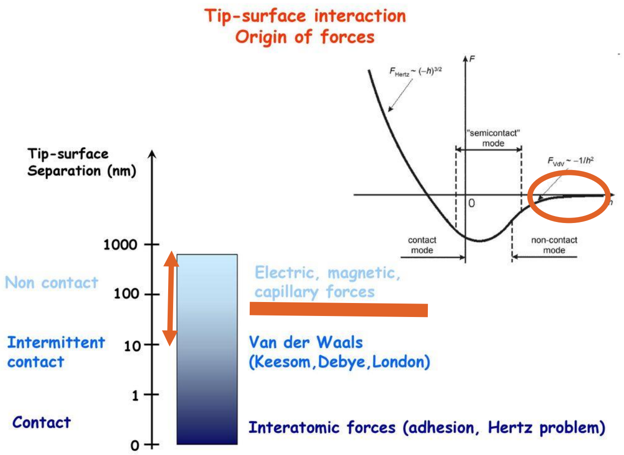


EPFL

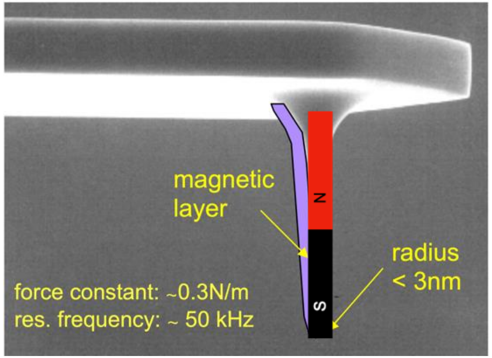
Magnetic forces



$$F_{ts} = F_{atom} + F_{vdW} + F_{capill} + F_{elec} + \boxed{F_{mag}}$$



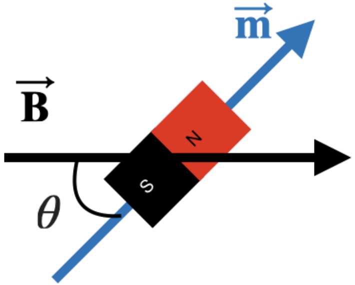
F_{mag} are due to microscopic currents of electrically charged electrons orbiting nuclei and the intrinsic magnetism of fundamental particles (such as electrons) that make up the material.



magnetic coated cantilever tip will act as a magnet
sample will create the magnetic stray field

Magnetic forces

Marcos Penedo

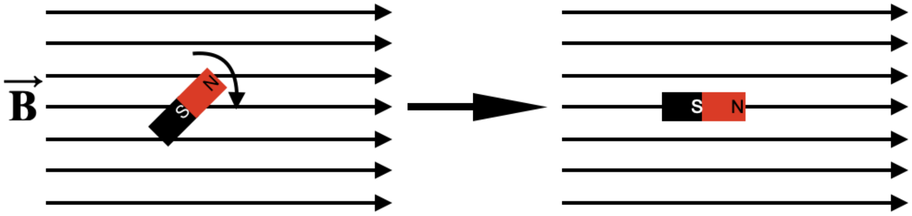


$$U_{mag} = -\vec{\mathbf{m}} \cdot \vec{\mathbf{B}} = -mB\cos\theta$$

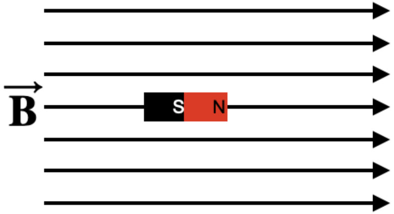
$$F_{mag} = \nabla(\vec{\mathbf{m}} \cdot \vec{\mathbf{B}})$$

U_{mag}: magnetic energy
$\vec{\mathbf{m}}$: magnetic dipole moment
$\vec{\mathbf{B}}$: magnetic stray field
θ: angle between $\vec{\mathbf{B}}$ and $\vec{\mathbf{m}}$

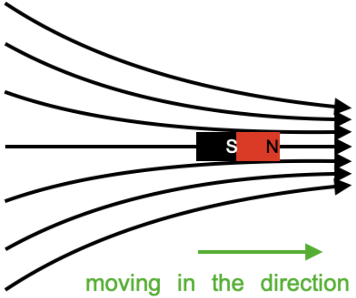
$\vec{\mathbf{m}}$ *aligns with* $\vec{\mathbf{B}}$



$\vec{\mathbf{m}}$ *only moves with non uniform* $\vec{\mathbf{B}}$



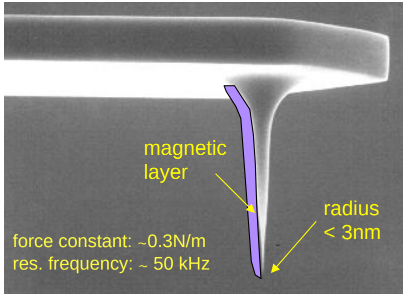
do not move, static



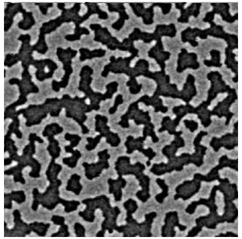
moving in the direction of the maximum gradient of $\vec{\mathbf{B}}$

Magnetic force microscopy (MFM)

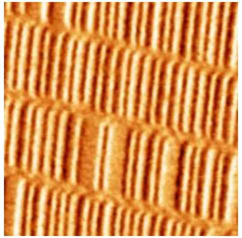
In magnetic force microscopy (MFM) a sharp tip coated with a magnetic layer scans a magnetic sample, where the tip-sample magnetic interactions are detected and used to reconstruct the magnetic structure of the sample surface, reaching nanometer resolution



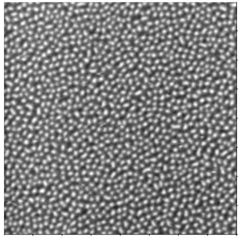
magnetic domains in Pt/Co thin films

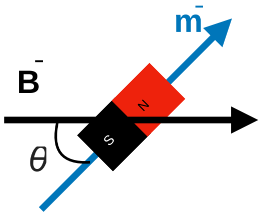


bits in a magnetic hard drive



Skyrmions lattice





$$U_{mag} = -\vec{m} \cdot \vec{B} = mB\cos\theta$$

$$F_{mag} = \nabla(\vec{m} \cdot \vec{B})$$

U_{mag}: magnetic energy
$\vec{m}$: magnetic dipole moment
$\vec{B}$: magnetic stray field
θ: angle between $\vec{B}$ and $\vec{m}$

$$U = -\mu_o \int_V \vec{\mathbf{M}}_{tip} \cdot \vec{\mathbf{H}}\, dV \qquad F = \mu_o \int_V \vec{\nabla}(\vec{\mathbf{M}}_{tip} \cdot \vec{\mathbf{H}})\, dV$$

