Magnetic Anisotropy and Magnetostriction

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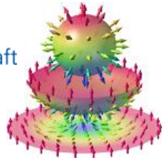
APPLIED SPIN PHENOMENA

OPTIMAS light-spin-matter

RPTU Rheinland-Pfälzische Technische Universität Kaiserslautern Landau

SPIN+X SFB/TRR 173 Kaiserslautern • Mainz

DFG Deutsche Forschungsgemeinschaft
priority programme
2137 Skyrmionics



European Union

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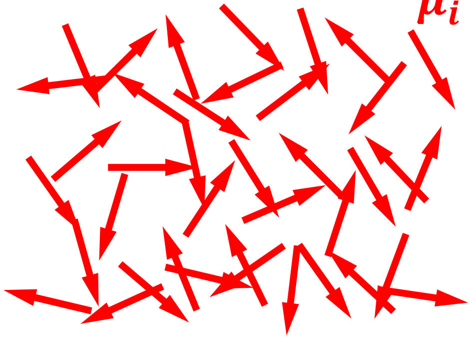
MAWICS

Magnetic Order

Paramagnet

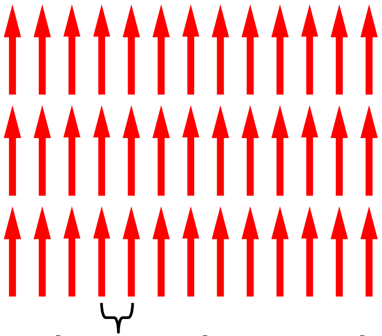
$\boldsymbol{\mu}_i$



$J_{\text{ex}} < k_B T$

$T < T_c$

Ferromagnet

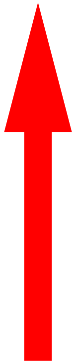


Exchange interaction

$k_B T < J_{\text{ex}}$

=

$\boldsymbol{M}$



Magnetization

$$\boldsymbol{M} = \frac{1}{V}\sum_{i=1}^{N} \boldsymbol{\mu}_i$$

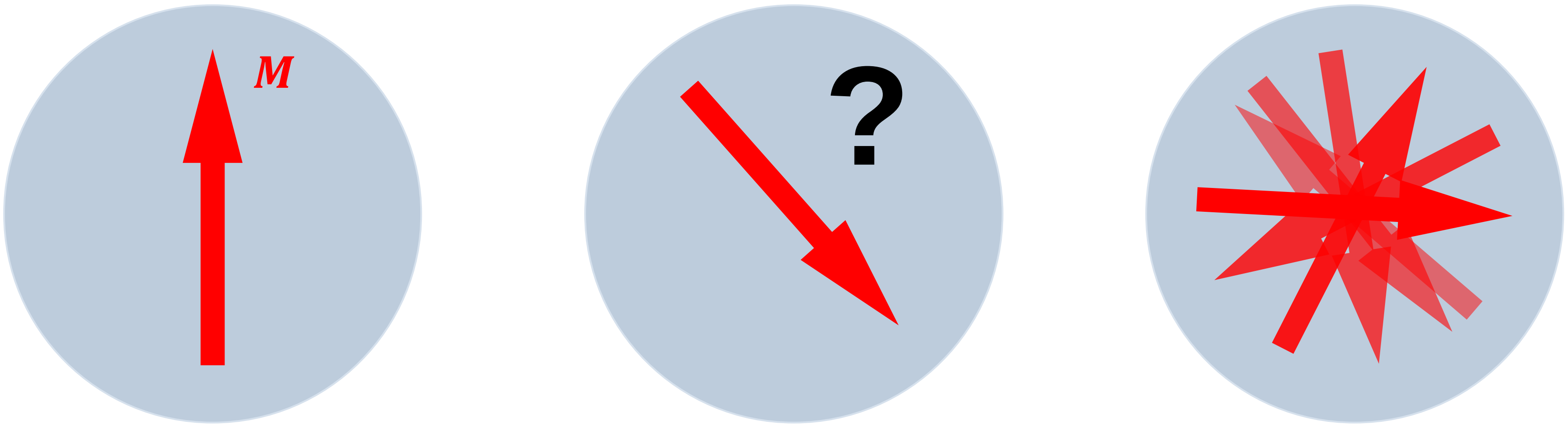
magnetic moment

$$\mu_i = g\,\mu_B\,J$$

Total angular momentum per atom: $\boldsymbol{J} = \boldsymbol{L} + \boldsymbol{S}$

- Phase transition
- Spontaneous symmetry breaking
- Spontaneous emergence of **macroscopic order parameter: Magnetization**

Anisotropy



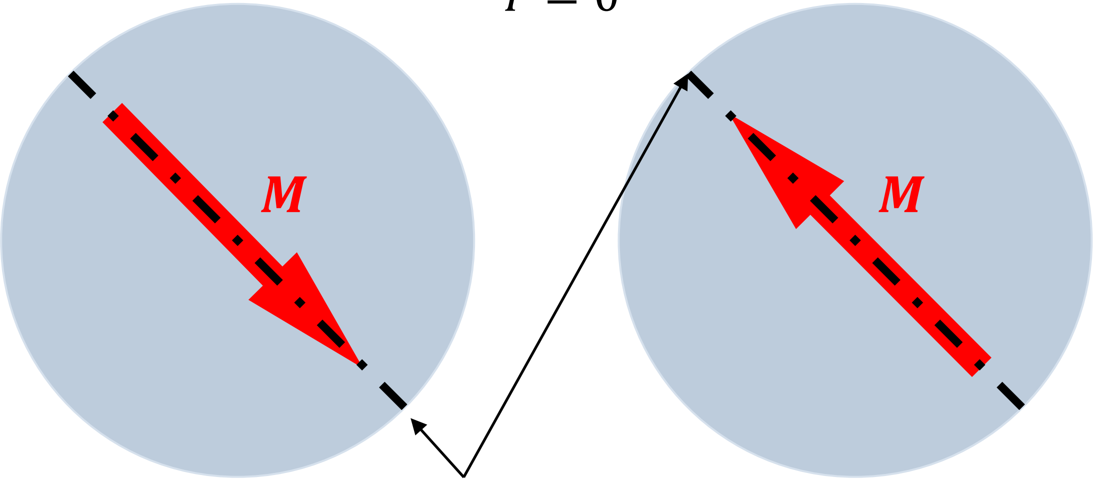
$\langle \boldsymbol{M} \rangle = \boldsymbol{0}$!

Without anisotropy there is no macroscopic, time-averaged magnetization

Limiting cases and applications

RPTU

$T = 0$



Preferred „easy“ axis

Thermal stability of magnetization direction:

$k_B T \leq K V$

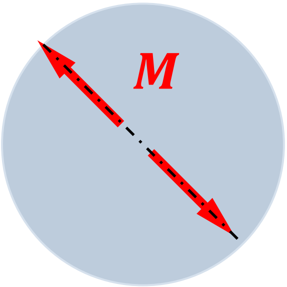
K: Anisotropy Constant

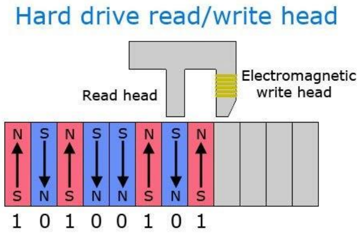
V: Volume

Anisotropy energy density / anisotropy constant: K

$$[K] = \frac{J}{m^3}$$

$k_B T > KV$





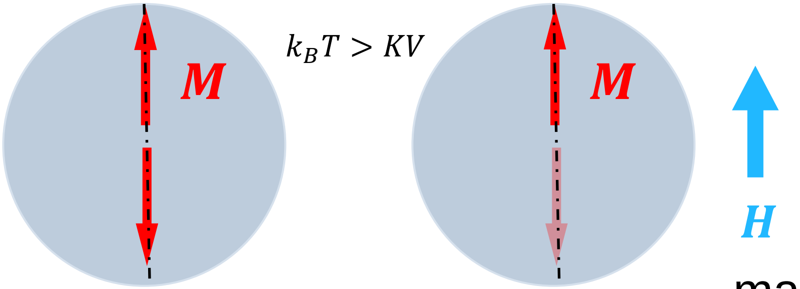
$\langle \boldsymbol{M} \rangle = 0$

anisotropy limits HDD bit size

Example: Uniaxial anisotropy

RPTU

$\boldsymbol{u}$: anisotropy axis direction (unit vector)



magnetic field

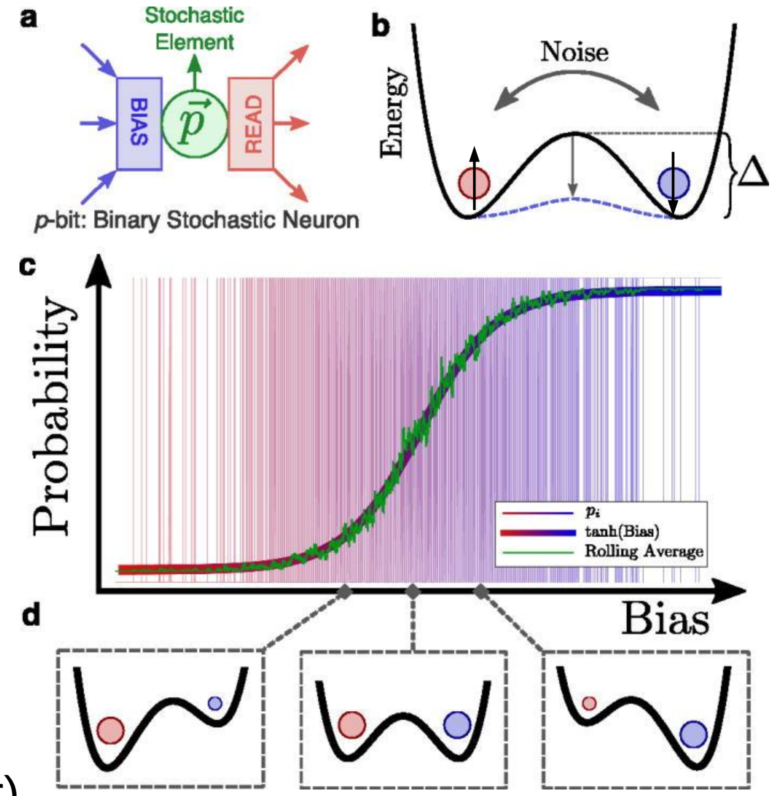
$\langle \boldsymbol{M} \rangle = 0$ $\langle \boldsymbol{M} \rangle \neq 0$

$E_Z = -\mu_0 V\, \boldsymbol{M} \cdot \boldsymbol{H}$ Zeeman energy

Magnetic free energy density

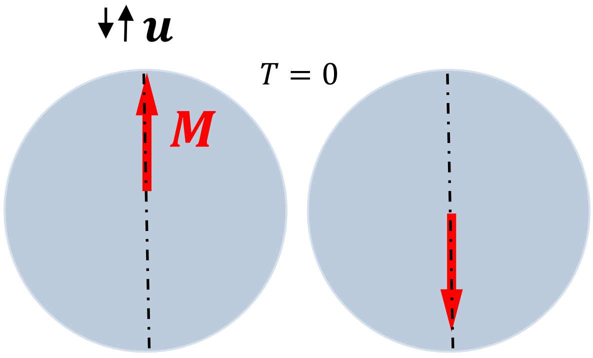
$F = -\mu_0 \boldsymbol{M} \cdot \boldsymbol{H} + K\, (\boldsymbol{u} \cdot \boldsymbol{m})^2$

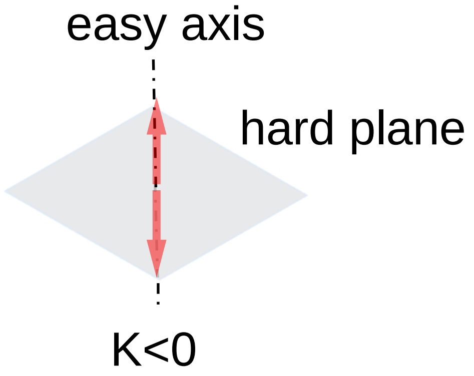
$\mathbf{m} = \frac{\boldsymbol{M}}{|\boldsymbol{M}|} = \frac{\boldsymbol{M}}{M_S}$ magnetization direction (unit vector)

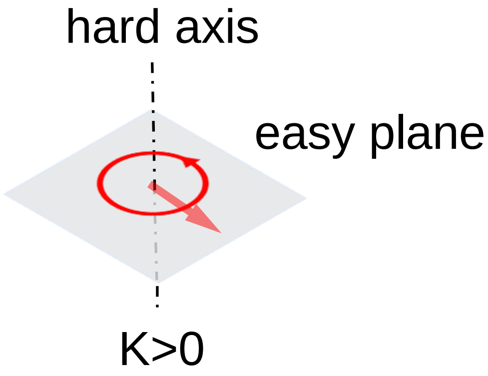


Appl. Phys. Rev. **6**, 011305 (2019)

Hard and easy axis







$$F = -\mu_0 \boldsymbol{M} \cdot \boldsymbol{H} + K\,(\boldsymbol{u} \cdot \boldsymbol{m})^2$$

