Magnetic Anisotropy

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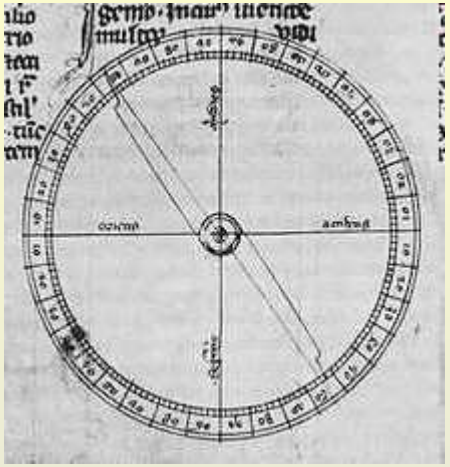
1. **relevance and definition of Magnetic Anisotropy – MA**
2. **phenomenological description of MA**
3. **microscopic origin of MA**
4. **theoretical description of MA**
5. **how to measure the strength of MA**
6. **symmetry and MA**
7. **tailoring and manipulating MA**
8. **summary**

1. Relevance and definition of Magnetic Anisotropy

early application of magnetic materials: ***the magnetic compass***

Model of a Han Dynasty (206 BC–220 AD) south-indicating ladle or *sinan*.



Pivoting compass needle in a 14th century copy of *Epistola de magnete* of Peter Peregrinus (1269)

How a magnetic compass works (Wikipedia):

A compass functions as a pointer to "magnetic north" because the magnetized needle at its heart aligns itself with the lines of the Earth's magnetic field. The magnetic field exerts a torque on the needle, pulling one end or pole of the needle toward the Earth's North magnetic pole, and the other toward the South magnetic pole

Origin of magnetic torque?

magnetic dipole in a uniform magnetic field:

$$E_m = -V \cdot \vec{M} \cdot \vec{B} = -V \cdot M \cdot B \cdot \cos\varphi$$ *Zeeman energy*

$\varphi = \angle$(M,B)

torque exerted on the ***magnetization*** $$T = \frac{dE_m}{d\varphi} = V \cdot M \cdot \sin\varphi$$

$$\vec{T} = V \cdot \vec{M} \times \vec{B}$$

$\Rightarrow$ stable equilibrium for $\varphi = 0$
i.e. ***M*** aligned with ***B***

torque on the ***needle***? $$T' = \frac{dE_a}{d\phi}$$ $\phi = \angle$(M, needle)

$\Rightarrow T' \neq 0$ only if $E_a = E_a(\phi)$, i.e. ***if magnetic anisotropy is present !!***

$$E_a(\phi_i) = V \cdot \varepsilon_a(\phi_i)$$ **anisotropy energy** $$\phi_i = \angle(\vec{M}, \vec{e}_i)$$

other applications of MA

- strong/large MA (*hard magnetic materials*)
  - permanent magnets
  - electric motors
  - loudspeakers, microphones
  - magnetic memories
  - . . .

- weak/small MA (*soft magnetic materials*)
  - transformers
  - electromagnets
  - electric motors
  - magnetic field sensors
  - . . .

2. phenomenological description of MA

required: $E_a(\phi_i) = V \cdot \varepsilon_a(\phi_i) \qquad \phi_i = \angle(\vec{M}, \vec{e}_i)$

series expansion $\varepsilon_a(\phi_i) = K_0 + K_1 \cdot F_1(\phi_i) + K_2 \cdot F_2(\phi_i) + ...$

$\leftrightarrow$ set of functions ***according to symmetries***

e.g. even functions of ϕ_i for inversion symmetry

K_i …. anisotropy constants

Remarks

i) concept of MA inplies uniform ***M !***

ii) MA different from anisotropy of M_S: $\leftrightarrow$ m_{orb}, m_{spin} , SOC

0.01 - 0.1% - effect in bulk cubic materials

% - effect at surfaces / in ML films

iii) anisotropic exchange interaction

$\mathcal{H} = \vec{D}_{12} \cdot (\vec{S}_1 \times \vec{S}_2)$ *Dzyaloshinski-Moriya interaction*

$\Rightarrow$ non-collinear spin structures

2. phenomenological description of MA

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$\leftrightarrow$ set of functions ***according to symmetries***

e.g. even functions of ϕ_i for inversion symmetry

K_i …. anisotropy constants

example: (uni)axial symmetry $\varepsilon_a = K_0 + K_1 \cdot \sin^2\varphi + K_2 \cdot \sin^4\varphi + ...$

hexagonal crystals, …

φ = $\angle$(M,symmetry axis)

uniaxial magnetic anisotropy (UMA) with $\varepsilon_a = K_U \cdot \sin^2\varphi$

K_U>0: easy axis, hard plane

K_U<0: hard axis, easy plane

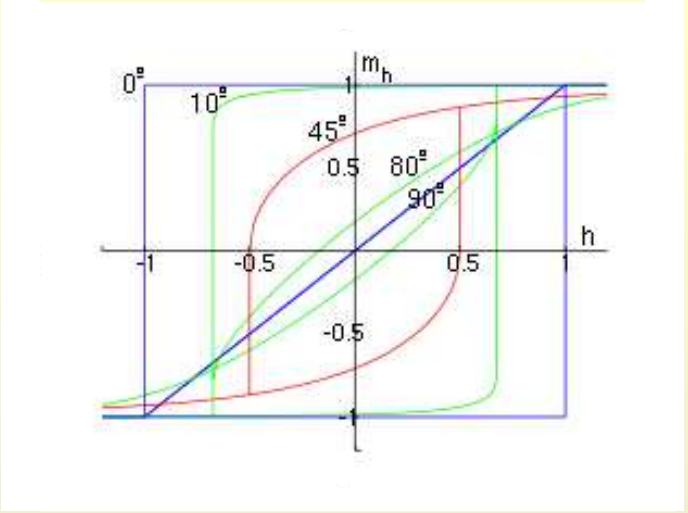
magnetization reversal in a uniaxial magnetic particle/film