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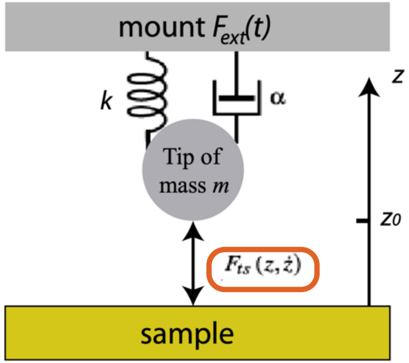
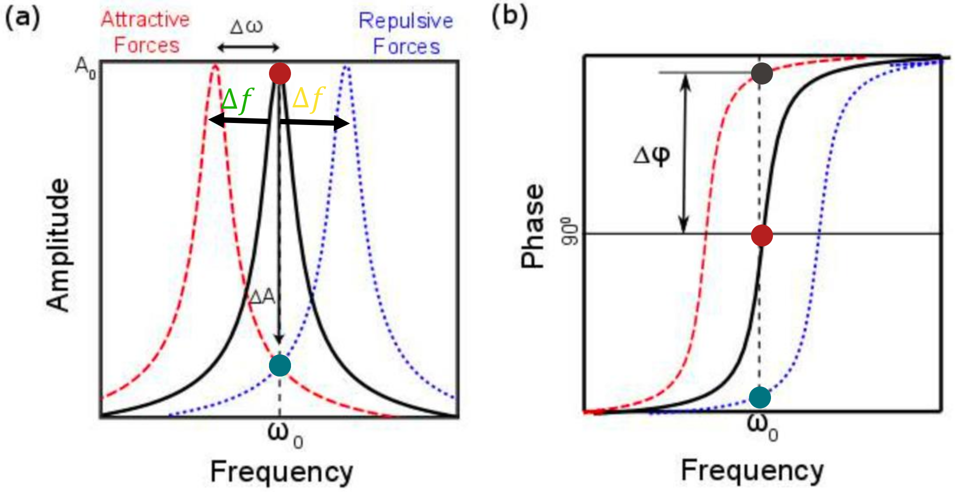
Tip/sample magnetic forces



$$m_{eff}\ddot{z}_0(t) + \alpha\dot{z}_0(t) + k_c z_0(t) = F_{ext}cos(\omega t) + F_{ts}(z,\dot{z})$$

$$\Delta\omega = -\frac{\omega_0}{k_c}\frac{\partial F_{mag}(z,\dot{z})}{\partial z} \qquad \Delta\Phi \approx -\frac{\partial F_{mag}(z,\dot{z})}{\partial z}$$

- No magnetic interactions (red dot)
- Attractive magnetic interactions (sample,tip): (+,-) and (-,+) (dark grey dot)
- Repulsive magnetic interactions (sample,tip): (+,+) and (-,-) (teal dot)



The phase (AM-MFM) or Δf (FM-MFM) will help to distinguish attractive and repulsive forces (magnetic orientations), origin of contrast in MFM.

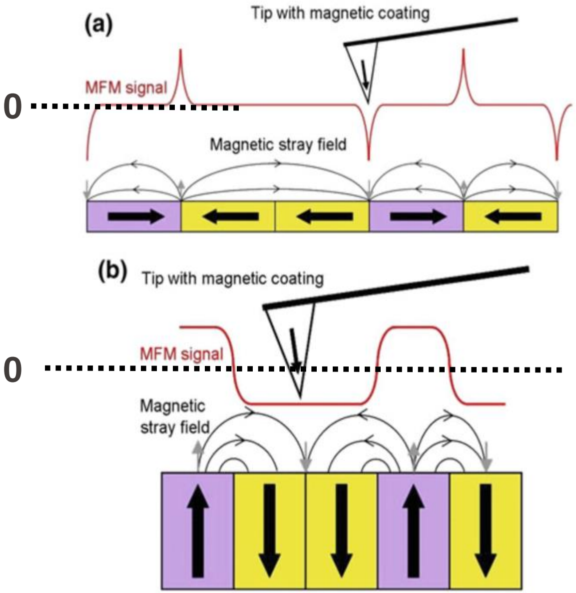
Influence of the tip magnetization on the magnetic signal

$$F = \mu_o \int_V \vec{\nabla}(\vec{\mathbf{M}}_{tip} \odot \vec{\mathbf{H}})dV$$

scalar product

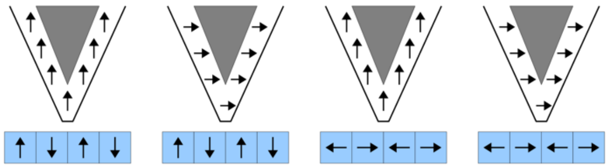
- Force maximizes when $\vec{\mathbf{M}}_{tip}$ and $\vec{\mathbf{H}}$ are parallel
- Force nullifies when $\vec{\mathbf{M}}_{tip}$ and $\vec{\mathbf{H}}$ are perpendicular

In-plane and out-plane sample magnetization and vertical tip magnetization

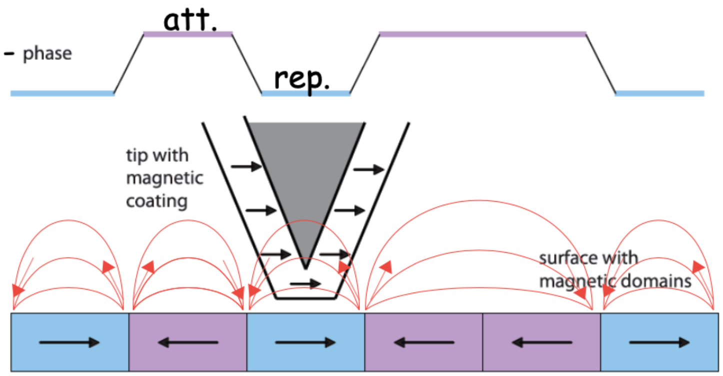


A. Hirohata et al. Magnetic Force Microscopy for Magnetic Recording and Devices

Relative orientations of the tip and sample magnetizations

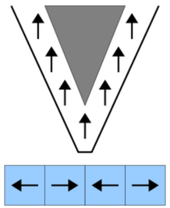


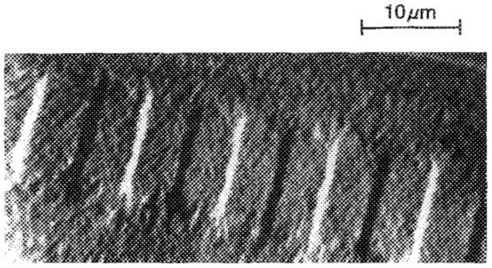
In-plane sample magnetization and horizontal tip magnetization