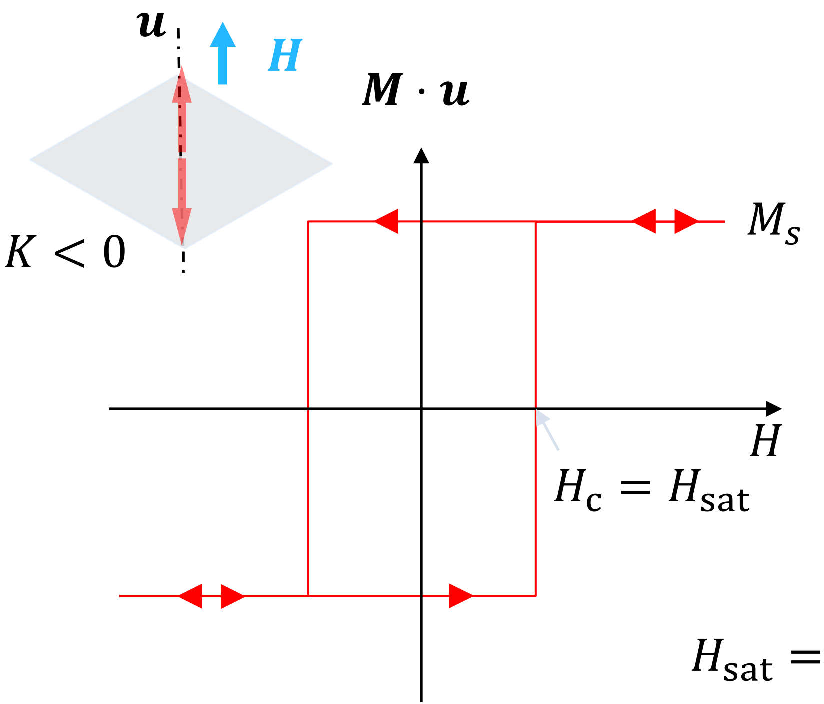
K<0: easy axis

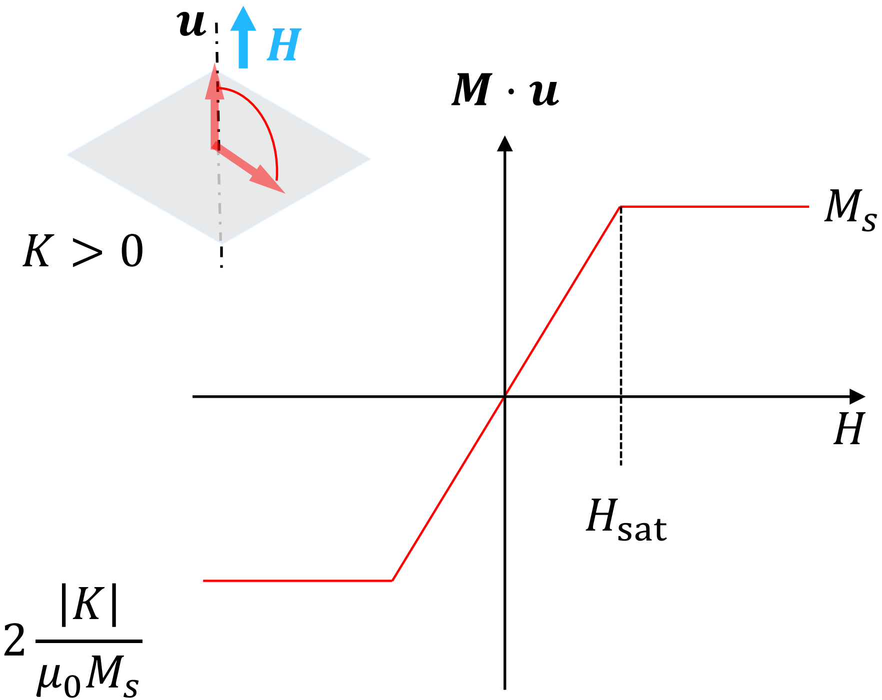
K>0: hard axis

Stoner-Wohlfarth Model

$$F = -\mu_0 \boldsymbol{M} \cdot \boldsymbol{H} + K\,(\boldsymbol{u} \cdot \boldsymbol{m})^2$$

The equilibrium **m** orientation minimizes F

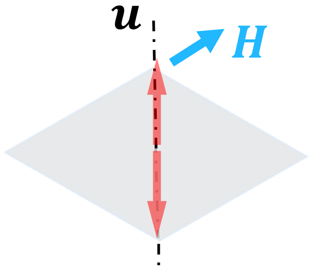




$$H_{\text{sat}} = 2\frac{|K|}{\mu_0 M_s}$$

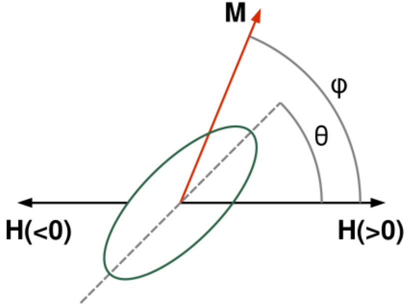
Stoner-Wohlfarth Model

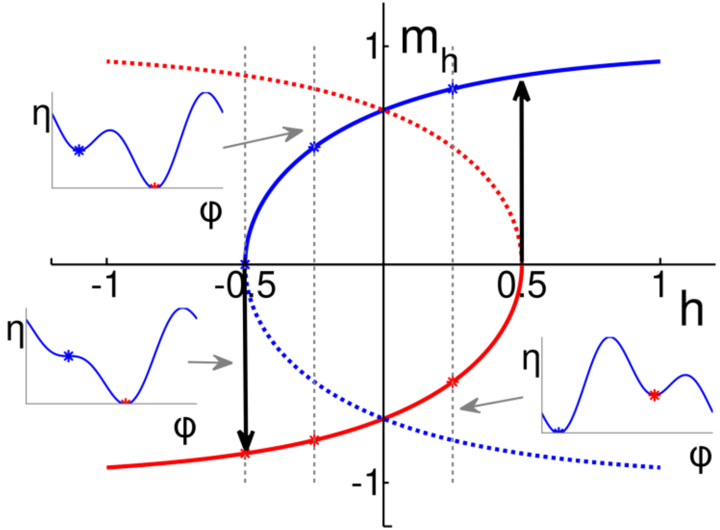
RPTU

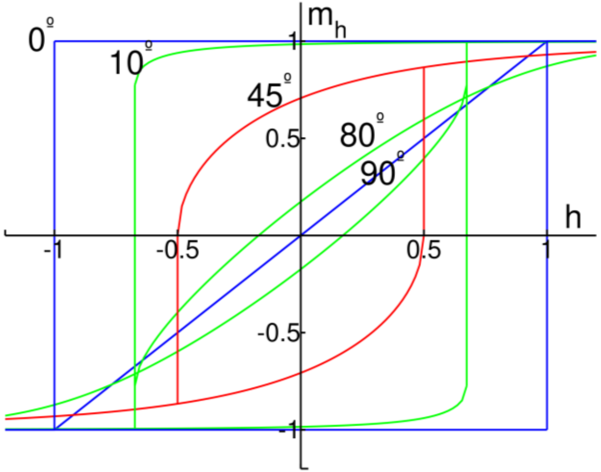


$$F = -\mu_0 \boldsymbol{M} \cdot \boldsymbol{H} + K\,(\boldsymbol{u} \cdot \boldsymbol{m})^2$$

The equilibrium **m** orientation minimizes F





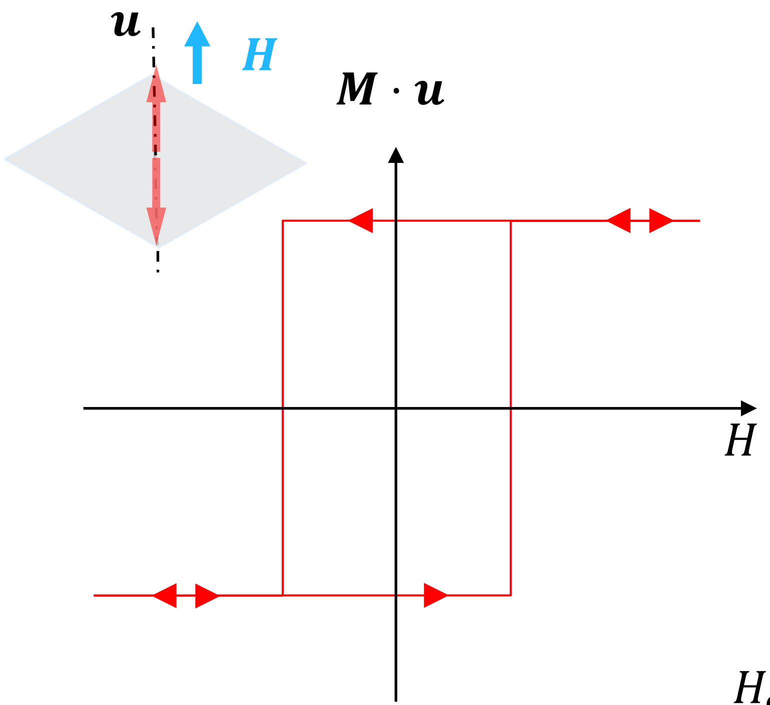


$$h = H / H_{\text{sat}}$$

$$H_{\text{sat}} = 2\frac{|K|}{\mu_0 M_s}$$

Images: Wikipedia

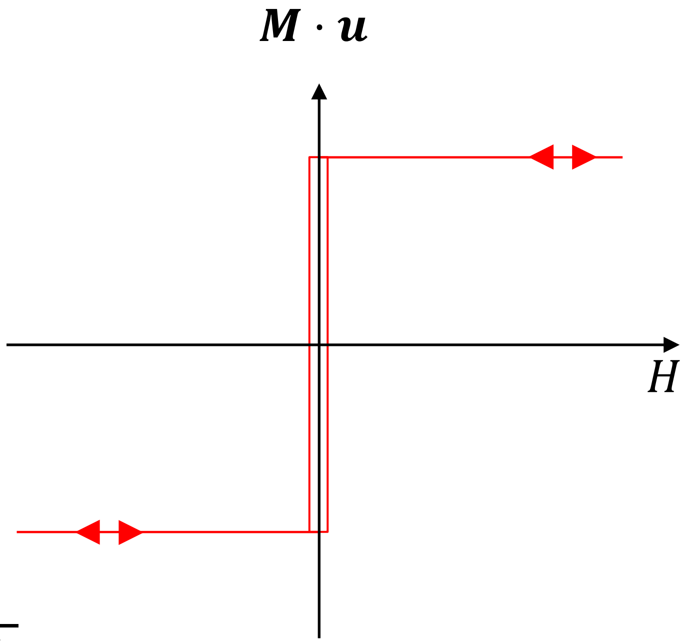
Soft and hard magnets



large K: hard magnet

e.g. permanent magnets

$$H_c = 2\frac{|K|}{\mu_0 M_s}$$

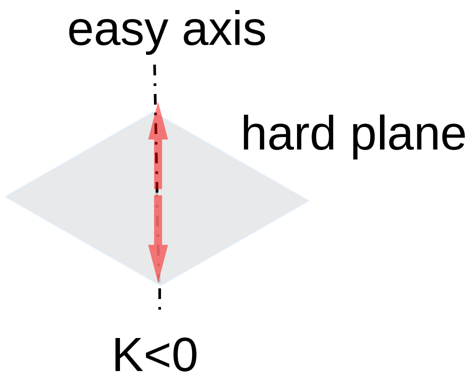


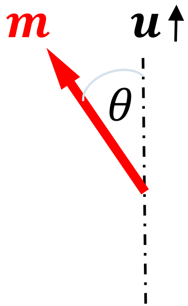
small K: soft magnet

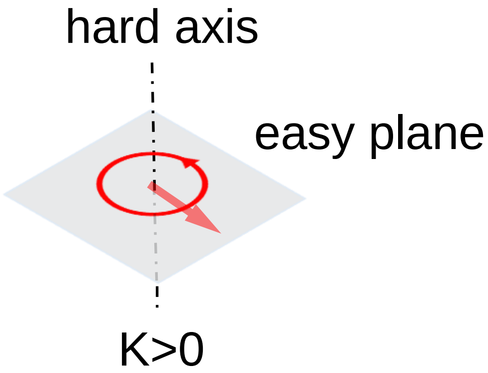
e.g. transformer cores

Effective field

RPTU







$F = -\mu_0 \boldsymbol{M} \cdot \boldsymbol{H} + K\,(\boldsymbol{u} \cdot \boldsymbol{m})^2$

K<0: easy axis

K>0: hard axis

Effective field: $\mu_0 \boldsymbol{H}_{\mathrm{eff}} = -\nabla_{\boldsymbol{m}}\, G$

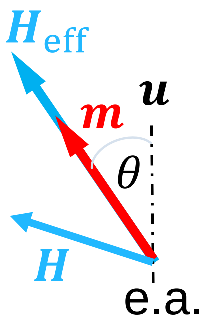
In equilibrium: $\boldsymbol{m} \parallel \boldsymbol{H}_{\mathrm{eff}}$

$$G \equiv \frac{F}{M} = -\mu_0 \boldsymbol{m} \cdot \boldsymbol{H} + \frac{K}{M_s}\,(\boldsymbol{u} \cdot \boldsymbol{m})^2$$

$$\mu_0 \boldsymbol{H}_{\mathrm{eff}} = \mu_0 \boldsymbol{H} - \frac{2K}{M_{\mathrm{s}}} \boldsymbol{u}\,(\boldsymbol{u} \cdot \boldsymbol{m}) = \mu_0 \boldsymbol{H} + \boldsymbol{B}_{\mathrm{u}} \cos(\theta)$$

With uniaxial anisotropy field: $\boldsymbol{B}_u = -\frac{2K}{M_s} \boldsymbol{u}$

Equation of motion



$$G = -\mu_0 \boldsymbol{m} \cdot \boldsymbol{H} + \frac{K}{M_s} (\boldsymbol{u} \cdot \boldsymbol{m})^2 \qquad \mu_0 \boldsymbol{H}_{\mathrm{eff}} = -\nabla_{\boldsymbol{m}} G$$

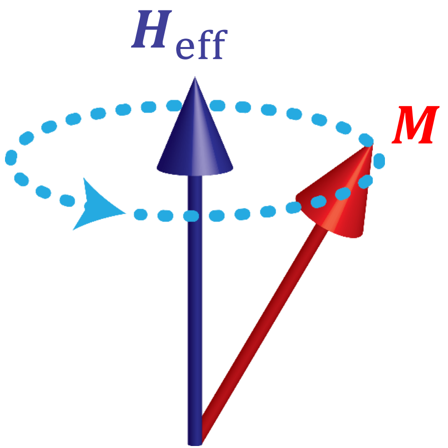
In equilibrium: $\boldsymbol{m} \parallel \boldsymbol{H}_{\mathrm{eff}}$

Torque: $\boldsymbol{T} = \boldsymbol{\mu} \times \boldsymbol{B} = \frac{d\boldsymbol{L}}{dt}$ with angular momentum $\boldsymbol{L} = -\frac{1}{\gamma}\boldsymbol{\mu}$

$$\frac{d\boldsymbol{L}}{dt} = -\frac{d\boldsymbol{\mu}}{dt}\frac{1}{\gamma} = \boldsymbol{\mu} \times \boldsymbol{B}$$

$$\boldsymbol{\mu} = \boldsymbol{m}\, M_s\, V$$

$$\boldsymbol{B} = \mu_0 \boldsymbol{H}_{\mathrm{eff}}$$



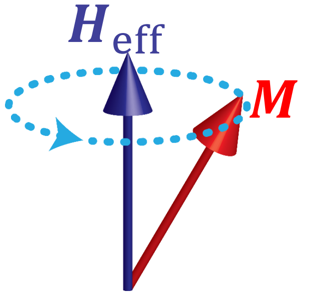
$$\frac{d\boldsymbol{m}}{dt} = -\gamma\, \mu_0\, (\boldsymbol{m} \times \boldsymbol{H}_{\mathrm{eff}})$$

Attention: $\boldsymbol{H}_{\mathrm{eff}} = \boldsymbol{H}_{\mathrm{eff}}(\boldsymbol{m})$!