by coherent rotation **Stoner-Wohlfarth model**

$$\varepsilon_m = K_U \cdot \sin^2 \varphi - \vec{M} \cdot \vec{H}$$

$$\frac{d\varepsilon_m}{d\varphi} = 0$$

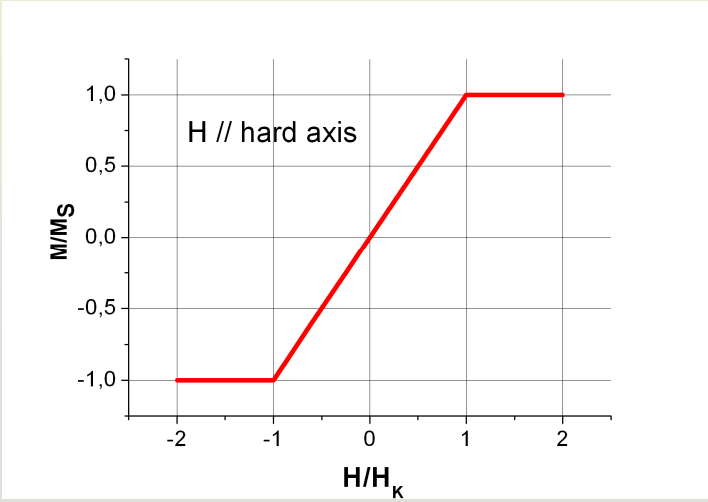
$\Rightarrow$

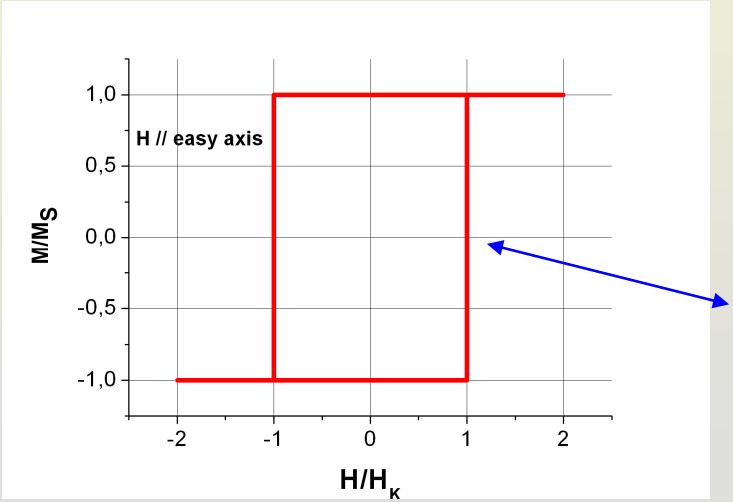


$$h = \frac{H}{H_K}$$

$$H_K = \frac{2K_U}{M_S}$$

anisotropy field





real materials:

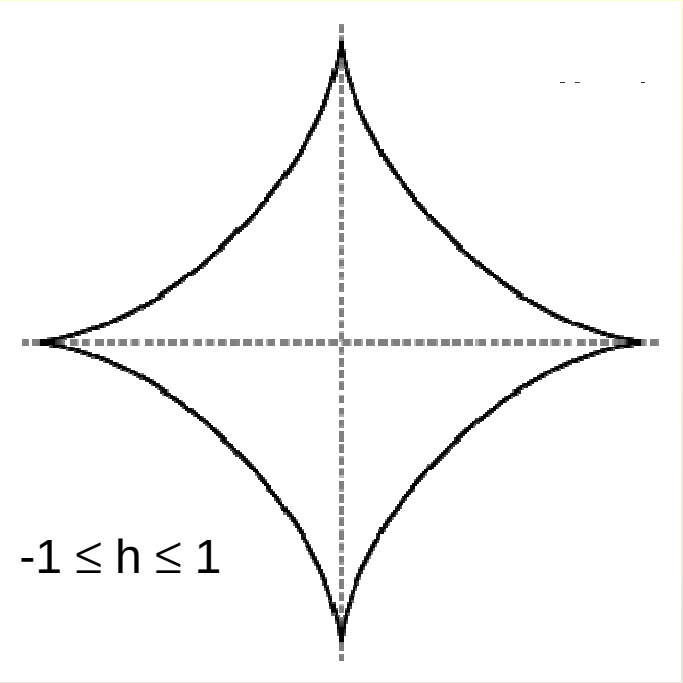
$H_C < H_K$

$\leftrightarrow$ *domain formation!*

switching field $H_{sw}(\alpha)$: ***Stoner-Wohlfarth astroid***

$$\frac{d\varepsilon_m}{d\varphi} = 0$$

$$\frac{d^2\varepsilon_m}{d\varphi^2} = 0$$

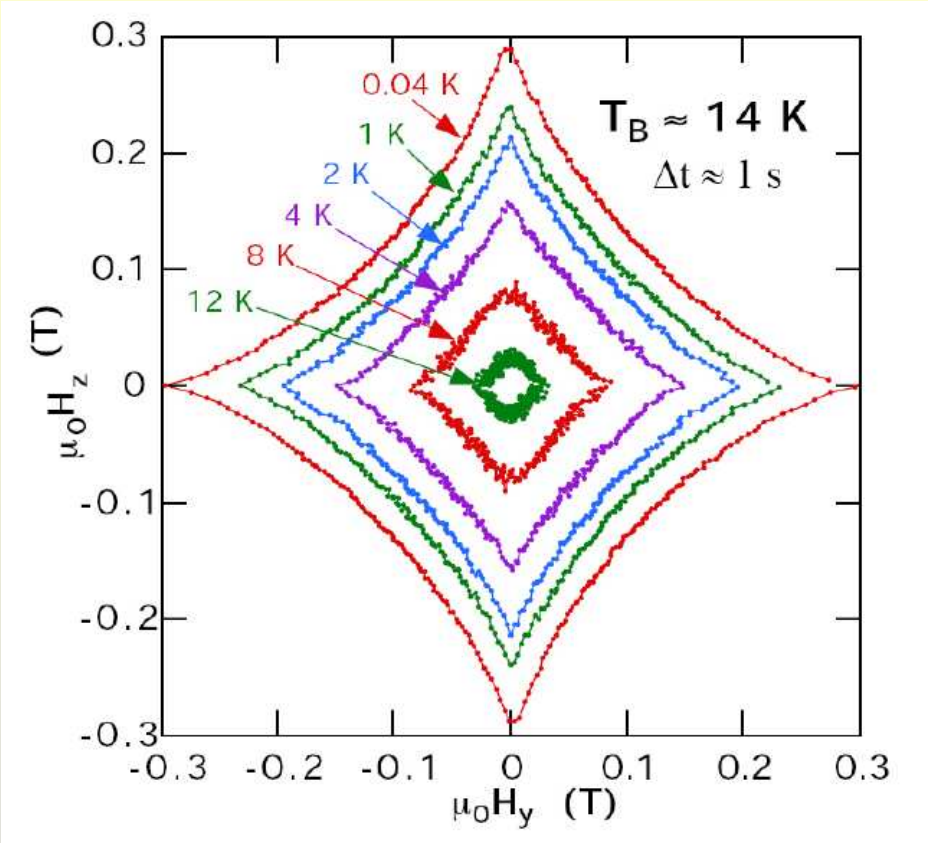


behaviour observed in sub-micron particles (*smaller than domain-wall width*):

W. Wernsdorfer et al., arXiv:cond-mat/0106035v1

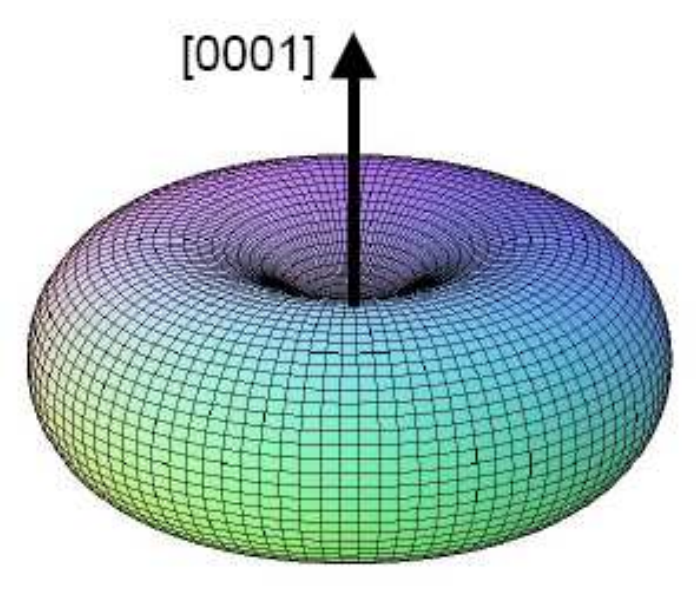
"Magnetization reversal by uniform rotation (Stoner-Wohlfarth model) in f.c.c. cobalt nanoparticles"

Jamet, Wernsdorfer et al., Phys. Rev. Lett. 86, 4676, 2001



3 nm Co cluster, micro-SQUID measurement
Wernsdorfer et al., PRL 2002

ε_a surfaces for different UMA cases: $\varepsilon_a(\varphi_i)$



$K_1 > 0,\ K_2 = 0$

ε_a surfaces for different UMA cases: $\varepsilon_a(\varphi_i)$

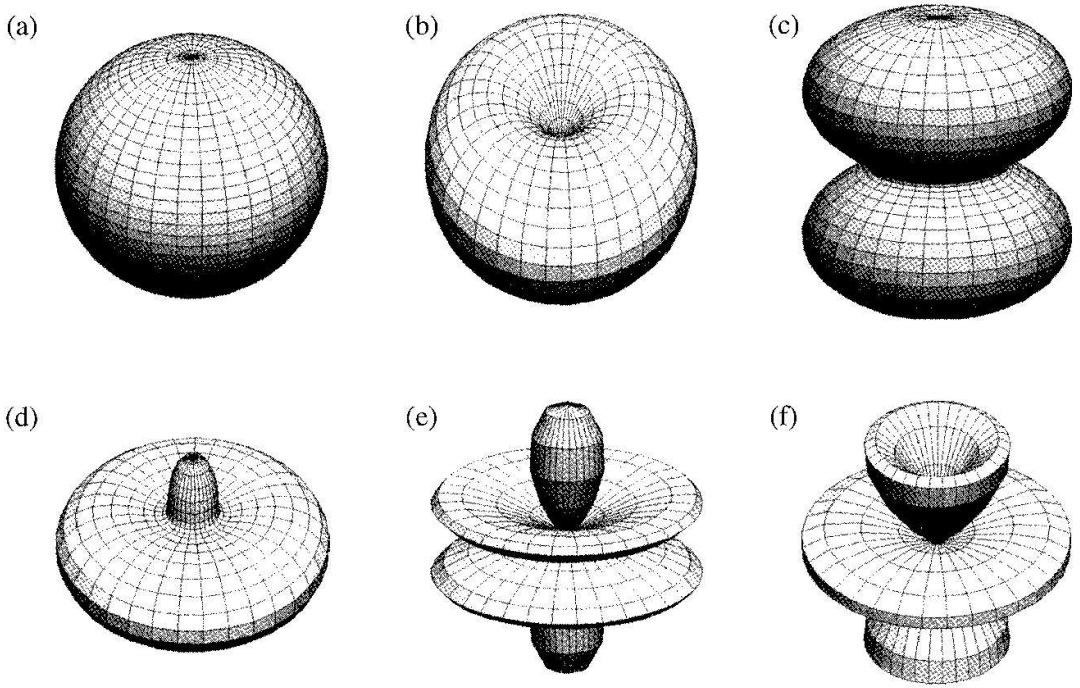


Fig. 3.2 Uniaxial anisotropy-energy landscapes: (a) isotropic, (b) easy axis, (c) easy plane, (d) easy cone, and (e–f) sixth-order landscapes.

d) for $K_1 < 0$, $K_2 > -K_1/2$

from: R. Skomski, "Simple Models of Magnetism "
Oxford University Press, 2008

$$H_K = \frac{2K_U}{M_S}$$

H_K sometimes treated as a <u>vector field</u>:

H_K // e.a. in FMR experiments $\Rightarrow$ $\boldsymbol{H_{eff} = H + H_K}$ for H // e.a.

caution !! $\rightarrow$ ***tensor quantity*** $\boldsymbol{H_{eff} = H - H_K}$ for H // h.a.

e.g. 2 x UMA with orthogonal e.a.