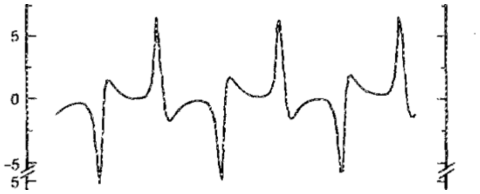
Influence of the tip magnetization on the magnetic signal

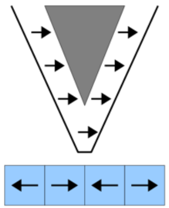
$$F = \mu_o \int_V \vec{\nabla}(\vec{M} \cdot \vec{H})dV$$

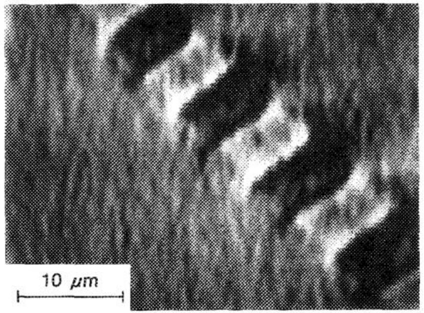




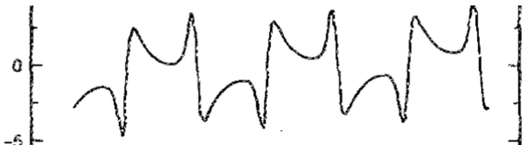
Wall domain contrast







Domain contrast

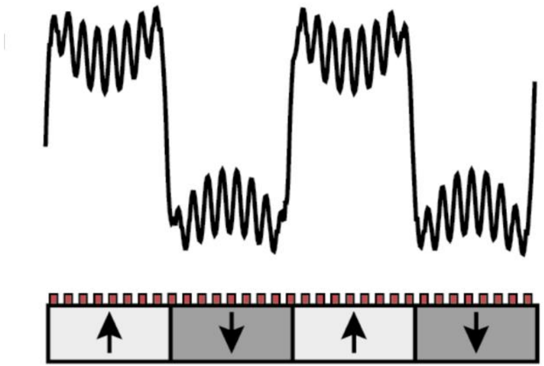


D. Rugar et al. *J. Appl. Phys.* **68**, 1169 (1990)

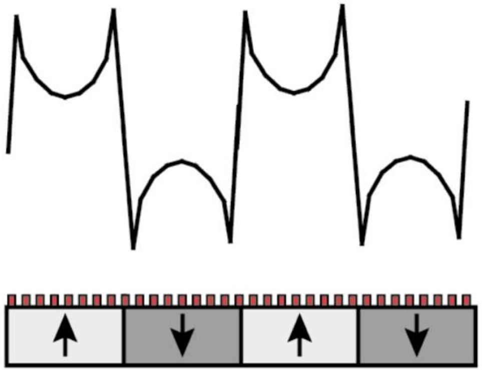
Marcos Penedo

Artefacts in MFM

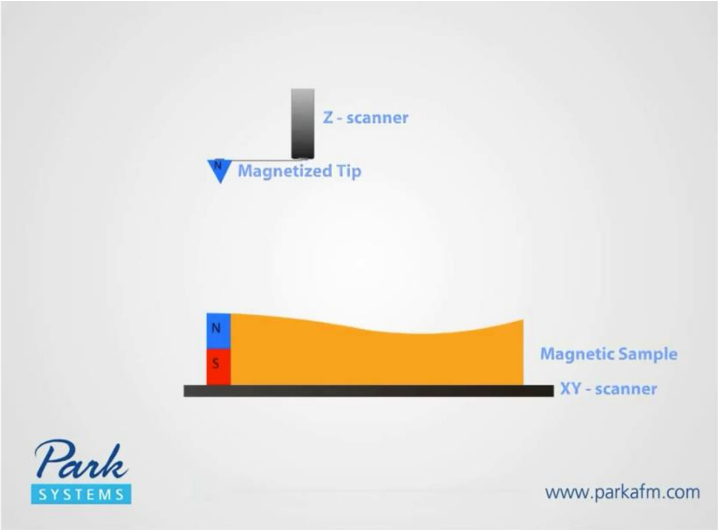
Topographic features on the MFM signal



Ideal MFM signal



MFM lift mode



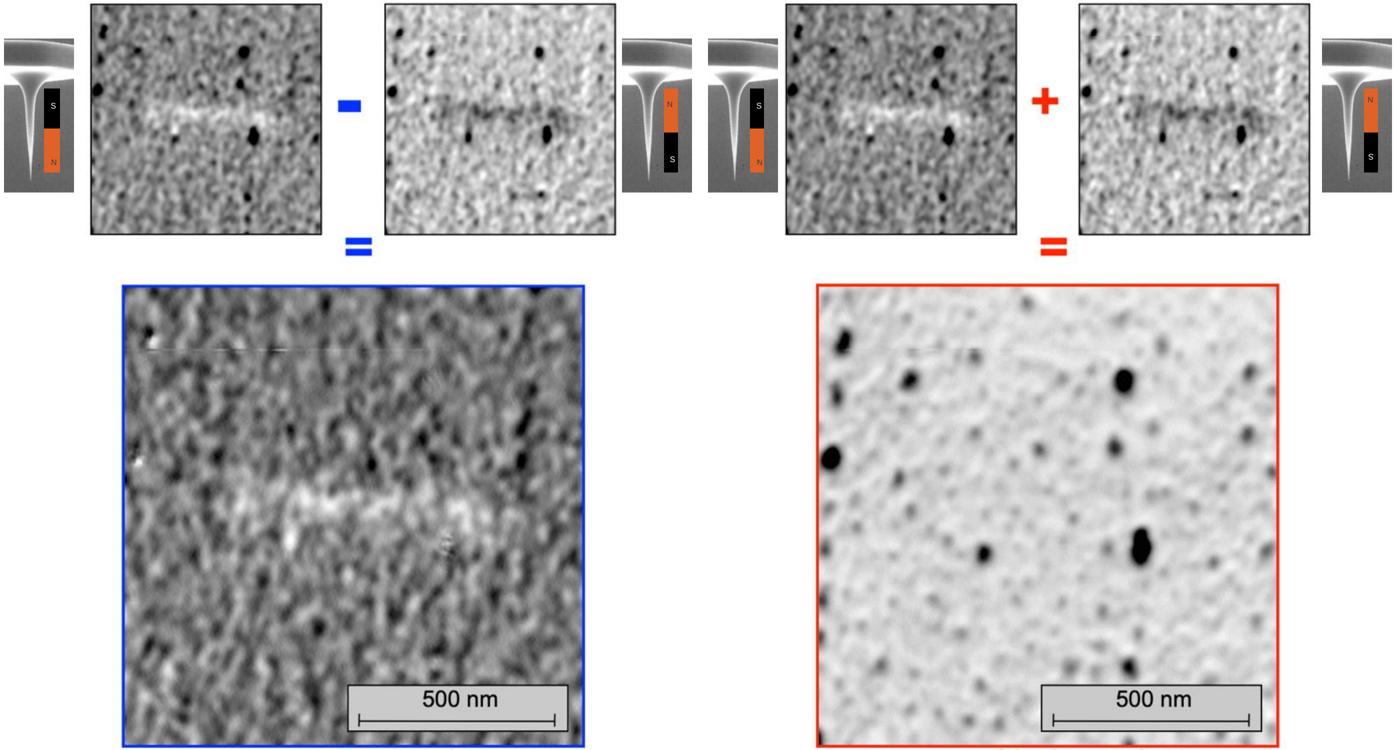
1. In the first pass, the topography is measured, close to the sample to maximize van der Walls interaction over magnetic interactions.