Equation of motion - solution

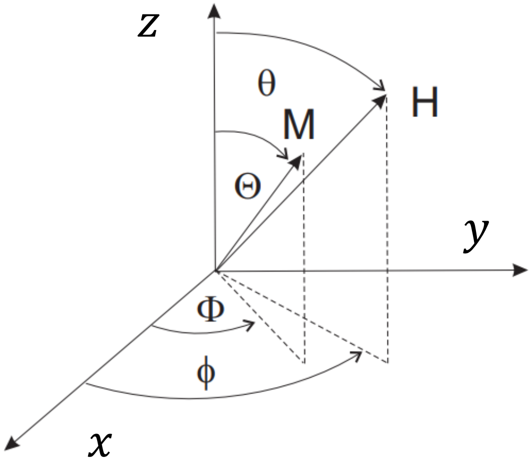
RPTU

$$G = -\mu_0 \boldsymbol{m} \cdot \boldsymbol{H} + \frac{K}{M_s} (\boldsymbol{u} \cdot \boldsymbol{m})^2 \qquad \mu_0 \boldsymbol{H}_{\text{eff}} = -\nabla_{\boldsymbol{m}} G$$



In equilibrium: $\boldsymbol{m} \parallel \boldsymbol{H}_{\text{eff}}$

$$\frac{d\boldsymbol{m}}{dt} = -\gamma \, \mu_0 \, (\boldsymbol{m} \times \boldsymbol{H}_{\text{eff}})$$



Solution in general only numerically possible!

$$\left(\frac{\omega}{\gamma}\right)^2 = \frac{1}{\sin^2\Theta} \left[\left(\frac{\partial^2}{\partial\Phi^2} G\right) \left(\frac{\partial^2}{\partial\Theta^2} G\right) - \left(\frac{\partial}{\partial\Phi} \frac{\partial}{\partial\Theta} G\right)^2 \right]_{\Phi_0,\Theta_0}$$

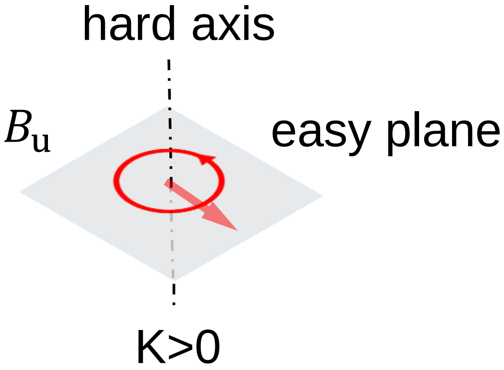
Philips Res. Rep. **10**, 113 (1955)

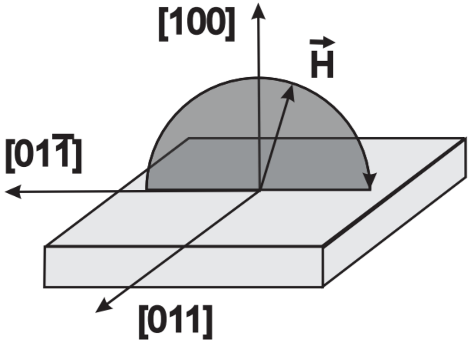
Ferromagnetic resonance (FMR) is a direct measure of anisotropy

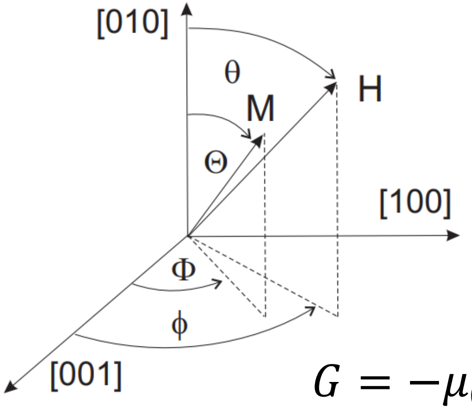
FMR measures anisotropy

$$\frac{d\boldsymbol{m}}{dt} = -\gamma\,\mu_0\,(\boldsymbol{m} \times \boldsymbol{H}_{\text{eff}})$$

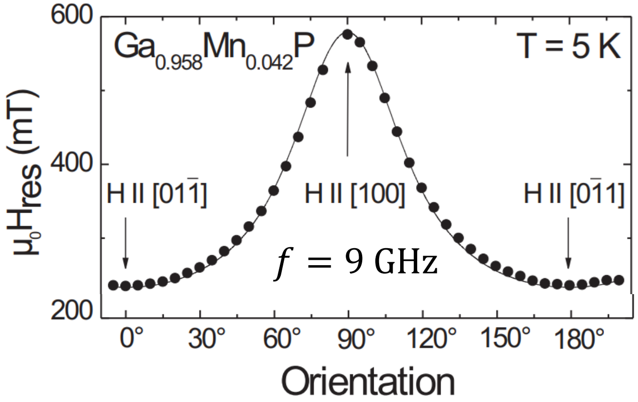
$$\mu_0 H_{\text{eff}}(\theta = \Theta = 0) = \frac{\omega}{\gamma} = \mu_0 H - B_{\text{u}}$$







$$G = -\mu_0 \boldsymbol{m} \cdot \boldsymbol{H} + \frac{K}{M_s}\,(\boldsymbol{z} \cdot \boldsymbol{m})^2$$

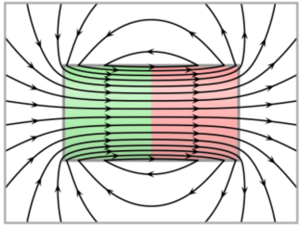


$$\left(\frac{2\pi f}{\gamma}\right)^2 = \frac{1}{\sin^2\Theta}\left[\left(\frac{\partial^2}{\partial\Phi^2}G\right)\left(\frac{\partial^2}{\partial\Theta^2}G\right) - \left(\frac{\partial}{\partial\Phi}\frac{\partial}{\partial\Theta}G\right)^2\right]_{\Phi_0,\Theta_0}$$

Phys. Rev. B **75**, 214419 (2007)

Origins of anisotropy

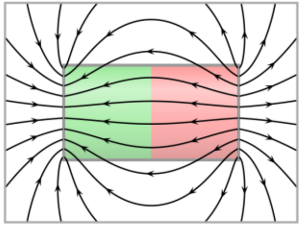
Shape anisotropy:



$\boldsymbol{B}$

$$\boldsymbol{B} = \mu_0(\boldsymbol{H}_D + \boldsymbol{M})$$
$$\boldsymbol{\nabla} \times \boldsymbol{H}_D = 0$$
$$\boldsymbol{\nabla} \cdot \boldsymbol{B} = 0$$

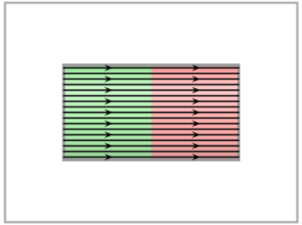
See lecture by Olivier Fruchart



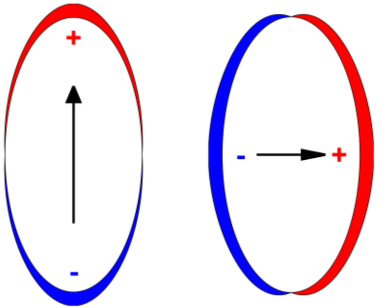
$\boldsymbol{H}_D$

Inside magnet: Demagnetizing field $\boldsymbol{H}_D$
Outside magnet: Stray field $\mu_0 \boldsymbol{H}_D = \boldsymbol{B}$

H_D: **field generated from (virtual) magnetic surface charges**



$\boldsymbol{M}$

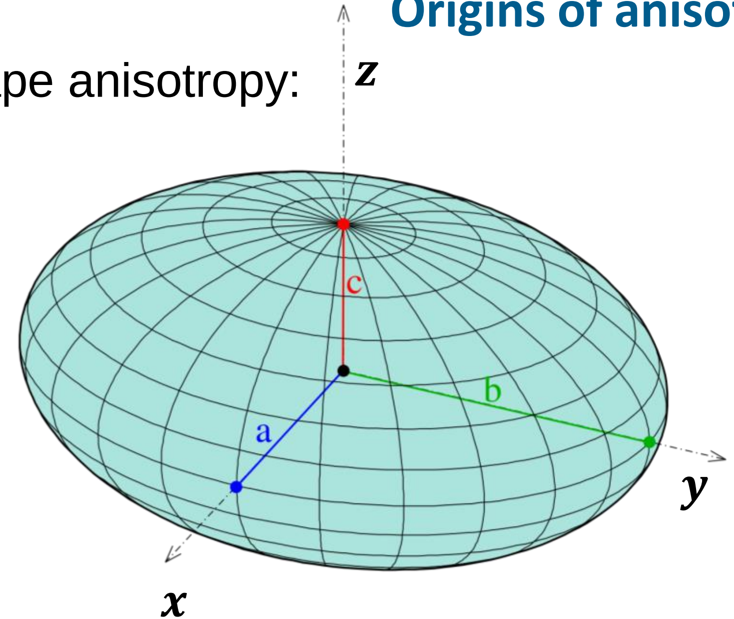


Surface charges & $\boldsymbol{H}_D$ reduced for $\boldsymbol{M}$ along long(er) axis.

Images: Wikipedia

Origins of anisotropy

Shape anisotropy:



ellipsoid

Demagnetization energy:

$$E = -\frac{\mu_0}{2}\int \boldsymbol{M}\cdot\ \boldsymbol{H}_D\, dV$$

$$\boldsymbol{H}_D = -M_s\, \widetilde{\boldsymbol{N}}\, \boldsymbol{m}$$

$$\widetilde{\boldsymbol{N}} \approx \begin{pmatrix} N_x & 0 & 0 \\ 0 & N_y & 0 \\ 0 & 0 & N_z \end{pmatrix}$$

Only valid for ellipsoids!

$$N_x + N_y + N_z = 1$$

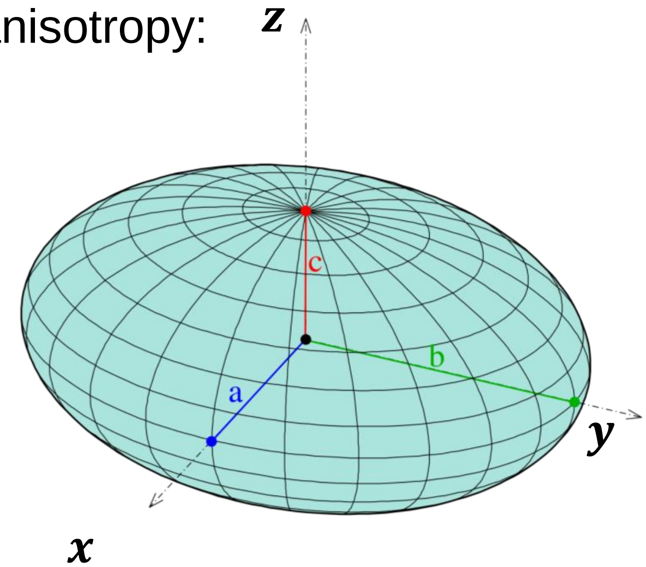
Uniaxial anisotropy: $\mu_0 \boldsymbol{H}_{\text{eff}} = \mu_0 \boldsymbol{H} + \boldsymbol{B}_{\text{u}}(\boldsymbol{u}\cdot\boldsymbol{m})$

General shape anisotropy: $\mu_0 \boldsymbol{H}_{\text{eff}} = \mu_0 \boldsymbol{H} + \mu_0 \boldsymbol{H}_{\boldsymbol{D}} = \mu_0 \boldsymbol{H} - \mu_0 M_s \widetilde{\boldsymbol{N}}\, \boldsymbol{m}$

FMR of the general ellipsoid

RPTU

Shape anisotropy:



ellipsoid

$$\boldsymbol{H}_D = -M_s\,\tilde{\mathbf{N}}\,\boldsymbol{m}$$

$$\tilde{\mathbf{N}} \approx \begin{pmatrix} N_x & 0 & 0 \\ 0 & N_y & 0 \\ 0 & 0 & N_z \end{pmatrix}$$

$$N_x + N_y + N_z = 1$$

General shape anisotropy:

$$\mu_0 \boldsymbol{H}_{\text{eff}} = \mu_0 \boldsymbol{H} - \mu_0 M_s \tilde{\mathbf{N}}\,\boldsymbol{m}$$

For $\boldsymbol{H}_{\text{eff}} \parallel \boldsymbol{z}$

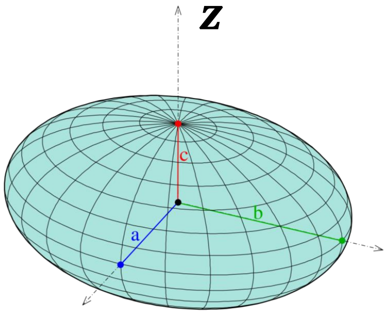
$$\frac{d\boldsymbol{m}}{dt} = -\gamma\,\mu_0\,(\boldsymbol{m} \times \boldsymbol{H}_{\text{eff}})$$

$$\omega_{FMR} = \mu_0\gamma\sqrt{[H + M_s(N_x - N_z)][H + M_s(N_y - N_z)]}$$

Kittel equation (derivation in spin wave lecture)

FMR of the general ellipsoid

Shape anisotropy:



For $\boldsymbol{H}_{\mathrm{eff}} \parallel \boldsymbol{z}$

$$\omega_{FMR} = \mu_0\gamma\sqrt{[H + M_s(N_x - N_z)][H + M_s(N_y - N_z)]}$$

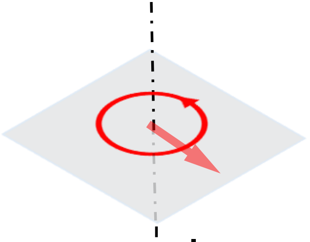
$$N_x + N_y + N_z = 1$$

Sphere: $N_x = N_y = N_z = \frac{1}{3}$ $\qquad \omega_{\mathrm{sphere}} = \mu_0\gamma H$

Out-of-plane magnetized thin film: $N_z = 1$ $\qquad \omega_{\mathrm{oop}} = \mu_0\gamma(H - M_s)$