?

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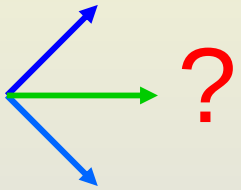

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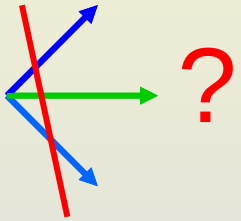

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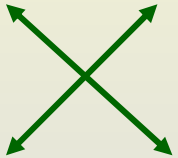


$$\varepsilon_a = K_U \cdot \sin^2 \varphi + K_U \cdot \sin^2(\tfrac{\pi}{2} - \varphi)$$
$$= K_U \cdot (\sin^2 \varphi + \cos^2 \varphi) = K_U$$

$\Leftrightarrow$ ***isotropic behavior !***

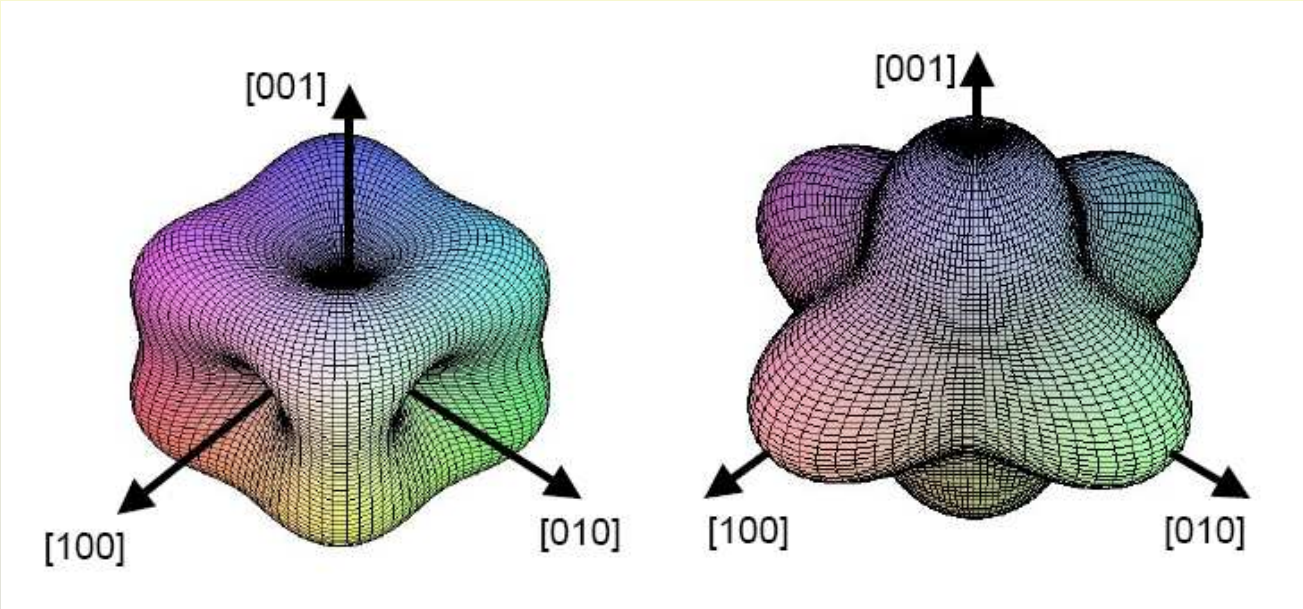
general case: **2 x UMA** $\rightarrow$ **UMA**

biaxial anisotropy not by superposition of 2 x UMA !!

cubic symmetry – *bcc-Fe, fcc-Ni, fcc-Co, alloys …*

$$\varepsilon_a = K_0 + K_1 \cdot (\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + K_2 \cdot \alpha_1^2\alpha_2^2\alpha_3^2 + ...$$

α_i = cos ∠(***M***,***e***$_i$)



$K_1 > 0$ (***Fe***), $K_2 = 0$ $K_1 < 0$ (***Ni***), $K_2 = 0$

cubic symmetry – *bcc-Fe, fcc-Ni, fcc-Co, alloys …*

$$\varepsilon_a = K_0 + K_1 \cdot (\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + K_2 \cdot \alpha_1^2\alpha_2^2\alpha_3^2 + ...$$

$\alpha_i = \cos \angle(\boldsymbol{M},\boldsymbol{e}_i)$

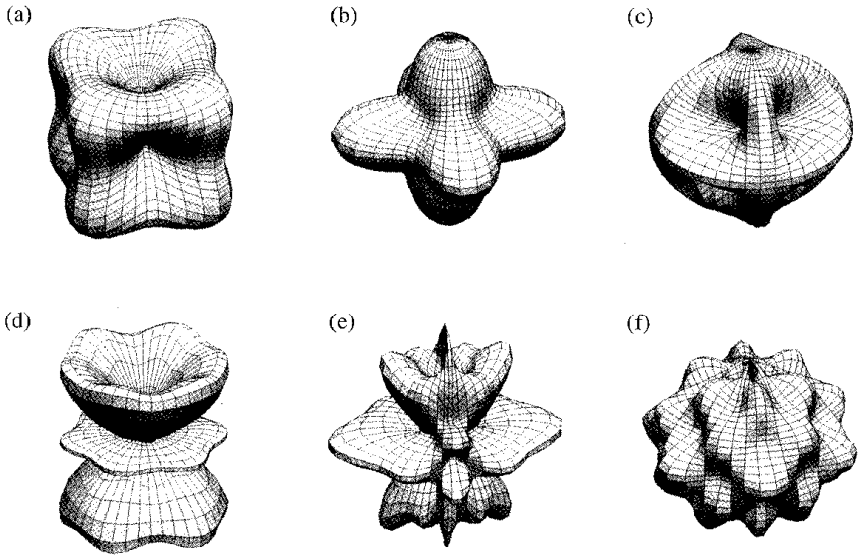


Fig. 3.3 Energy surfaces for higher-order anisotropies: (a–c) cubic magnets and (d–f) magnets with low symmetry.