2. The second pass is performed at constant high, following the topographic features measured on the first pass: at distances larger than 30-50 nm, magnetic forces dominate, and can be measured independently from the topography.

Disadvantages: large recording time since topographic and MFM images cannot be acquired simultaneously, and reduced lateral resolution due to the large tip-sample separation.

Separation of topography and magnetism

Measure with opposite magnetization states of tip



magnetic signal

topographical perturbation

High resolution magnetic force microscopy

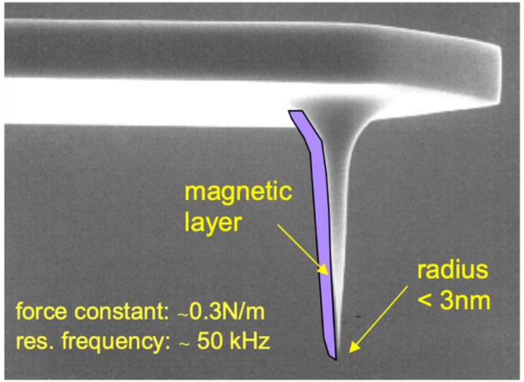
- Maximize force (derivative) sensitivity of cantilever
  - minimal measurable force and force derivative:

$$\delta F_{min} = \sqrt{\frac{4k_c k_B T B}{\omega_0 Q}} \qquad \delta F'_{min} = \sqrt{\frac{4k_c k_B T B}{\omega_0 Q \langle z_{osc}^2 \rangle}}$$

k_c: force constant, ω_0: cantilever resonance, Q : quality factor
T: temperature, z_{osc}^2: amplitude, B: bandwidth

$$Q_{air} \approx 100 \Rightarrow Q_{vac} \approx 40000 \Rightarrow Q_{vac,new} \approx 1000000$$

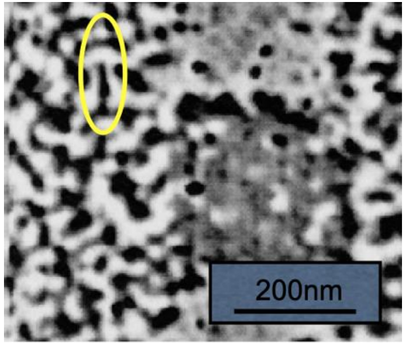
$$\delta F_{min_{air}} \Rightarrow \delta F_{min_{vac}} = \frac{\delta F_{min_{air}}}{20} \Rightarrow \delta F_{min_{vac,new}} = \frac{\delta F_{min,air}}{100}$$



  - use sharp, high aspect ratio tip coated on one side with a thin ferromagnetic layer
  - **measure in vacuum**

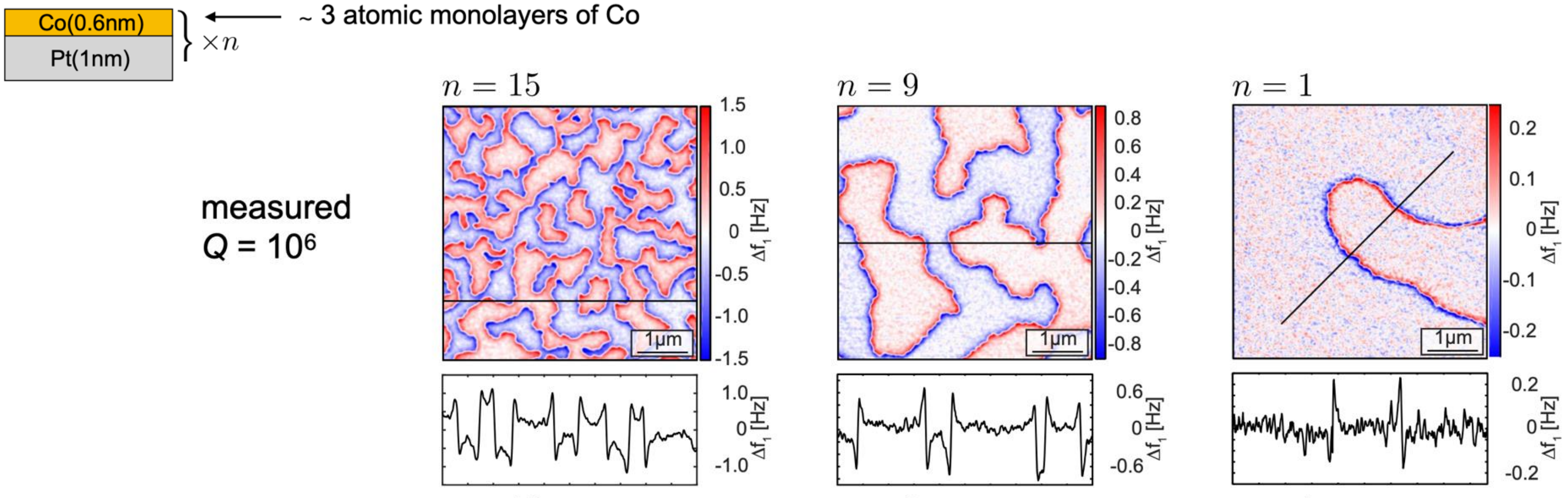
- Measure where the signal is strongest: close to the sample
  - non-contact distance control[1,2,3] with capacitive methods (AM on 2nd mode or FM on 1st mode), distance to the sample is kept constant around 5 - 15 nm above the surface