In-plane magnetized thin film: $N_y = 1$ $\qquad \omega_{\mathrm{ip}} = \mu_0\gamma\sqrt{H[H + M_s]}$
(y: oop)

hard axis



easy plane

FMR of the general ellipsoid

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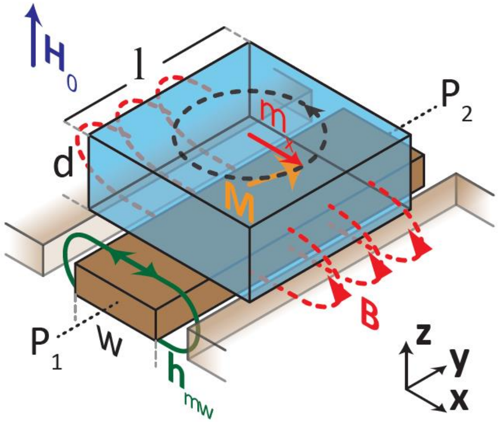
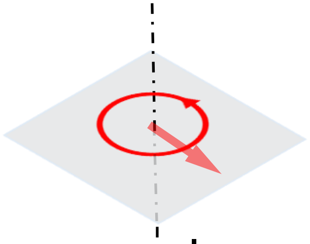
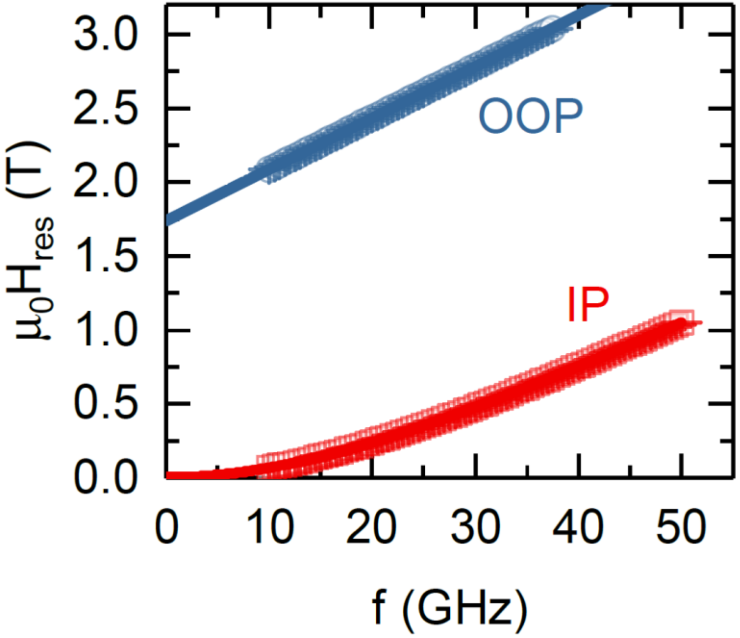
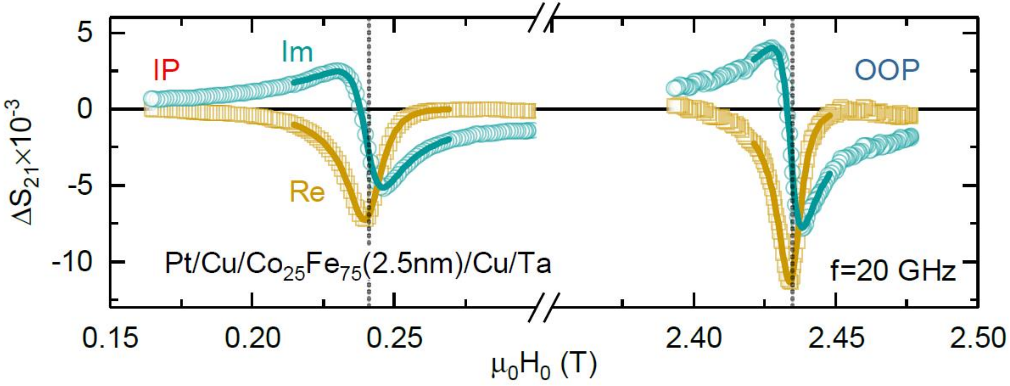




$$\omega_{\text{oop}} = \mu_0\gamma(H - M_s)$$



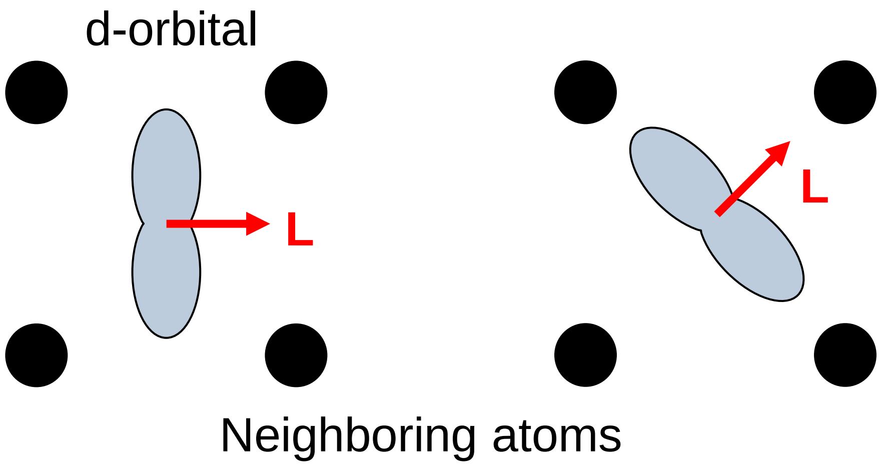
$$\omega_{\text{ip}} = \mu_0\gamma\sqrt{H[H + M_s]}$$



Origins of anisotropy

RPTU

Crystalline anisotropy:



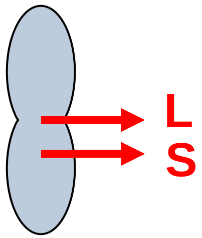
L: orbital angular momentum

Crystal field splitting: d-orbital orientation matters due to Coulomb repulsion

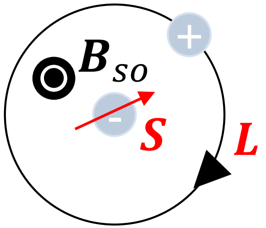
Origins of anisotropy

Crystalline anisotropy:

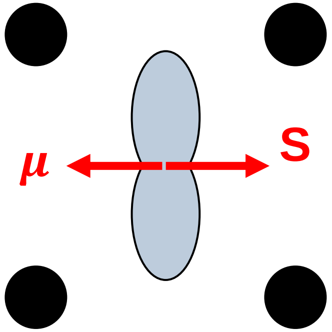
d-orbital



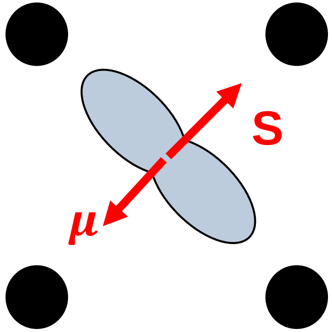
Spin-orbit coupling:



$$H_{so} = \lambda\, \boldsymbol{L} \cdot \boldsymbol{S} \qquad \Rightarrow \boldsymbol{L} \parallel \pm \boldsymbol{S}$$



Easy axis



hard axis

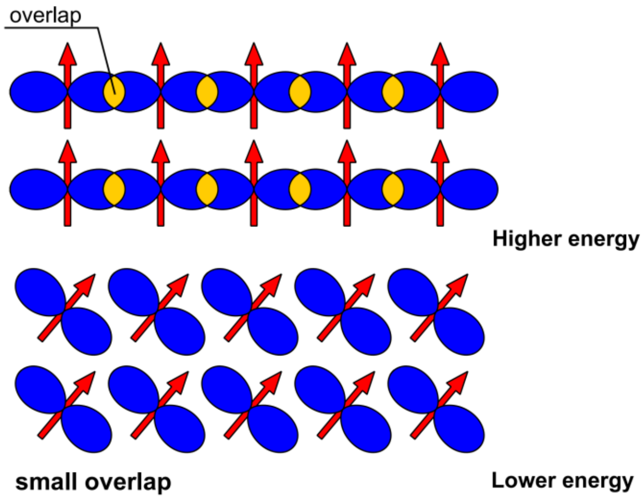
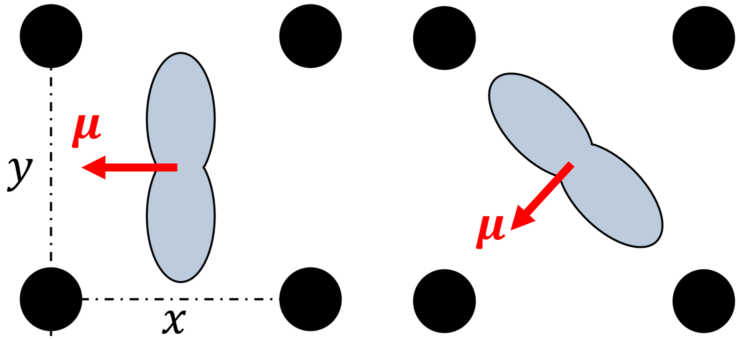


Image: Maciej Urbaniak

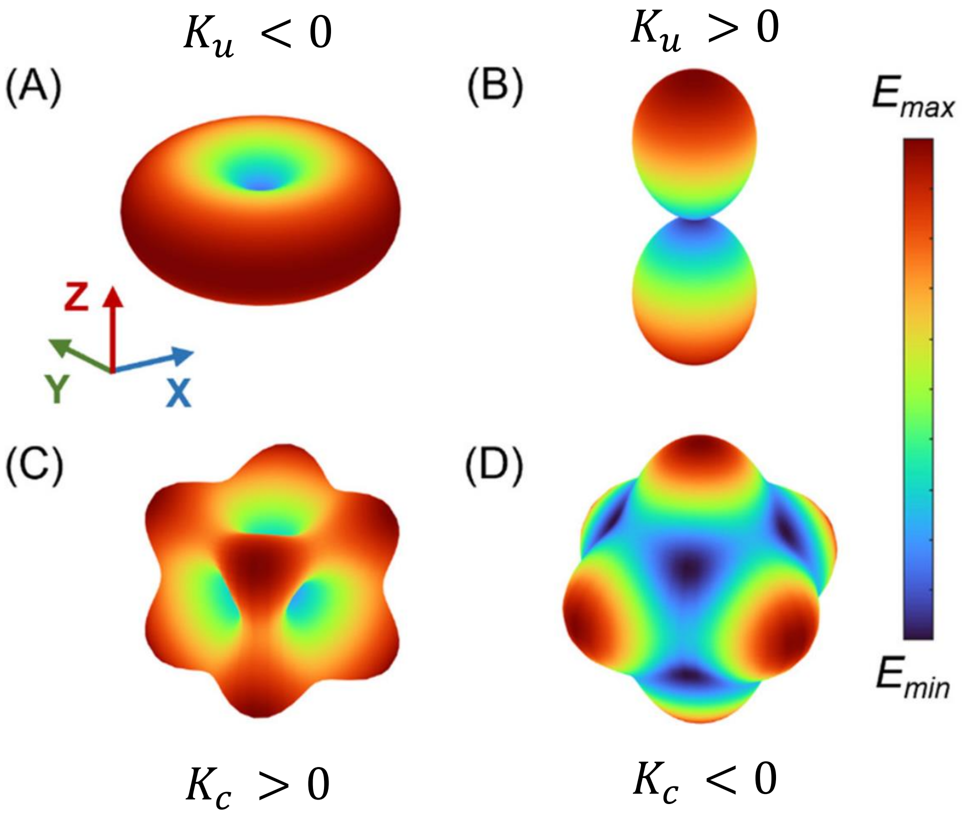
Origins of anisotropy

Crystalline anisotropy:



Easy direction hard direction

$$F_{\text{uniax}} = K_u\, m_z^2$$
$$F_{\text{cubic}} = K_c\left[m_x^2\, m_y^2 + m_y^2\, m_z^2 + m_x^2\, m_z^2\right]$$



Total magnetic free energy density of the general ellipsoid

$$F_{\text{demag}} = \frac{\mu_0}{2} M_s^2 \left[N_x m_x^2 + N_y m_y^2 + N_z m_z^2\right]$$

$$F_{\text{uniax}} = K_u\, m_u^2$$

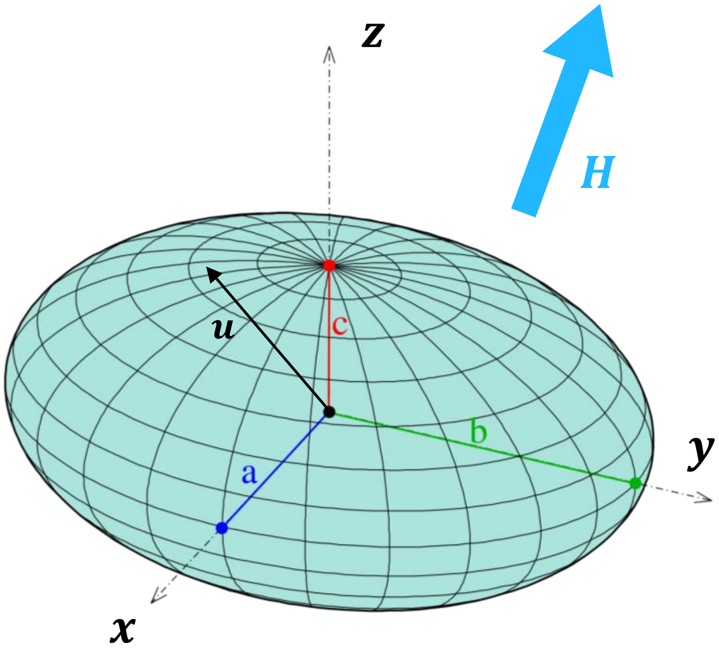
$$F_{\text{cubic}} = K_c \left[m_a^2\, m_b^2 + m_b^2\, m_c^2 + m_a^2\, m_c^2\right]$$

$$F_{\text{Z}} = -\mu_0\, \boldsymbol{M} \cdot \boldsymbol{H}$$

$$F_{\text{tot}} = F_{\text{demag}} + F_{\text{uniax}} + F_{\text{cubic}} + F_{\text{Z}}$$

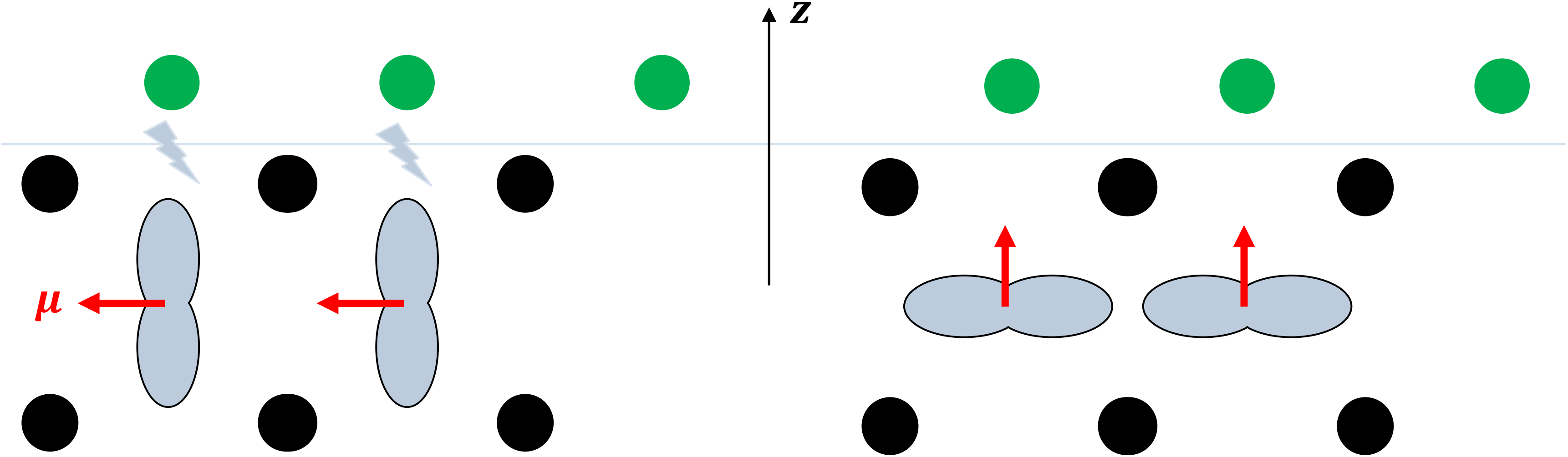
$$G = \frac{F_{\text{tot}}}{M_{\text{s}}}$$

$$\mu_0 \boldsymbol{H}_{\text{eff}} = -\nabla_{\boldsymbol{m}}\, G \qquad \frac{d\boldsymbol{m}}{dt} = -\gamma\, \mu_0\, (\boldsymbol{m} \times \boldsymbol{H}_{\text{eff}})$$