a) $K_1 > 0$ (***Fe***), $K_2 = 0$

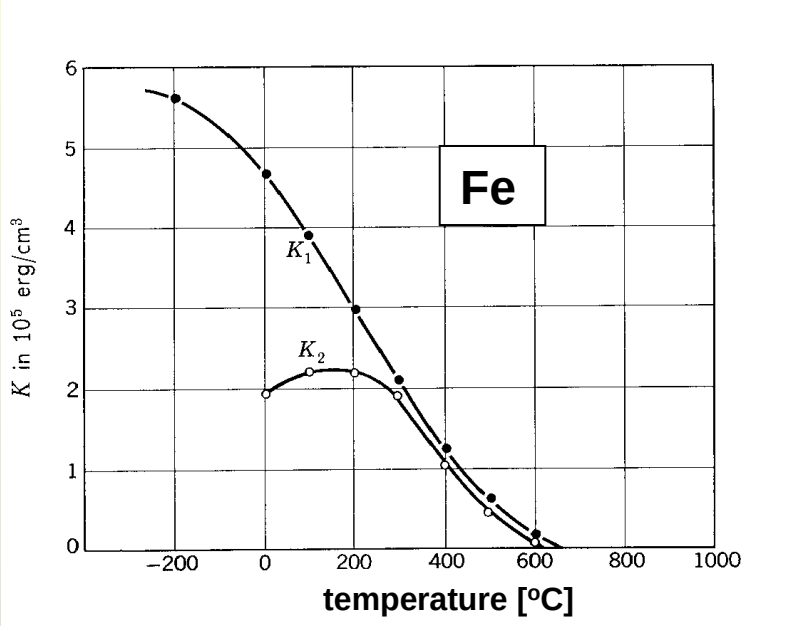
b) $K_1 < 0$ (***Ni***), $K_2 = 0$

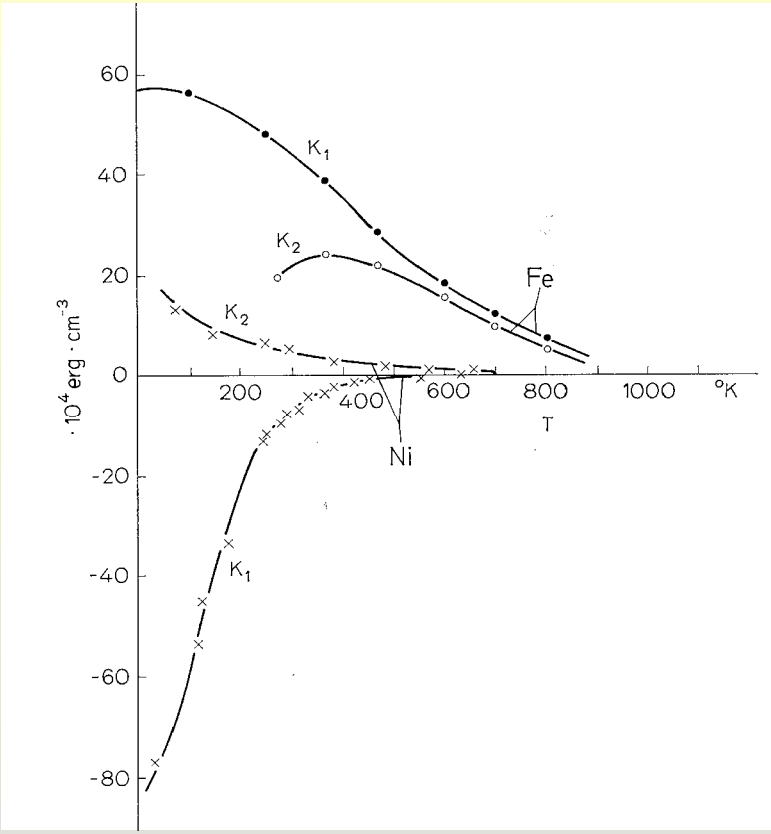
c) $K_1 \neq 0$, $K_2 > 0$

from: R. Skomski, "Simple Models of Magnetism "

Further remarks:

i) K_i vary with temperature





Further remarks:

i) K_i vary with temperature

ii) K_i values not unique, e.g. K_2 and K_3 for ***Fe***; why?

- methods!
- slow convergence; K_i not independent $\leftrightarrow$
  series expansion not orthogonal,not normalized

iii) K_i not "material property"; e.g. K_i vary with film thickness

3. microscopic origin of MA

magnetic order due to *exchange interaction;*
Heisenberg-type exchange interaction is ***isotropic***

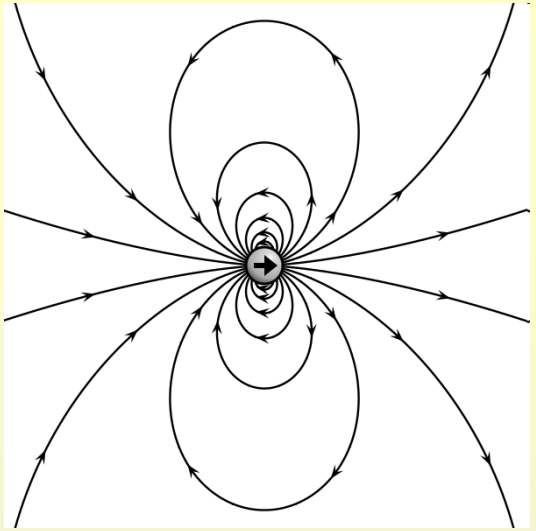
MA results from two fundamental interactions**:**