10 nm wide domain



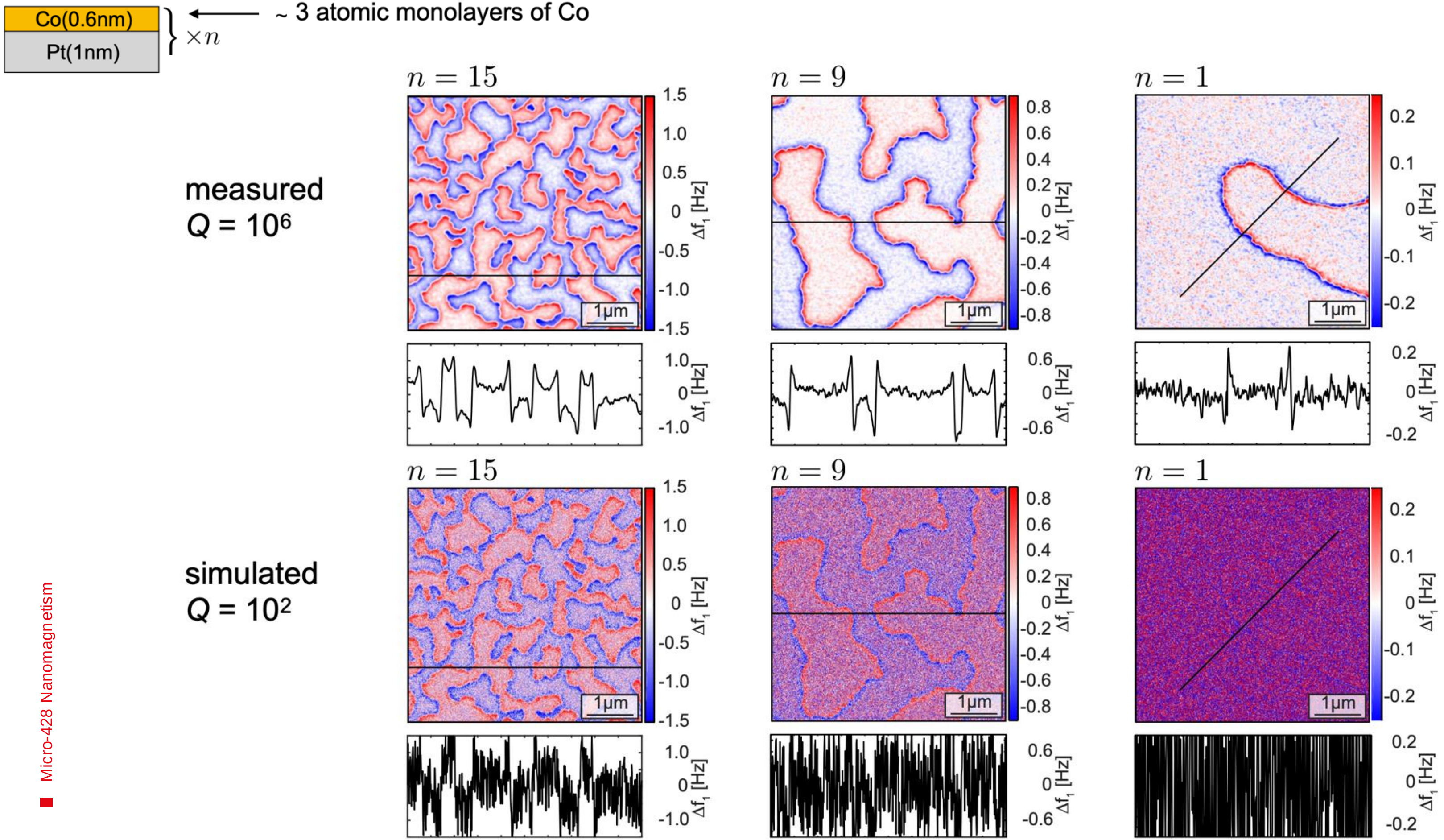
[1] J. Schwenk et al. *Appl. Phys. Lett.* **104**, 112412 (2014)
[2] J. Schwenk et al. *Appl. Phys. Lett.* **107**, 132407 (2015)
[3] X. Zhao et al. *New J. Phys.* **20**, 013018 (2018)