Origins of anisotropy

Interfacial anisotropy in thin films:



Spin-orbit coupling can lead to anisotropy from a preferred orbital orientation at interfaces

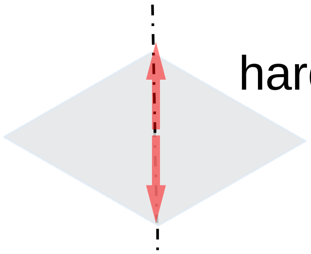
$$F_{\mathrm{int}} = -\frac{1}{d} K_{int}\, m_z^2$$

Origins of anisotropy

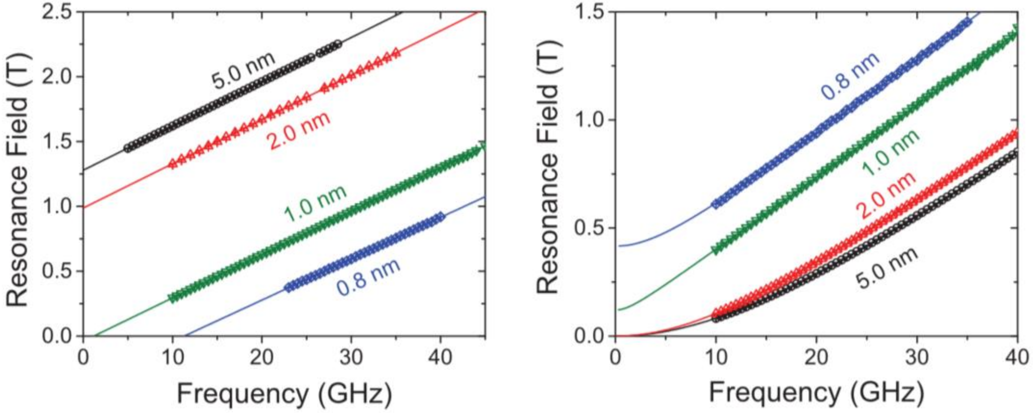
$$F_{\text{int}} = -\frac{1}{d} K_{int}\, m_z^2 \qquad F_{\text{demag}} = \frac{\mu_0}{2}\, M_s^2 m_z^2$$

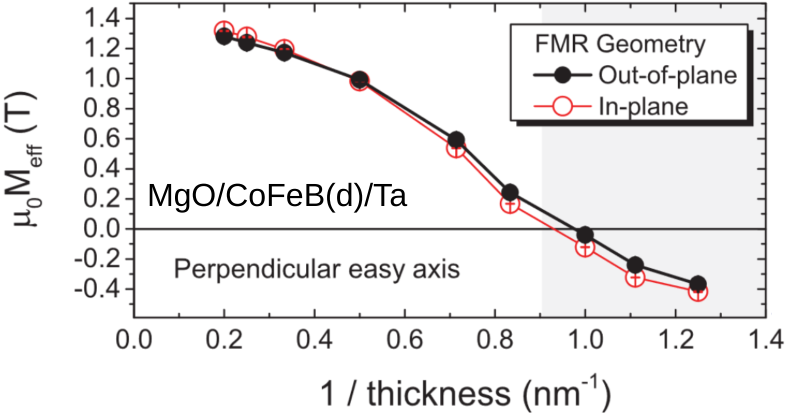
$$M_{\text{eff}} = M_{\text{s}} - H_{\text{k}} \qquad \mu_0 H_{\text{k}} = \frac{2K_{int}}{d\, M_s}$$

$$\omega_{\text{oop}} = \mu_0 \gamma (H - M_{\text{eff}}) \qquad \omega_{\text{ip}} = \mu_0 \gamma \sqrt{H[H + M_{\text{eff}}]}$$



$M_{\text{eff}} < 0$: Perpendicular magnetic anisotropy

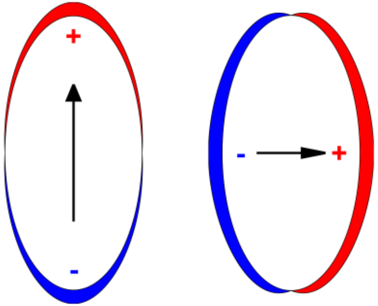




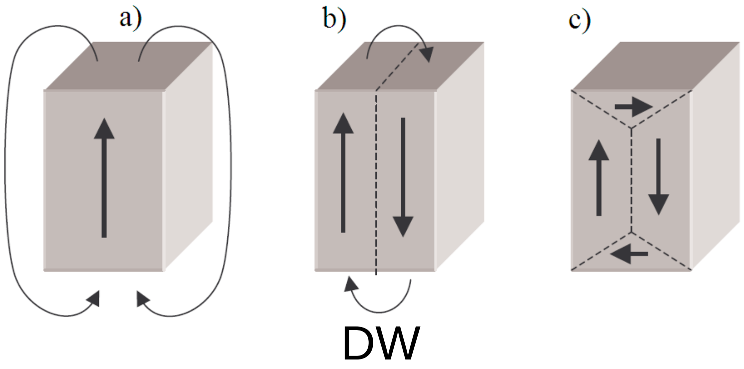
Interfacial anisotropy in thin films

IEEE Magnetics Letters **6**, 3500404 (2015).

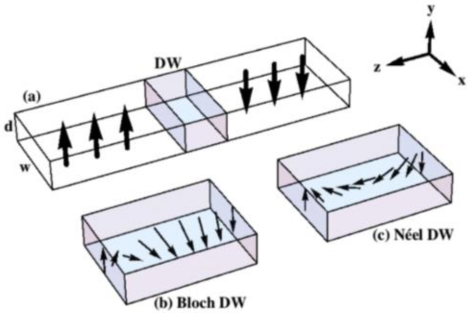
Magnetic Domains



$$E = -\frac{\mu_0}{2}\int \boldsymbol{M}\cdot\,\boldsymbol{H}_D\,dV$$

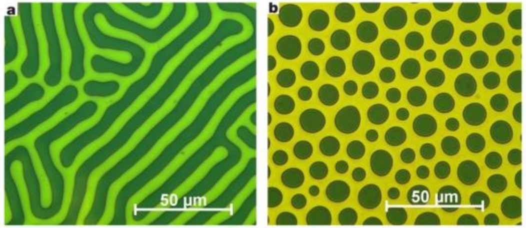


Demagnetization fields can be further reduced by domain formation



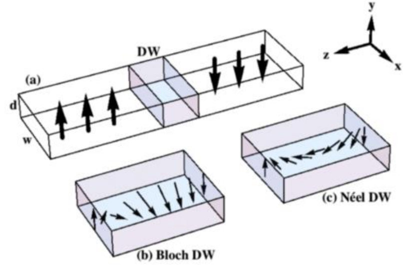
PRB **92**, 214420 (2015)

Stripe domains Bubble domains

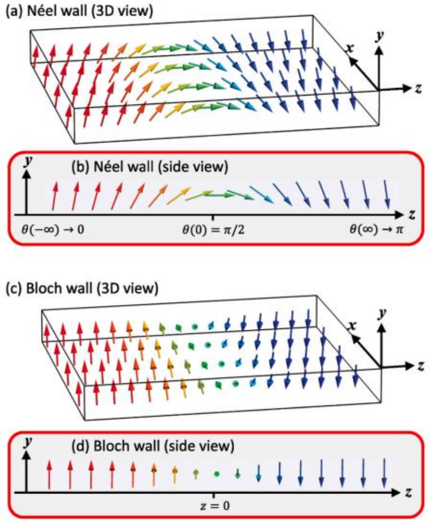


Images: Wikipedia, Matesy

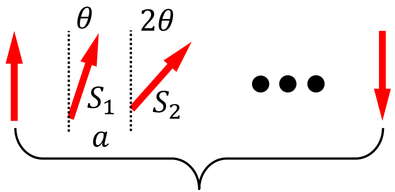
Magnetic Domains



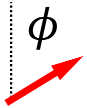
PRB **92**, 214420 (2015)



Surface Science Reports **78**, 100605 (2023)



e.a.



$$\delta = N\,a \qquad \theta = \frac{\pi}{N}$$

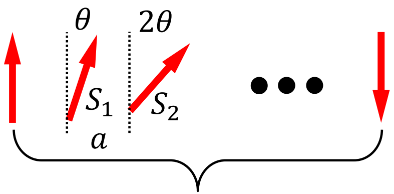
$$H_{\mathrm{ex}} = -2\,J\,\boldsymbol{S}_1\boldsymbol{S}_2 = -2\,JS^2\cos\theta \approx -2\,J\,S^2\left(1-\frac{\theta^2}{2}\right)$$

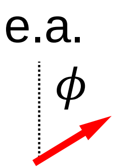
$$\Delta E_{\mathrm{ex}} = N\,JS^2\left(\frac{\pi}{N}\right)^2 = \frac{\mathrm{J}S^2\pi^2}{N}\text{; minimzed for } N\rightarrow\infty$$

$$E_0 = K_u^V\sin^2\phi$$

$$\Delta E_a = \frac{N}{\pi}\int_0^{\pi}E_0\,d\phi = \frac{NK_u^V}{2}\text{; minimized for } N\rightarrow 0$$

Magnetic Domains





$$\delta = N\,a \qquad \theta = \frac{\pi}{N}$$

$$\Delta E_{\text{tot}} = \Delta E_{\text{ex}} + \Delta E_a = \frac{\mathrm{J}S^2\pi^2}{N} + \frac{N K_u^V}{2}$$

$$\Delta E_{\text{ex}} = \frac{\mathrm{J}S^2\pi^2}{N}\text{ ; minimzed for } N \rightarrow \infty$$

Energy minimization $\Rightarrow N = \pi S \sqrt{\frac{2J}{K_u^V}}$

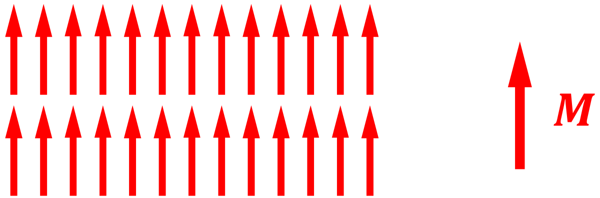
$$\Delta E_a = \frac{N K_{\mathrm{u}}}{2}\text{; minimized for } N \rightarrow 0$$

$$\delta = N\,a \approx 300\ \mathrm{nm}$$

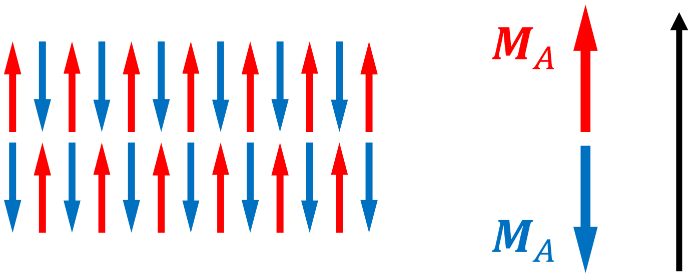
for $J = 1\ \mathrm{eV},\ K_u^V = 10^{-23}\mathrm{J},\ a\ = 1\ \mathrm{nm},\ S = \frac{1}{2}$

Without external magnetic field, ferromagnetic particles larger than some micrometers feature magnetic domains

Anisotropy in Ferromagnets and Antiferromagnets



Ferromagnet



Antiferromagnet

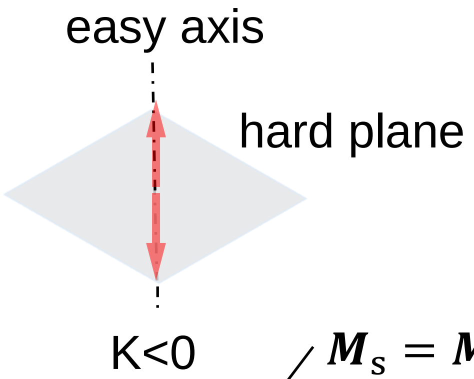
$$\boldsymbol{M} = \boldsymbol{M}_A + \boldsymbol{M}_B = 0$$

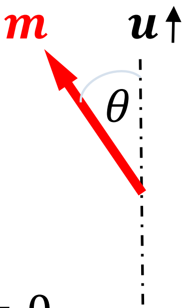
$$\boldsymbol{N} = \boldsymbol{M}_A - \boldsymbol{M}_B$$

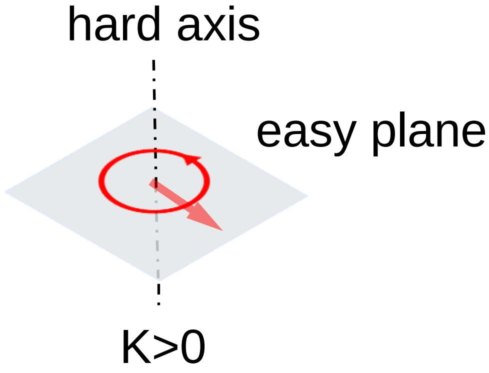
Néel Vector

For many purposes, it is practical to model AFMs as two antiferromagnetically coupled ferromagnetic sub-lattices

Anisotropy in Antiferromagnets





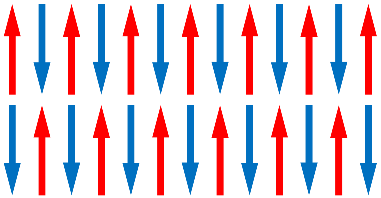


$$\boldsymbol{M}_s = \boldsymbol{M}_A + \boldsymbol{M}_B = 0$$

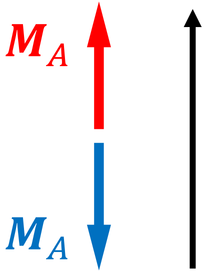
$$F_{\text{demag}} = \frac{\mu_0}{2} M_s^2 \left[N_x m_x^2 + N_y m_y^2 + N_z m_z^2\right] = 0$$

$$F_{\text{uniax}} = K_u \, m_u^2$$

$$F_{\text{cubic}} = K_c \left[m_a^2 \, m_b^2 + m_b^2 \, m_c^2 + m_a^2 \, m_c^2\right]$$



Antiferromagnet



$$\boldsymbol{N} = \boldsymbol{M}_A - \boldsymbol{M}_B$$

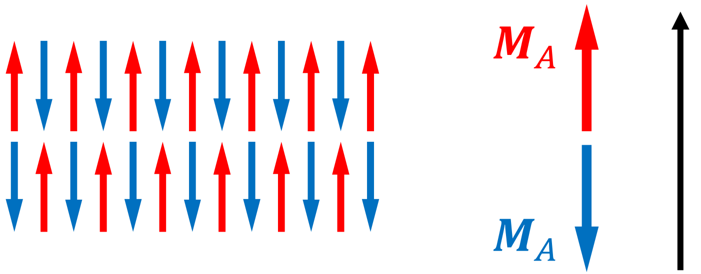
Néel Vector

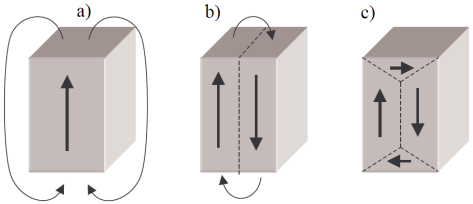
Other than demag, anisotropies still work the same in AFM!