- dipolar (dipole-dipole) interaction
- spin-orbit interaction/coupling (SOC)

3.1 dipolar interaction

field of a point dipole $\vec{m}$

$$\vec{B}_d(\vec{r}) = \frac{\mu_0}{4\pi}\frac{3(\vec{m}\cdot\vec{r})\vec{r} - r^2\vec{m}}{r^5}$$



potential energy of two dipoles

$$E_{dd}(\vec{r}_i,\vec{r}_j) = -\frac{1}{4\pi\mu_0}\frac{3\vec{m}_i\cdot\vec{R}_{ij}\vec{m}_j\cdot\vec{R}_{ij} - \vec{m}_i\cdot\vec{m}_j R_{ij}^2}{R_{ij}^5}$$

$$\vec{R}_{ij} = \vec{r}_i - \vec{r}_j$$

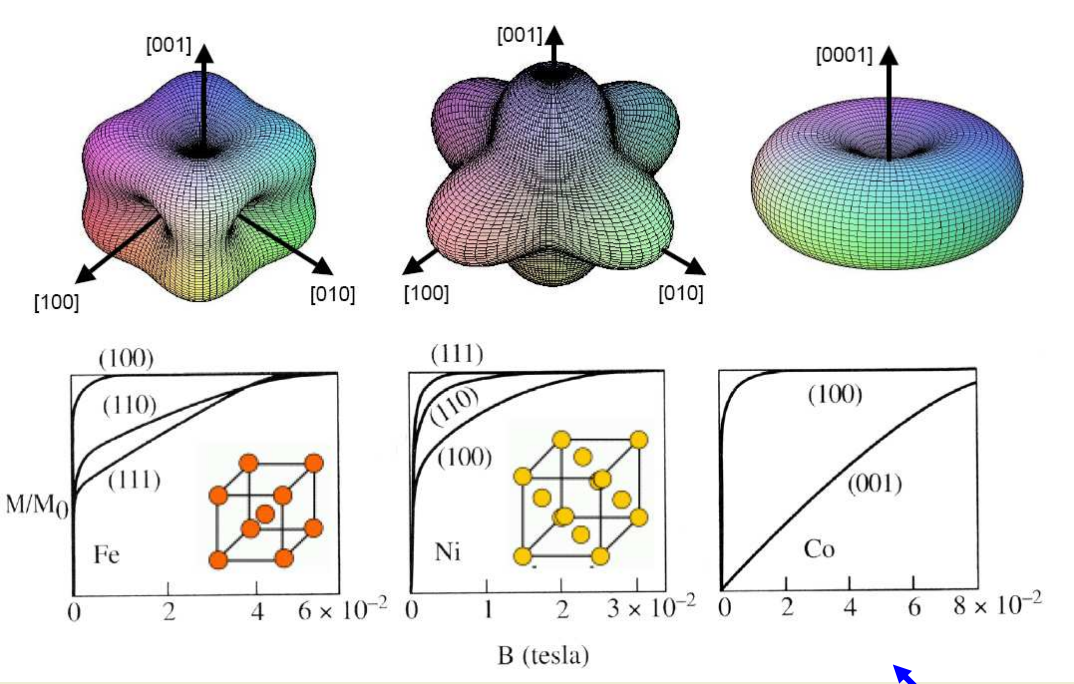
dipolar energy of a lattice of point dipoles

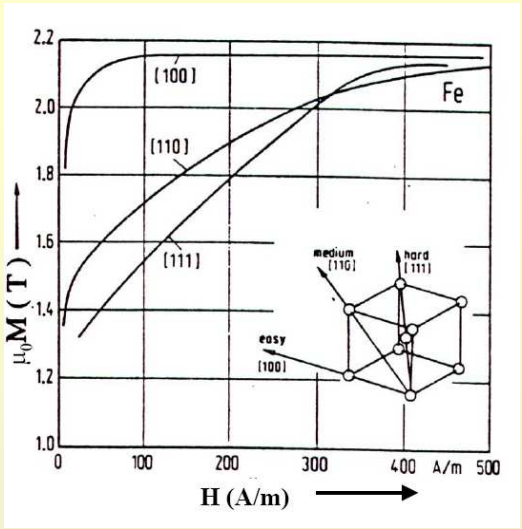
$$E_d = \sum_{i,j} E_{dd}(\vec{r}_i,\vec{r}_j)$$

$E_d \neq 0$ for non-cubic lattices

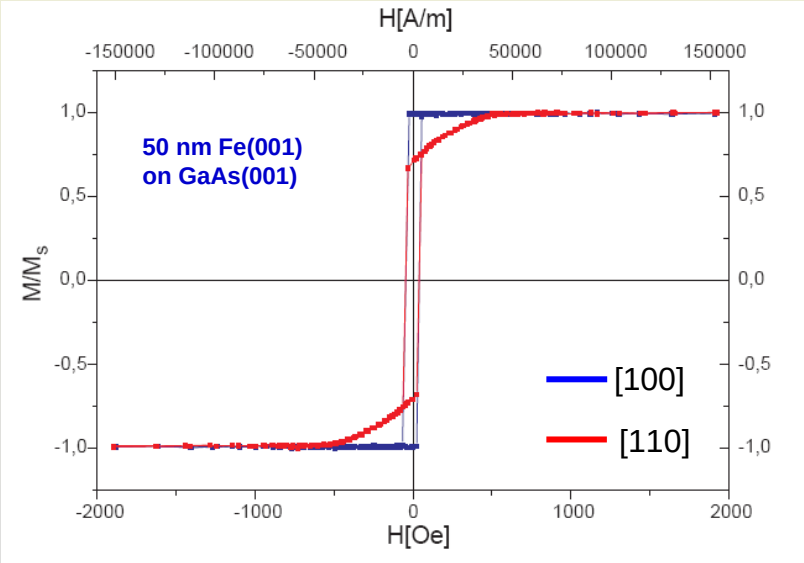
$E_d = 0$ ***for an infinite cubic lattice***

$\Rightarrow$ **dipolar interaction *irrelevant for Fe / Ni ?***





why $M_R < M_S$ along e.a.?