MFM with Q = 1’000’000 versus Q = 100

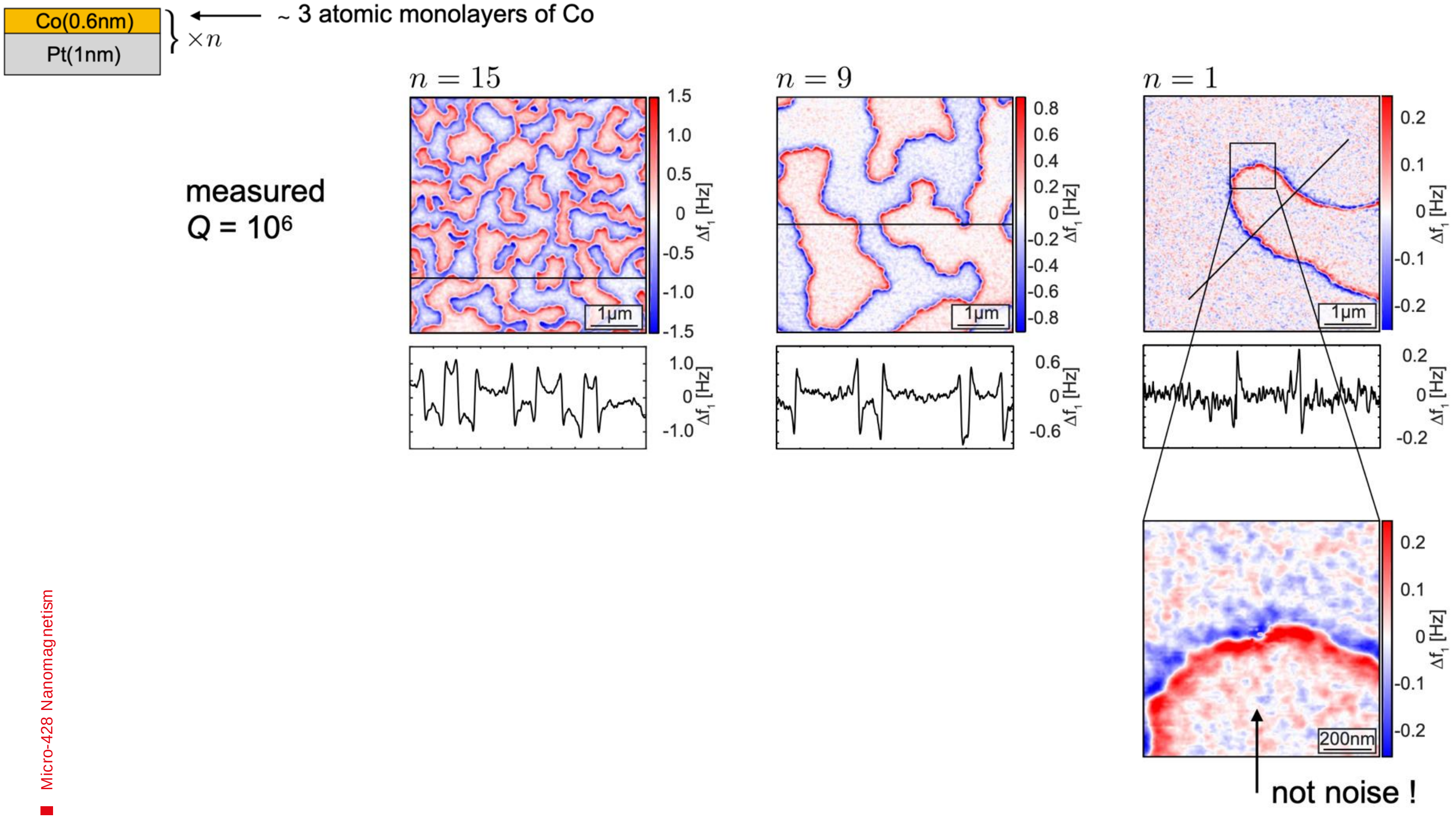


measured
$Q = 10^6$

MFM with Q = 1'000'000 versus Q = 100



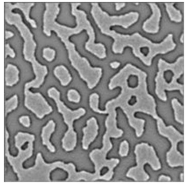
MFM with Q = 1’000’000 versus Q = 100



Calibrated transfer function for quantitative MFM

image

Δf



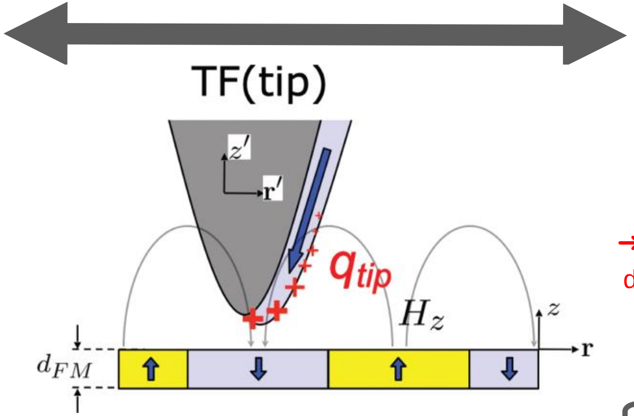
physical quantity

$\vec{\mathbf{M}}$

$\vec{\mathbf{M}}$

$H_z(\vec{\mathbf{M}})$

$\partial_z H_z(\vec{\mathbf{M}})$



➜ magnetic charge of tip depends on wavelength

- MFM tip calibration[1,2] $\leftrightarrow$ Connect measured Δf with fields[3] and $\int_{\text{tip}} d\bar{m}$
  - Requires sample with known magnetization pattern (thus H_z)
  - Measure Si/Pt_{10nm} [Pt_{1nm}/$Co_{0.6nm}$/Pt_{1nm}]$_{x5}$/Pt_{3nm}

Tip's transfer function

$$\Delta f_{mag}(\mathbf{k}, z) = \boxed{ICF_{\delta f,\partial H_z}(\mathbf{k})} \cdot \frac{\partial H_z(\mathbf{k}, z)}{\partial z}$$

Calibrate ≡ find $ICF_{\delta f,\partial H_z}(\mathbf{k})$ for known Δf, $H_z(\mathbf{k})$

- We can now calculate the contrast pattern in Δf expected for any arbitrary pattern of $\vec{\mathbf{M}}$ and vice-versa

H. J. Hug et al. J.. *Appl. Phys.* **83**, 5609 (1998), P. J. A. van Schendel et al. J.. *Appl. Phys.* **88**, 435 (2000), Simulations (Matlab): *https://qmfm.empa.ch/qmfm/*

MFM Tip Calibration

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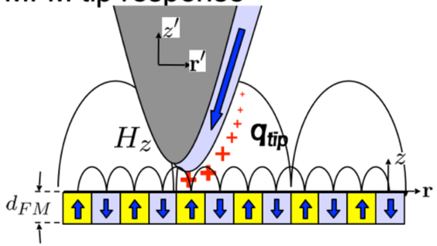
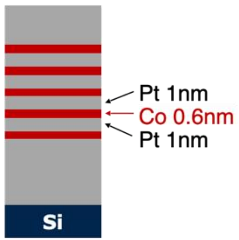
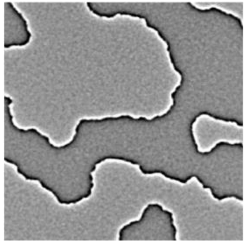
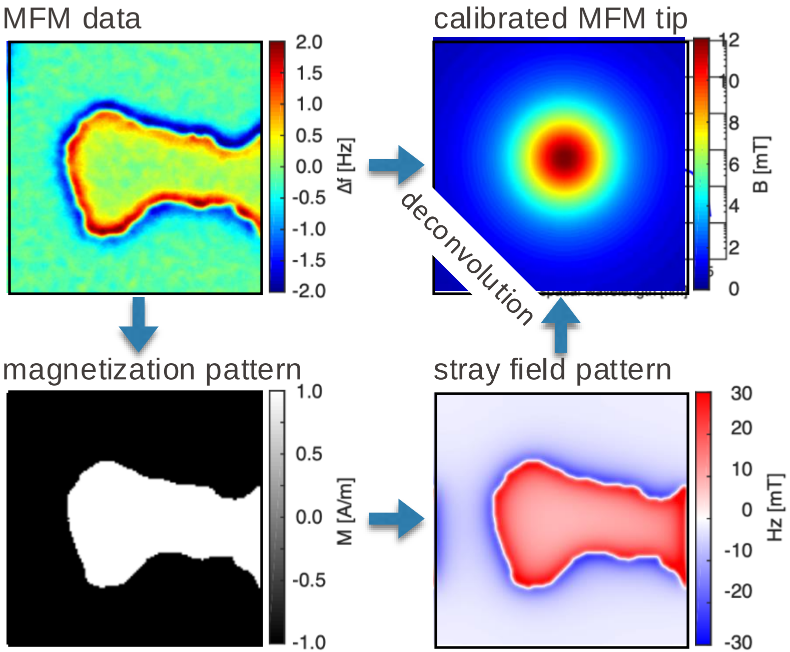


calibration sample

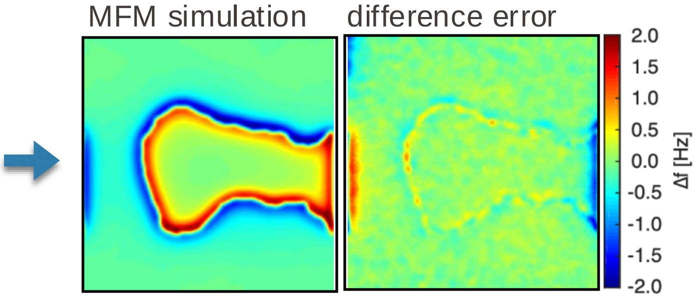




M_{avg} = 347kA/m
$\mu_0 H_c$ = 900.4mT
K_{eff} = 0.469 MJ/m³
K_{ms} = 0.681MJ/m³
K_u = 1.150 MJ/m³