Anisotropy in Antiferromagnets and Ferromagnets

$$\boldsymbol{M}_s = \boldsymbol{M}_A + \boldsymbol{M}_B = 0$$

$$F_{\text{demag}} = \frac{\mu_0}{2} M_s^2 \left[N_x m_x^2 + N_y m_y^2 + N_z m_z^2\right] = 0$$

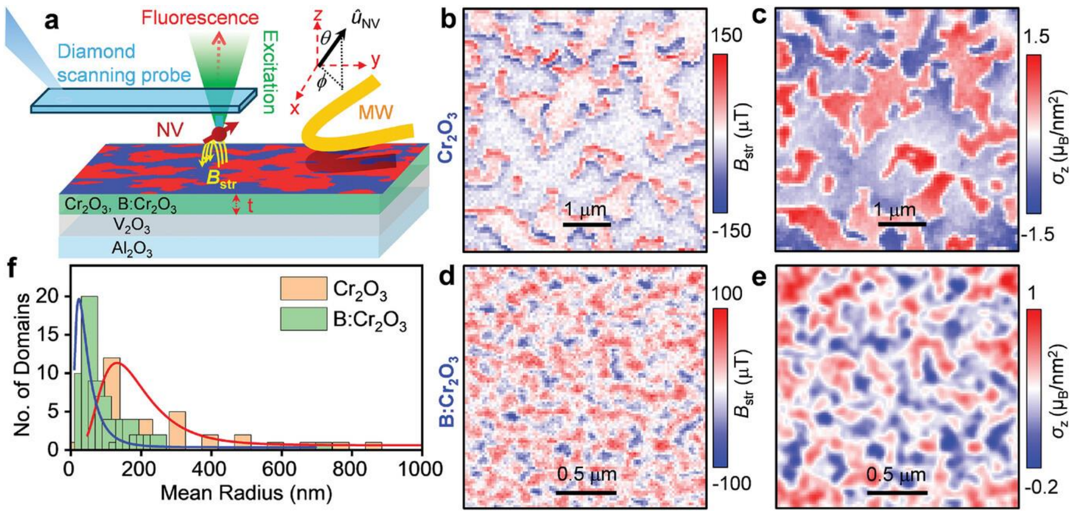




$$\boldsymbol{M}_s = 0 \;\rightarrow \boldsymbol{H}_D = 0$$

$$E_{\text{demag},\,AFM} = -\frac{\mu_0}{2} \int \boldsymbol{M} \cdot \boldsymbol{H}_D \, dV = 0$$

- Experimental observation : AFM have small domains – why?



Adv. Funct. Mater. **34**, 2408542 (2024)

Magnetostriction

- We have so far ignored one important contribution to anisotropy: magnetostriction

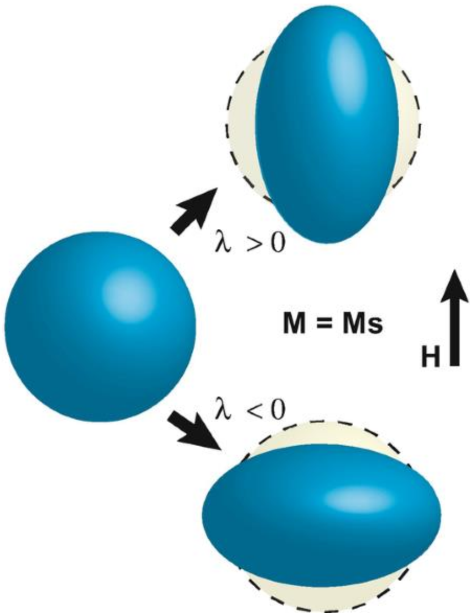
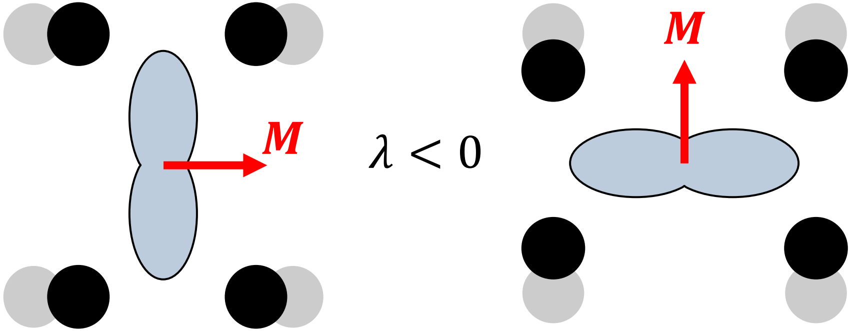


Image: Handbook of Magnetism and Magnetic Materials

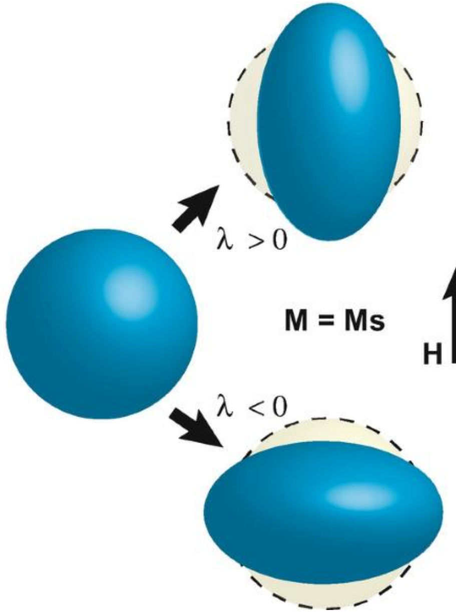
Spin-orbit interaction + crystal field



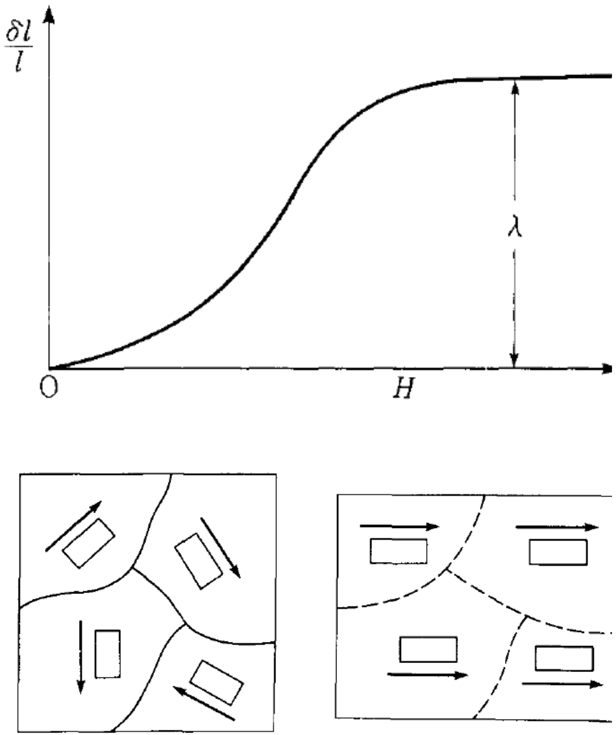
Magnetized bodies change their shape: Magnetostriction

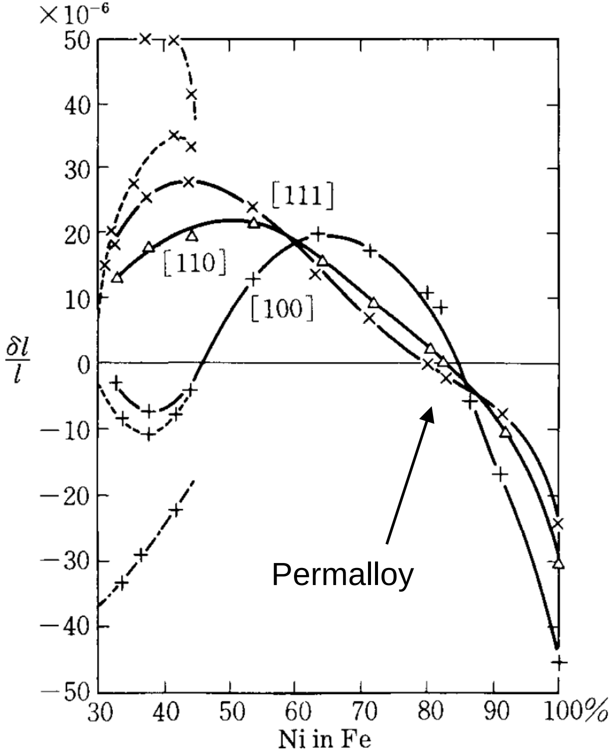
Strain modifies magnetization orientation: Magnetoelasticity

Magnetostriction



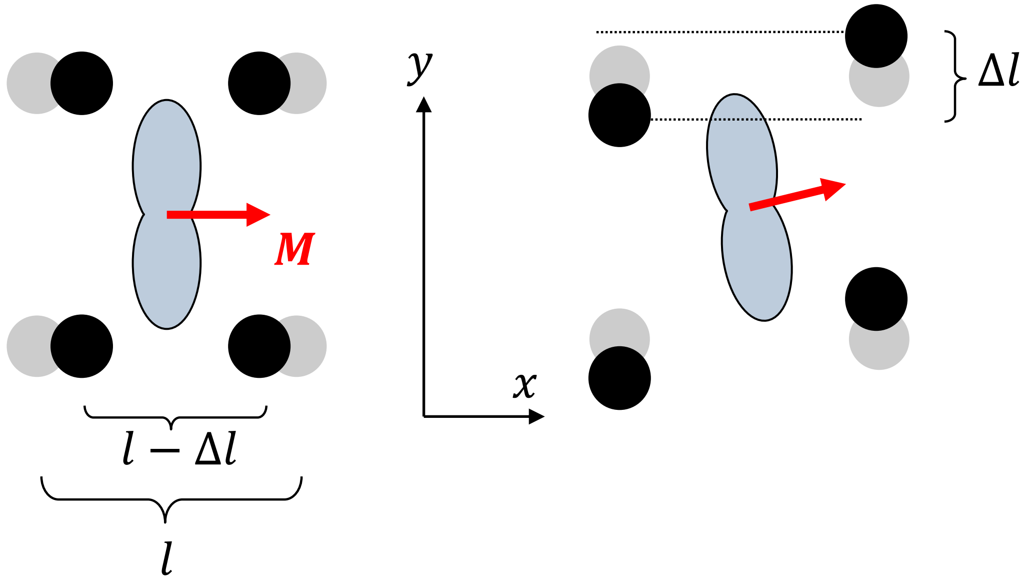
Handbook of Magnetism and Magnetic Materials





Chikazumi: Physics of Ferromagnetism

Magnetoelastic free energy density



$$G_{\text{tot}} = G_{\text{demag}} + G_{\text{uniax}} + \\ + G_{\text{cubic}} + G_{ME} + G_{\text{Z}}$$

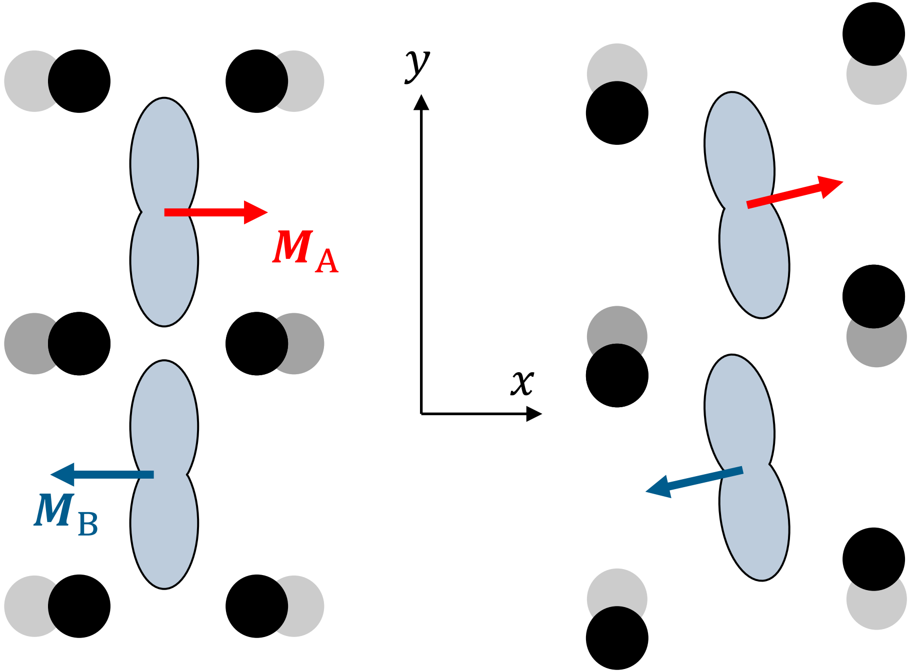
$$\mu_0 \boldsymbol{H}_{\text{eff}} = -\nabla_{\boldsymbol{m}} G_{\text{tot}}$$

$$b_1, b_2 \approx 10\ \text{T}$$

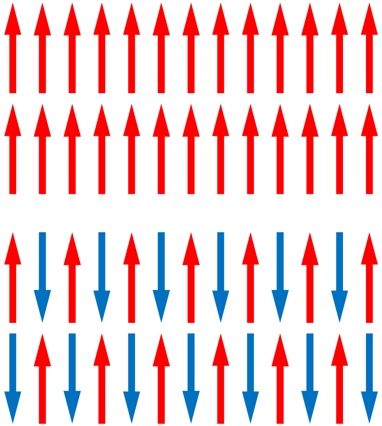
pure strain: $\varepsilon_{xx} = \dfrac{\Delta l_x}{l_x}$ shear strain: $\varepsilon_{xy} = \dfrac{\Delta l_y}{l_x}$

$$G_{\text{ME}} = b_1\left[\varepsilon_{xx} m_x^2 + \varepsilon_{yy} m_y^2 + \varepsilon_{zz} m_z^2\right] + 2b_2\left[\varepsilon_{xy} m_x m_y + \varepsilon_{xz} m_x m_z + \varepsilon_{yz} m_y m_z\right]$$

Magnetoelastic ferromagnets and antiferromagnets



Magnetostriction and magnetoelasticity work for FM and AFM!