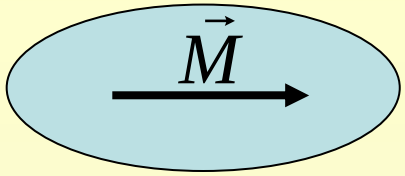
bulk (spherical) samples

thin film, M // film plane

difference:

dipolar / demagnetizing field

ferromagnetic body – ellipsoid, sphere homogeneously magnetized



$$\vec{\nabla}\vec{B} = 0$$

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

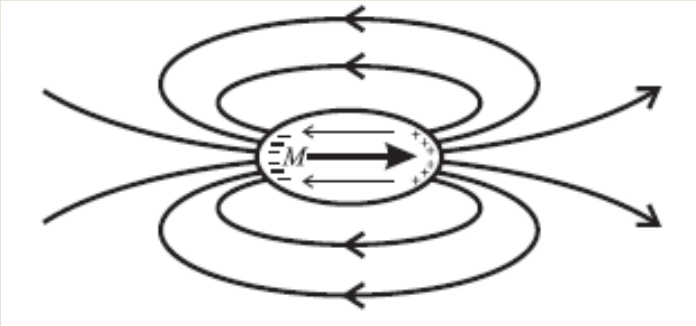
$$\Rightarrow \quad \vec{\nabla}\vec{M} = -\vec{\nabla}\vec{H}$$

$$\vec{\nabla}\vec{M} = \frac{dM_x}{dx} + \frac{dM_y}{dy} + \frac{dM_z}{dz}$$

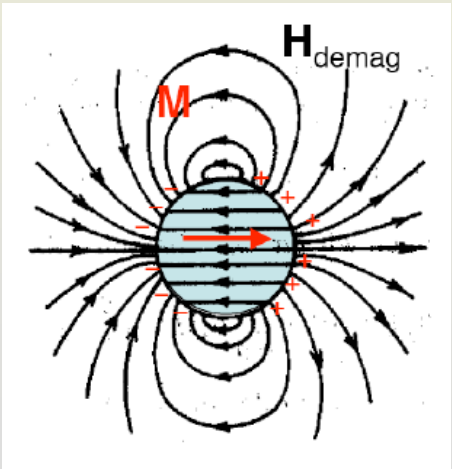
$$\vec{\nabla}\vec{H} = C \cdot \rho_m \quad \Rightarrow$$

magnetic pole /charge density

$\rho_m \neq 0$ if $\vec{\nabla}\vec{M} \neq 0$



sources of magnetic stray field / demagnetizing field



demagnetizing field H_d ↔ shape anisotropy

$$\vec{H}_d = -\mathcal{D} \cdot \vec{M}$$

$\mathcal{D}$ … demagnetizing tensor

H_d homogeneous only for ellipsoidal bodies !

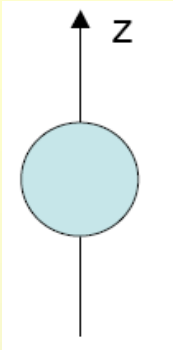
after diagonalization:

$$\mathrm{Tr}\,\mathcal{D} = D_x + D_y + D_z = \begin{cases} 1 & \text{SI units} \\ 4\pi & \text{cgs units} \end{cases}$$

for non-ellipsoidal objects: $\vec{H}_d = \vec{H}_d(\vec{r})$ ***position-dependent***

to be numerically calculated with micromagnetic codes

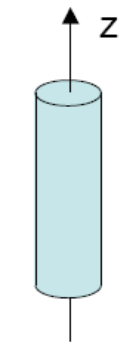
sphere



$$\mathcal{D} = \begin{pmatrix} \frac{1}{3} & 0 & 0 \\ 0 & \frac{1}{3} & 0 \\ 0 & 0 & \frac{1}{3} \end{pmatrix}$$

isotropic

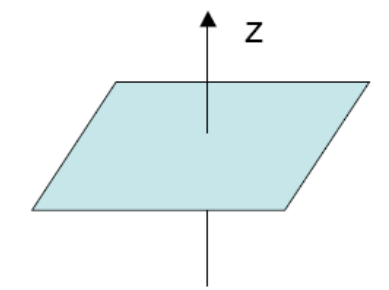
cylindrical wire (∞)



$$\mathcal{D} = \begin{pmatrix} \frac{1}{2} & 0 & 0 \\ 0 & \frac{1}{2} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

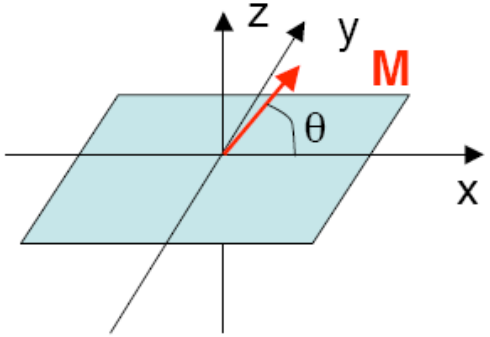
UMA
e.a./hard plane

thin plate/film (∞)



$$\mathcal{D} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

UMA
easy plane/h.a.



$$\mathbf{M} = M \begin{pmatrix} \cos\Theta \\ 0 \\ \sin\Theta \end{pmatrix}$$

$$E_{demag} = \tfrac{1}{2}\mu_0 \mathbf{M}\mathcal{D}\mathbf{M} = \tfrac{1}{2}\mu_0 M^2 \begin{pmatrix} \cos\Theta \\ 0 \\ \sin\Theta \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\Theta \\ 0 \\ \sin\Theta \end{pmatrix} =$$

$$= \tfrac{1}{2}\mu_0 M^2 \begin{pmatrix} \cos\Theta \\ 0 \\ \sin\Theta \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ \sin\Theta \end{pmatrix} = \tfrac{1}{2}\mu_0 M^2 \sin^2\Theta$$