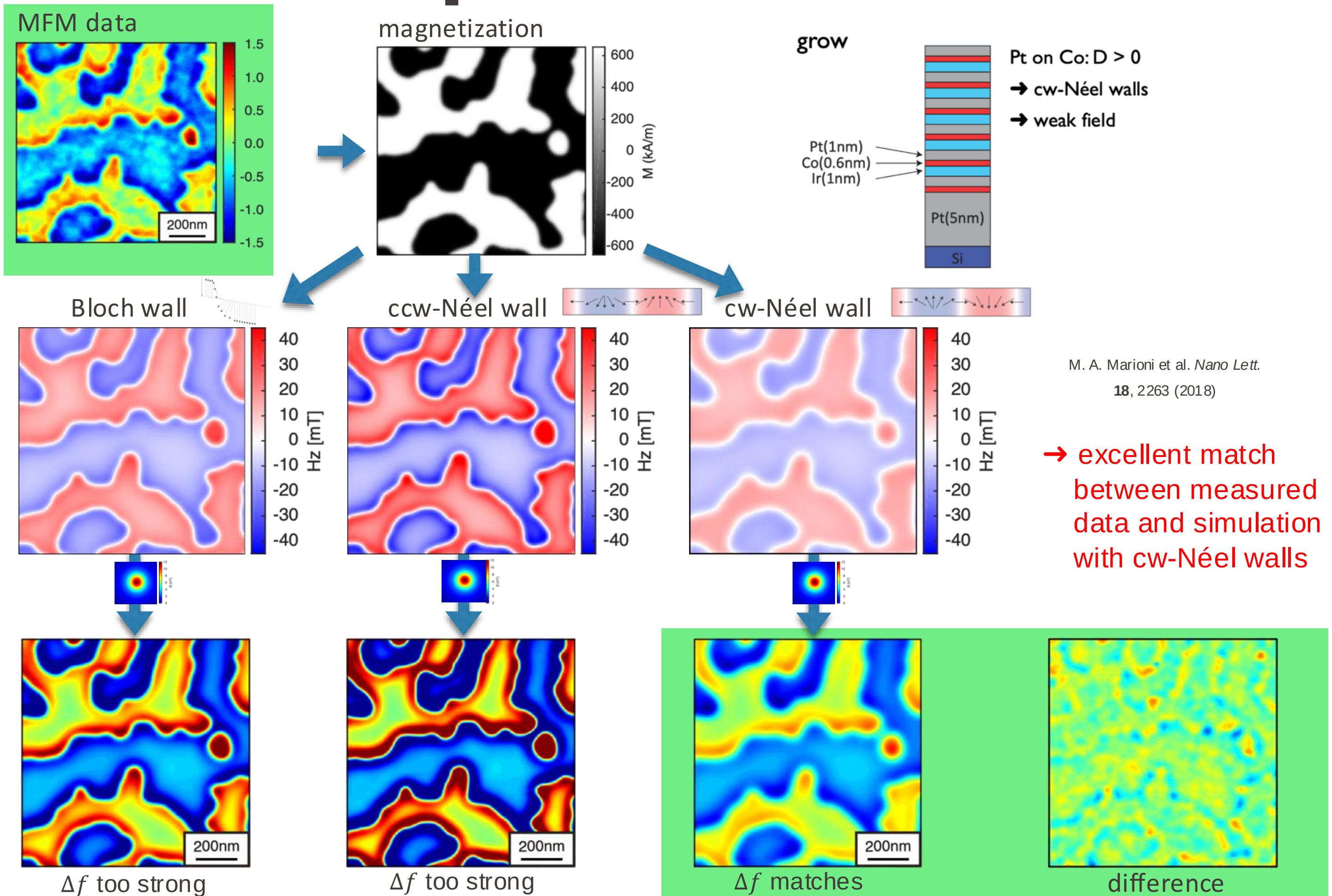


Repeat the process to average



qMFM: P. J. A. van Schendel et al. J.. *Appl. Phys.* **88**, 435 (2000)
Simulations (Matlab): *https://qmfm.empa.ch/qmfm/*

Domains in samples with interfacial DMI

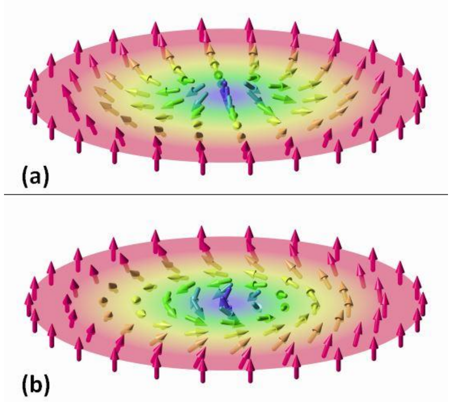


M. A. Marioni et al. *Nano Lett.* **18**, 2263 (2018)

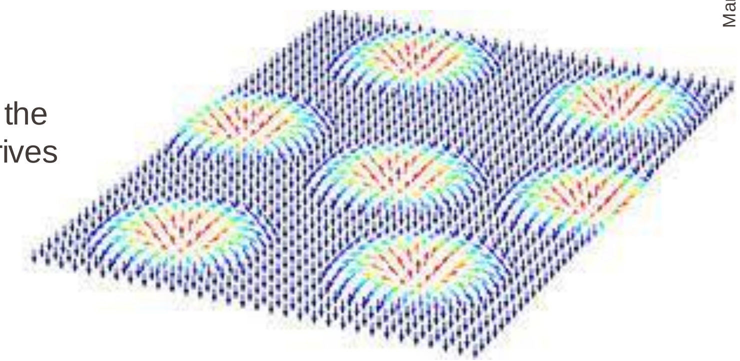
➜ excellent match between measured data and simulation with cw-Néel walls