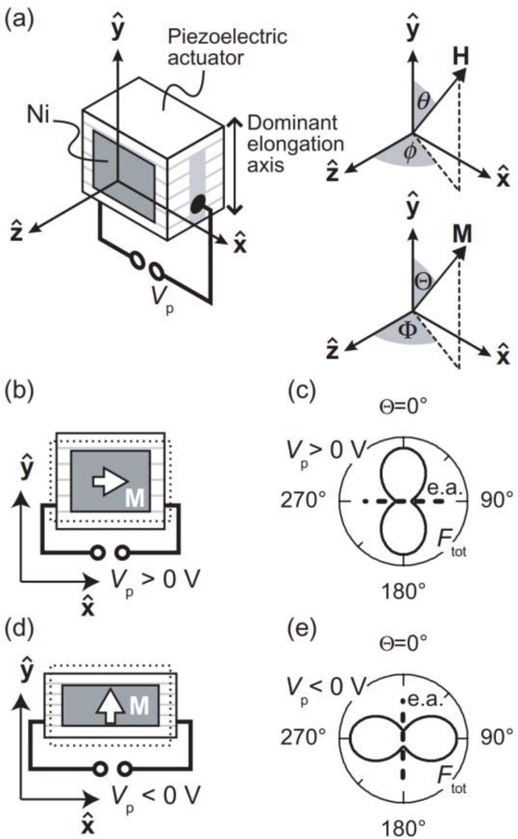


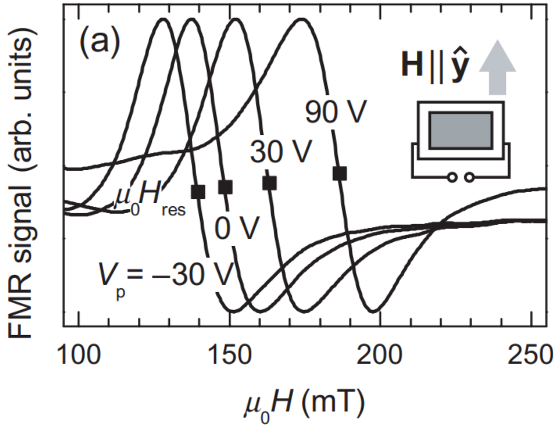
$$G_{\mathrm{ME}}^{A} = b_1\left[\varepsilon_{xx}m_{Ax}^2 + \varepsilon_{yy}m_{Ay}^2 + \varepsilon_{zz}m_{Az}^2\right] + 2b_2\left[\varepsilon_{xy}m_{Ax}m_{Ay} + \varepsilon_{xz}m_{Ax}m_{Az} + \varepsilon_{yz}m_{Ay}m_{Az}\right]$$

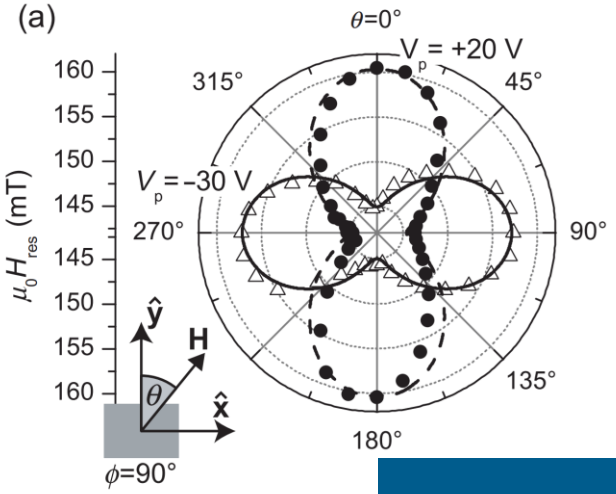
$$G_{ME} = G_{\mathrm{ME}}^{A} + G_{\mathrm{ME}}^{B} = 2G_{\mathrm{ME}}^{A}$$

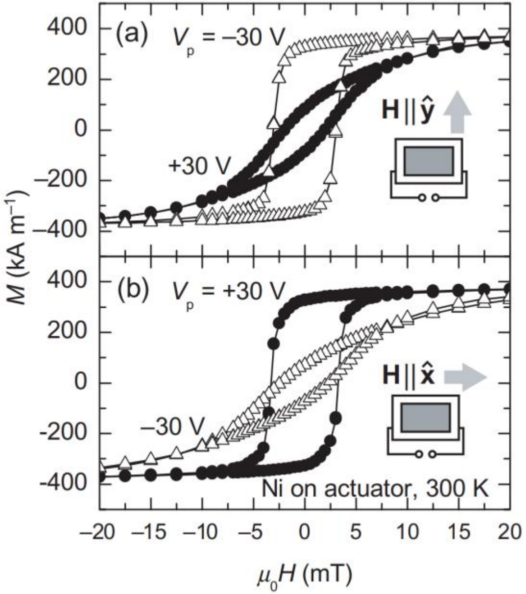
Balancing elastic energy and magnetoelastic energy: Domains in AFM

Magnetoelastic control of anisotropy









Strain controls anisotropy

New J. Phys. **11**, 013021 (2009)

Interaction of sound and spin

RPTU

Interaction of Spin Waves and Ultrasonic Waves in Ferromagnetic Crystals*

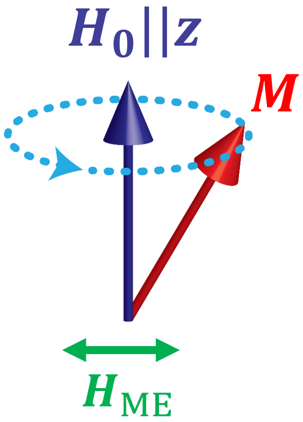
C. Kittel
Department of Physics, University of California, Berkeley, California
(Received January 9, 1958)

Phys. Rev. **110**, 836 (1958)

Magnetoelastic free energy contribution: $m_z \approx 1 \gg m_x, m_y$

$$G_{\mathrm{ME}} = b_1\left[\varepsilon_{xx} m_x^2 + \varepsilon_{yy} m_y^2 + \varepsilon_{zz} m_z^2\right] + 2b_2\left[\varepsilon_{xy} m_x m_y + \varepsilon_{xz} m_x m_z + \varepsilon_{yz} m_y m_z\right]$$

Compressional strain — Shear strain



$$\mu_0 \boldsymbol{H}_{\mathrm{ME}} = -\nabla_{\boldsymbol{m}} G_{\mathrm{ME}} \approx 2b_2 \begin{pmatrix} \varepsilon_{xz} \\ \varepsilon_{yz} \\ 0 \end{pmatrix}$$

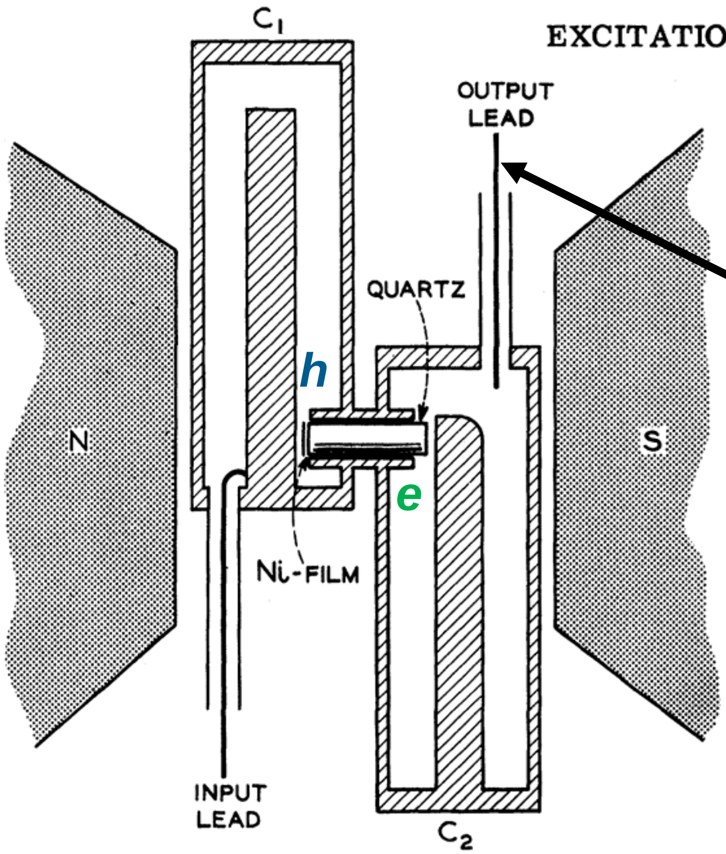
$b_2 \approx 10\ \mathrm{T}$
$\varepsilon \approx 10^{-3}$
$\mu_0 H_{\mathrm{ME}} \approx 10\ \mathrm{mT}$

$$\frac{\partial \boldsymbol{M}}{\partial t} = -\gamma\mu_0\, \boldsymbol{M} \times \boldsymbol{H}_{\mathrm{eff}}$$

$$\boldsymbol{H}_{\mathrm{eff}} = \boldsymbol{H}_0 + \boldsymbol{H}_{\mathrm{ME}} + \cdots$$

Phys. Rev. B **86**, 134415 (2012)

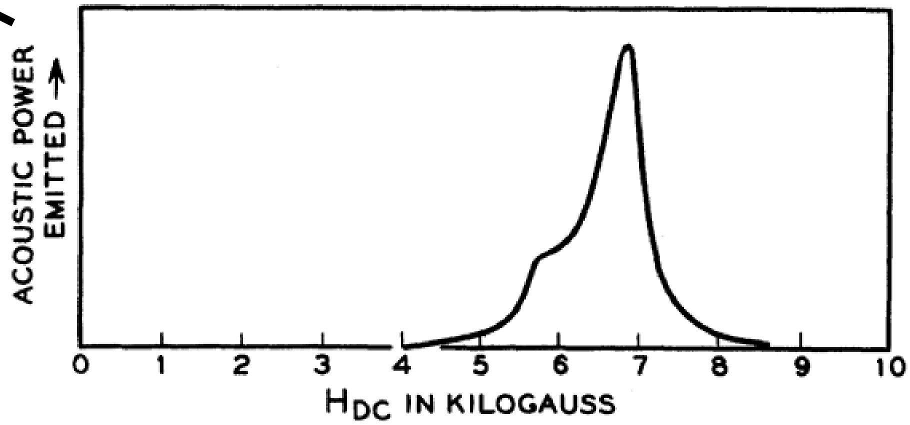
Interaction of sound and spin



EXCITATION OF HYPERSONIC WAVES BY FERROMAGNETIC RESONANCE

H. Bömmel and K. Dransfeld
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received June 18, 1959)

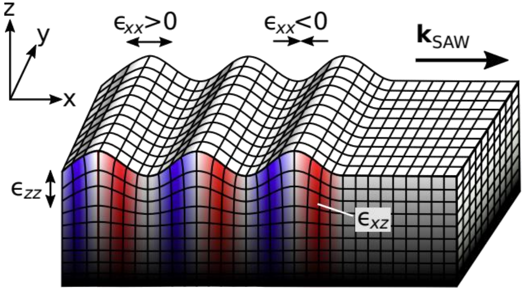
Phys. Rev. Lett. **3**, 83 (1959)



FMR ↔ Soundwave ↔ E-Field

Surface Acoustic Wave + Magnetic thin films

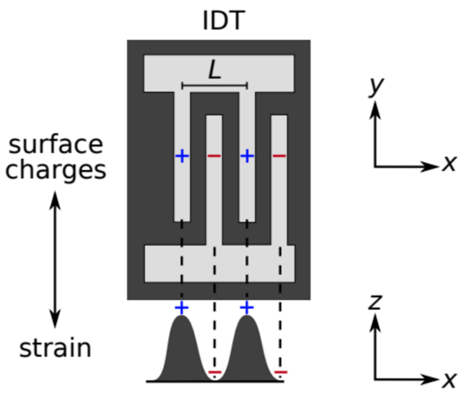
RPTU

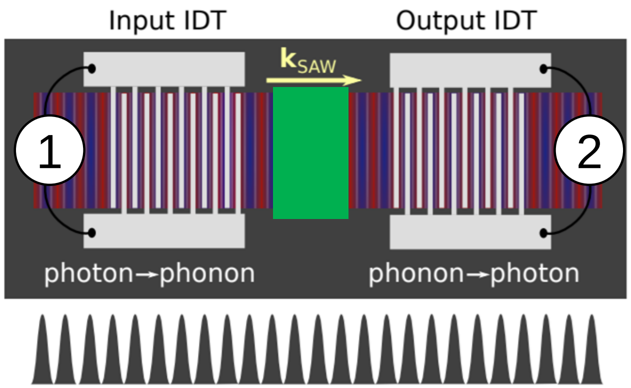


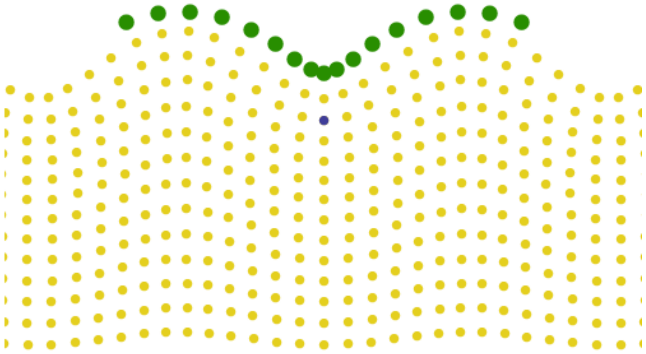
Surface Acoustic Wave (SAW)