Skyrmions

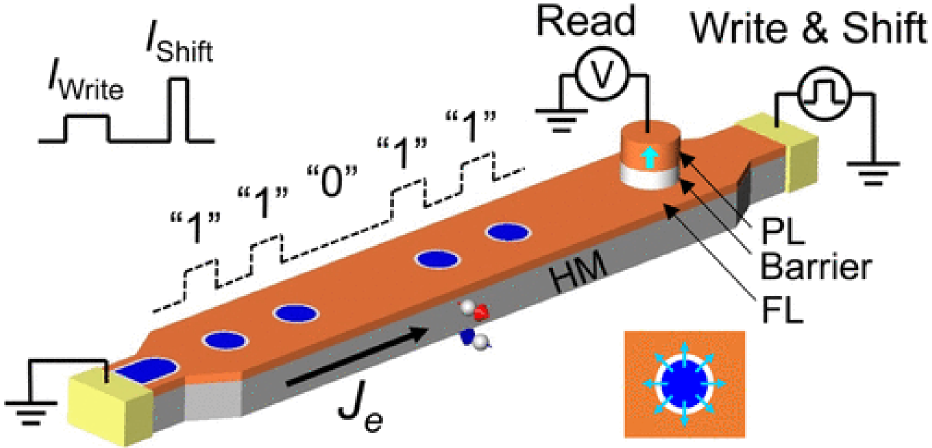
Skyrmions: nano sized magnetic structures
which have a single spin point core



They can be used to increase the
bit density in magnetic hard drives



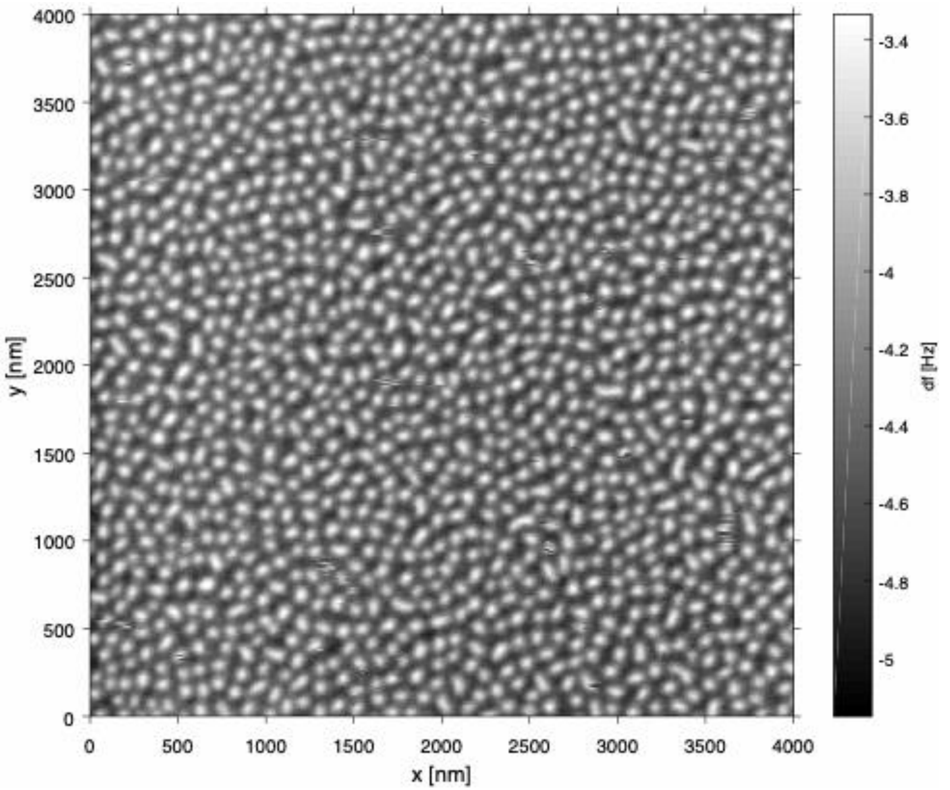
Racetrack memory



Nano Lett. 2017, 17, 1, 261–268

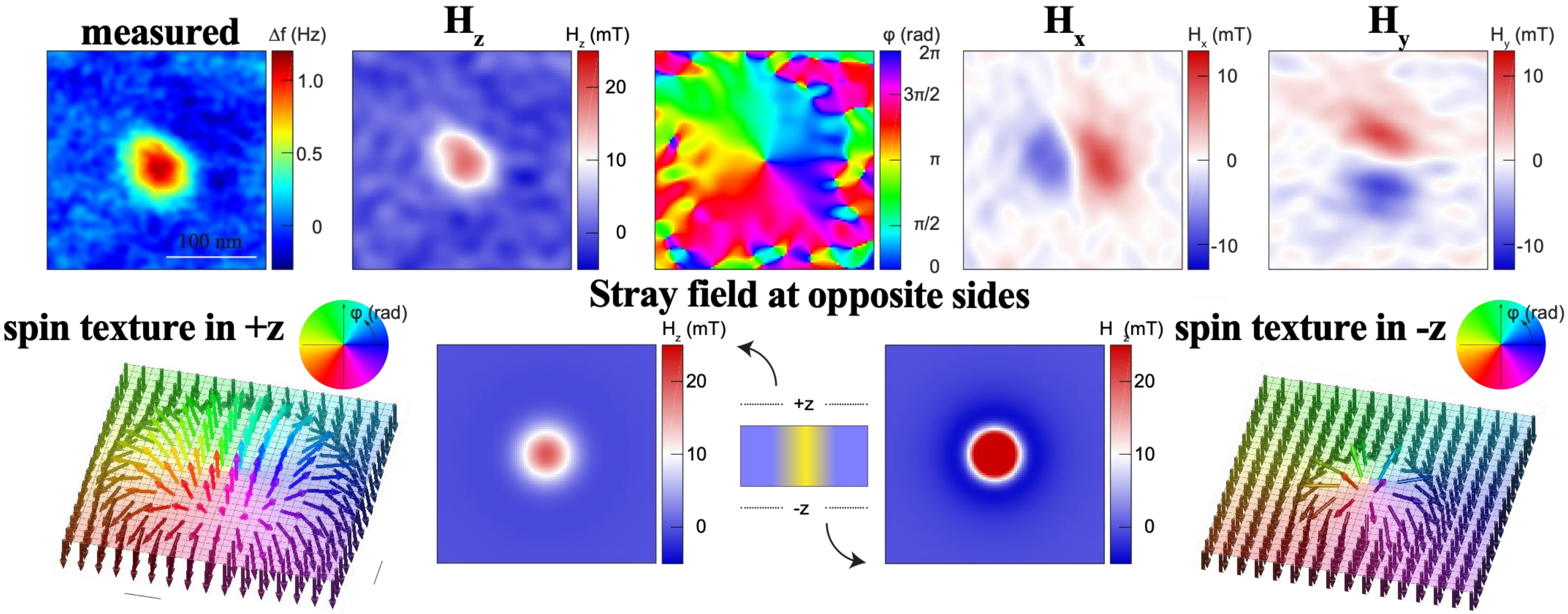
Skyrmions

Skyrmion lattice
measure with MFM



M. A. Marioni et al. *Nano Lett.* **18**, 2263 (2018)

MFM quantitative measurements of skyrmions



M. A. Marioni et al. *Nano Lett.* **18**, 2263 (2018)