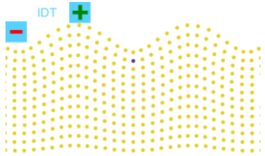
Macroscopic: Earthquake

Microscopic: Mobile communication



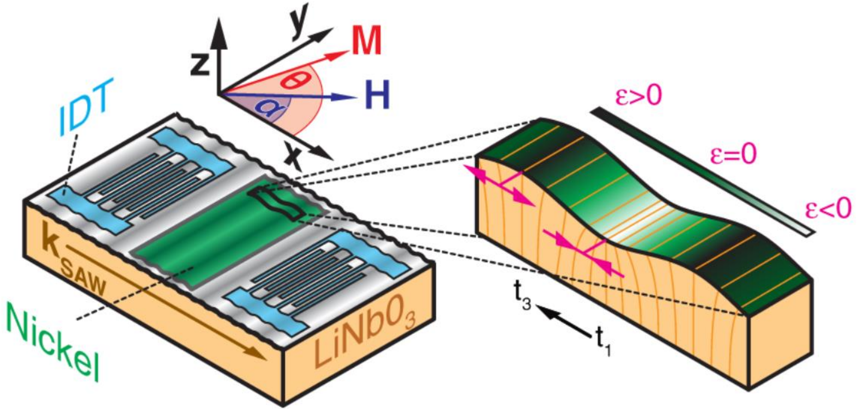


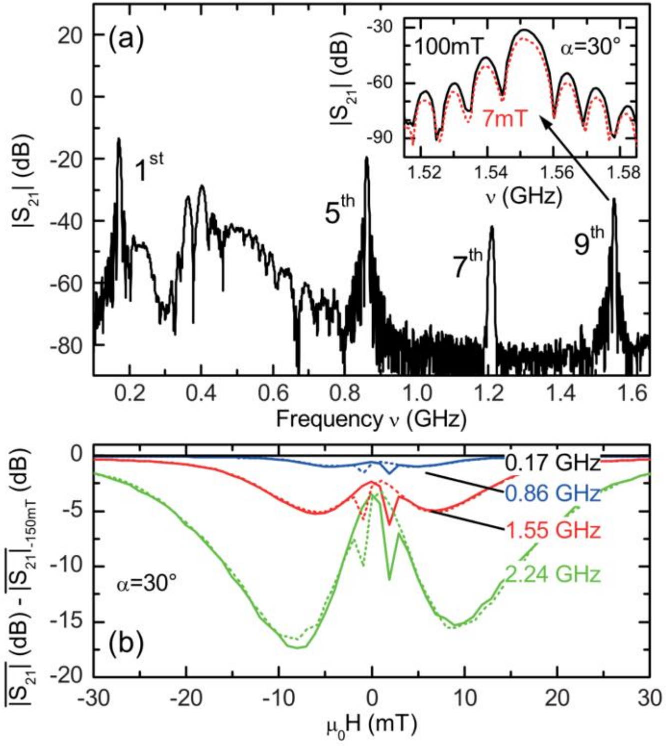




Interdigital transducer (IDT)

Interaction of sound and spin





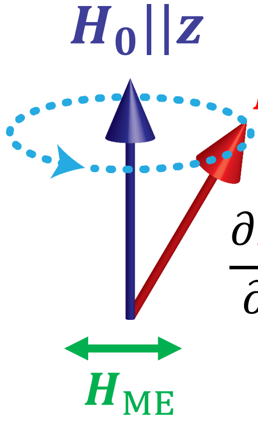
Phys. Rev. Lett. **106**, 117601 (2011)

Symmetry of the magneto-acoustic interaction

Magnetoelastic free energy contribution:

$$G_{\mathrm{ME}} = b_1 \left[\varepsilon_{xx} m_x^2 + \varepsilon_{yy} m_y^2 + \varepsilon_{zz} m_z^2\right] + 2b_2\left[\varepsilon_{xy} m_x m_y + \varepsilon_{xz} m_x m_z + \varepsilon_{yz} m_y m_z\right]$$

Pure strain — Shear strain



$$\mu_0 \boldsymbol{H}_{\mathrm{ME}} = -\nabla_{\boldsymbol{m}} G_{\mathrm{ME}}$$

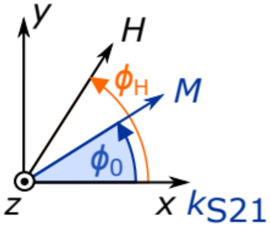
$$\boldsymbol{H}_{\mathrm{eff}} = \boldsymbol{H}_0 + \boldsymbol{H}_{\mathrm{ME}} + \cdots$$

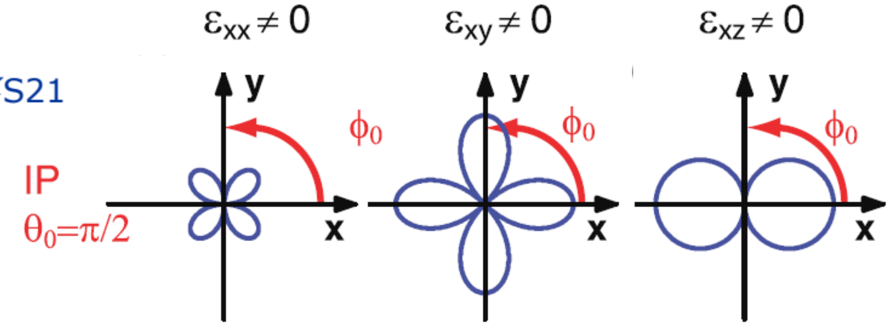
$b_{1,2} \approx 10\ \mathrm{T}$

$\varepsilon \approx 10^{-3}$

$\mu_0 H_{\mathrm{ME}} \approx 10\ \mathrm{mT}$

$$\frac{\partial \boldsymbol{M}}{\partial t} = -\gamma\mu_0\, \boldsymbol{M} \times \boldsymbol{H}_{\mathrm{eff}}$$

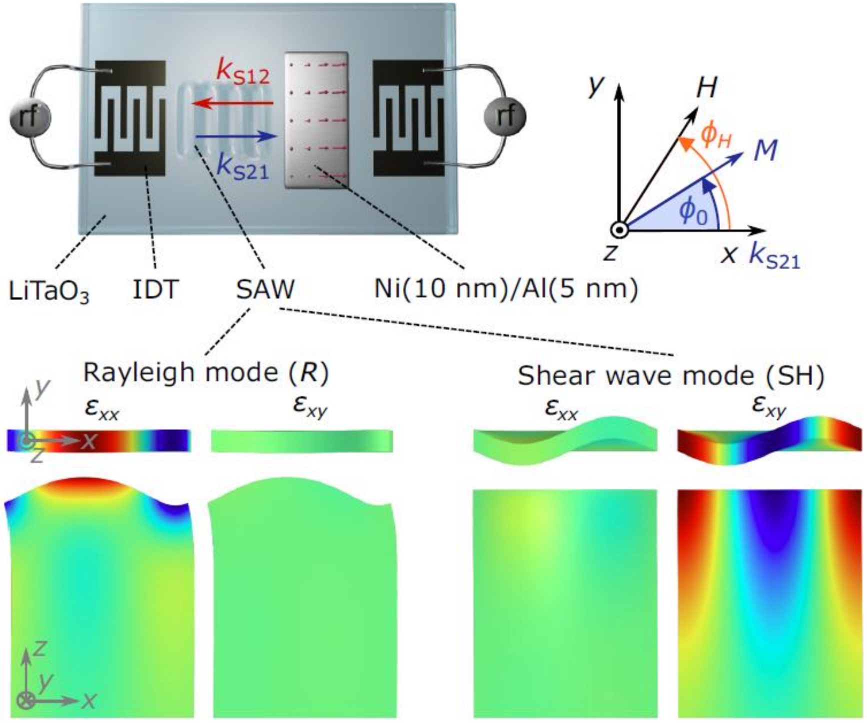




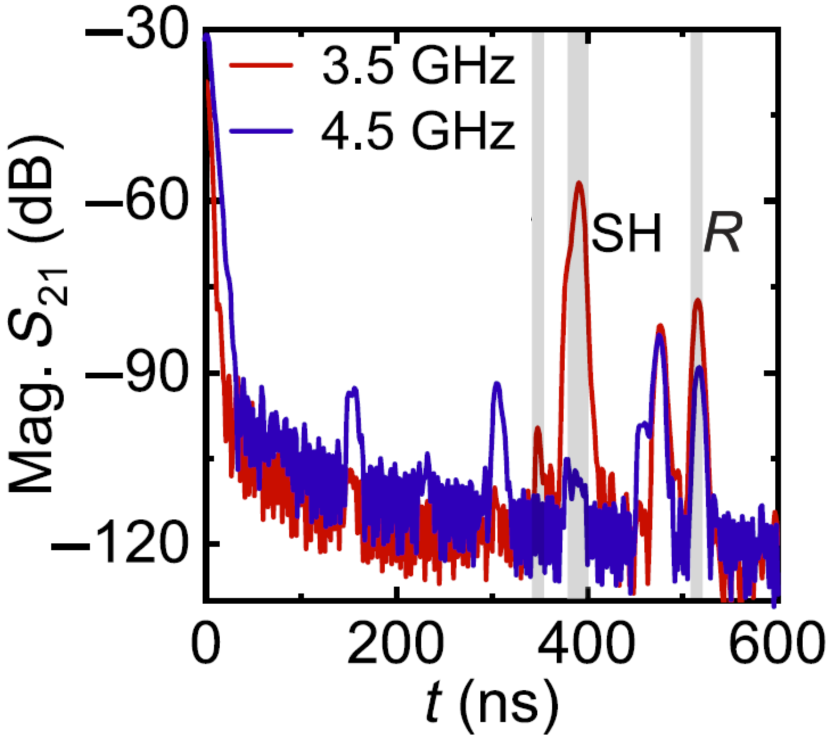
Phys. Rev. **110**, 836 (1958),
Phys. Rev. Lett. **3**, 83 (1959)
Phys. Rev. B **86**, 134415 (2012)

Symmetry of the magneto-acoustic interaction

RPTU

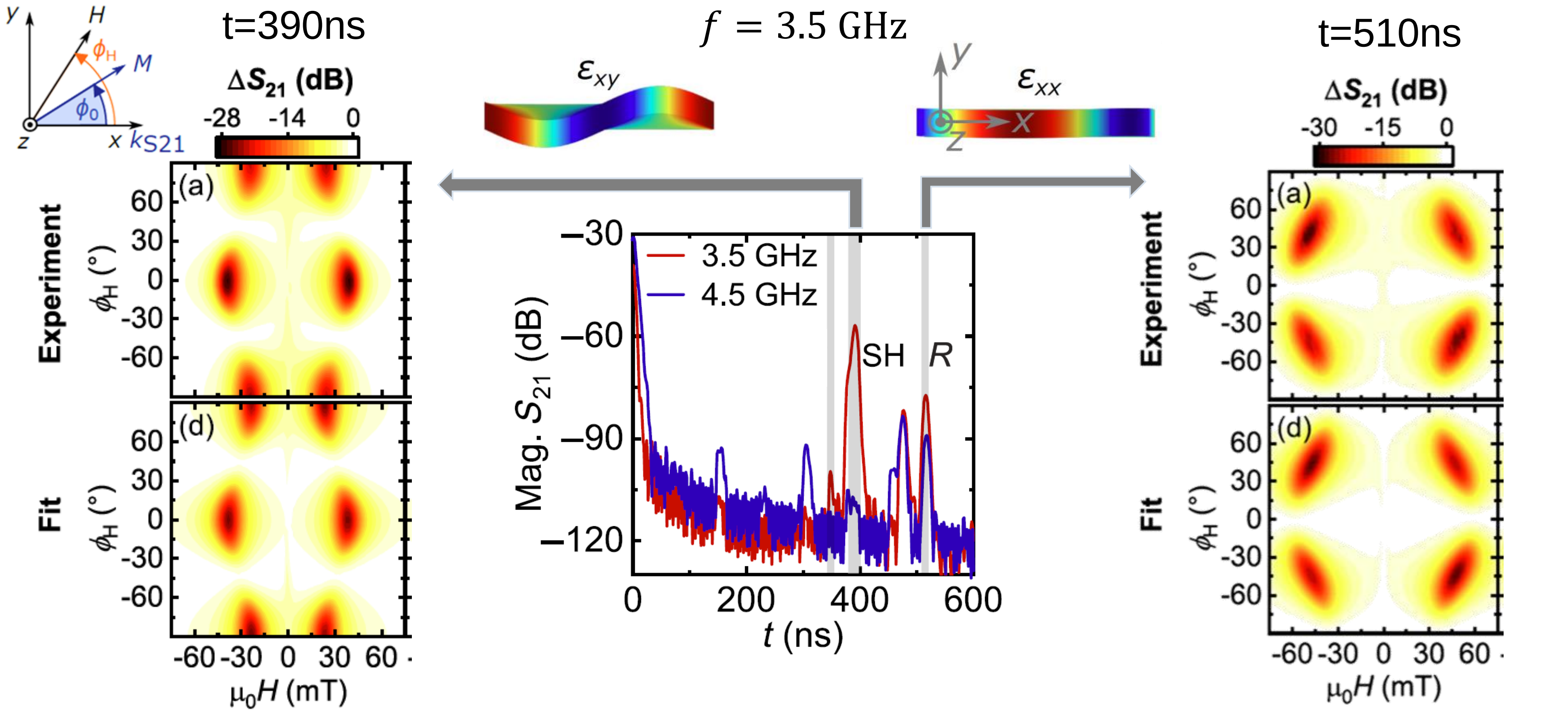


$$v_{\mathrm{R}} = 3105\,\frac{\mathrm{m}}{\mathrm{s}} \qquad v_{\mathrm{SH}} = 4075\,\frac{\mathrm{m}}{\mathrm{s}}$$



Symmetry of the magneto-acoustic interaction

RPTU



$\mu_0 h \propto \varepsilon_{xz} \cos{(2\phi_0)}$

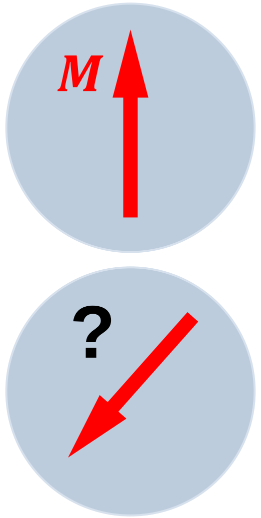
$\mu_0 h \propto \varepsilon_{xx} \sin\phi_0 \cos\phi_0$

Phys. Rev. Applied **15**, 034046 (2021)

Summary

Magnetic anisotropy

- Required for stable net magnetic moment
- Originates from shape (stray fields), or spin-orbit interaction
- Described by magnetic free energy density or effective fields
- Impacts magnetization dynamics



Magnetostriction & Magnetoelasticity

- Strain controls magnetization direction and vice versa
- Strain generates effective magnetic fields
- Alternating strain can drive magnetization dynamics