$K_U = ½\ \mu_0 M_S^2$

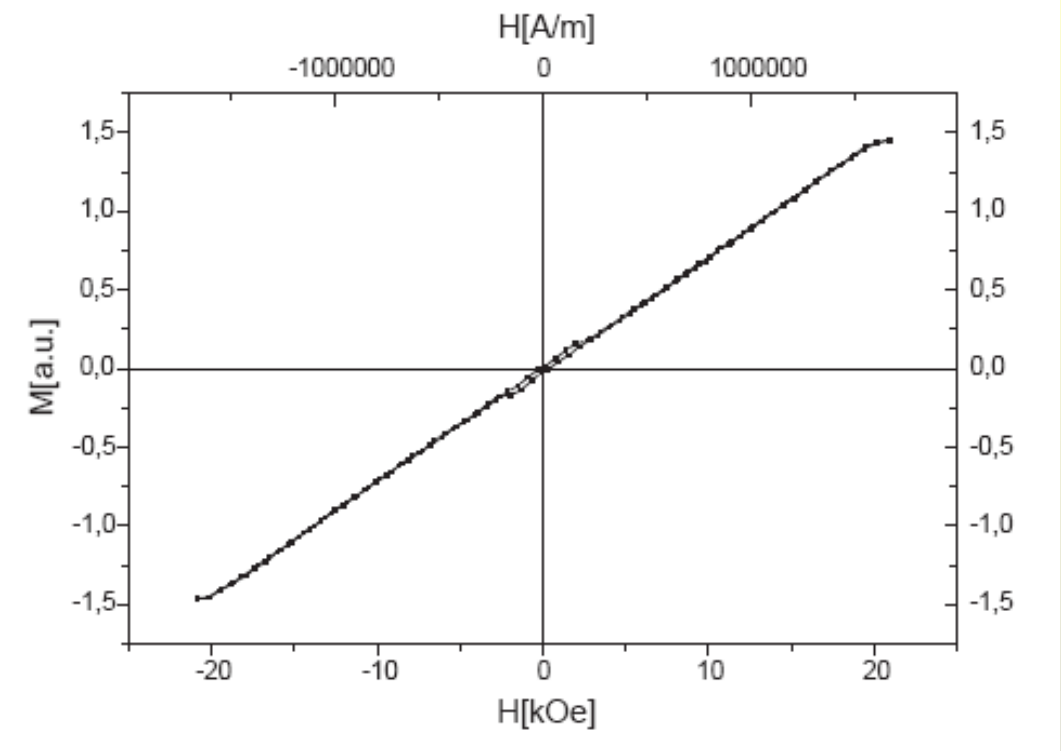
	M / (A/m)	$\frac{1}{2}\mu_0 M^2$ / (J/m³)
Fe	$1.72 \cdot 10^6$	$1.86 \cdot 10^6$
Co	$1.42 \cdot 10^6$	$1.27 \cdot 10^6$
Ni	$0.48 \cdot 10^6$	$0.14 \cdot 10^6$

$$B_K = \frac{2K_U}{M_S} \quad \Rightarrow \quad \begin{aligned} \boldsymbol{H_K} &= \boldsymbol{M_S} \\ \boldsymbol{B_K} &= \boldsymbol{\mu_0 M_S} \end{aligned} \qquad \textit{SI}$$

$$H_K = \frac{2K_U}{M_S} \qquad \boldsymbol{H_K = 4\pi M_S} \qquad \textit{cgs}$$

thin film (L >> t)

$B_{sat}^{\perp} = \mu_0 H_K = \mu_0 M_S$ **Fe: $\mu_0 M_S$ = 2.1 T** @ 300K



VSM: $M_{\perp}(H_{\perp})$

for 50 nm Fe(001)/GaAs(001)

determination of M_S ?

MOKE, AHE, …

Problems:

- other anisotropies *(surface, strain)*
- **$D_z < 1$** with structural defects *(surface roughness)*

Remark:

shape anisotropy, $\mathcal{D}$ $\leftrightarrow$ **continuum model,**
not strictly valid / fails for ultrathin films

also: atomistic model of <u>point dipoles</u> at lattice points
incorrect !

better: $\sigma(\vec{r})$ **from DFT**

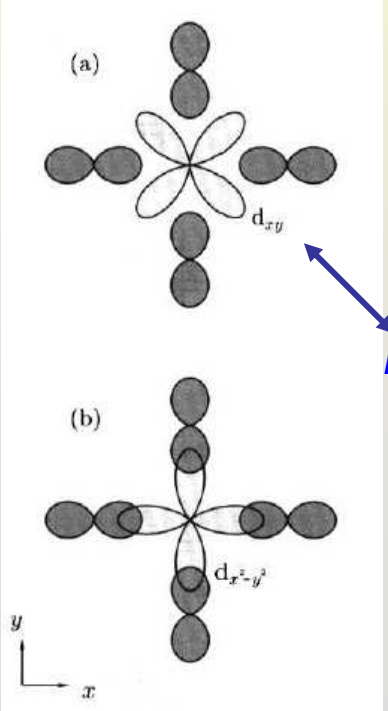
3.2 spin-orbit interaction (SOC)

MA by *SOC* + *crystal field interaction*

free atom: charge distribution related to orbital angular momentum;

s-, p-, d-wave functions; m_l ↔ orientation in space

lattice: crystal field ⟶ orientation of orbital angular momentum due to Coulomb interaction



lower energy

3d metals:

orbital momentum is quenched by CF, but not completely due to SOC

from *"Magnetism in Condensed Matter"*, S. Blundell, 2001

rotation of ***S*** by B_{ext} $\Rightarrow$ SOC: rotation of ***q(r)*** $\Rightarrow \Delta E_{Coul} \neq 0 \leftrightarrow$ **MA !**

magnetic moment ***m***:

orbital moment - preferential orientation via crystal field (*3d*)
spin moment - preferential orientation via SOC

crystal field $\leftrightarrow$ crucial influence of local symmetry on MA!

bulk / surface
cubic / distorted lattice
perfect lattice / defects: steps, …

4. theoretical description of MA

ideally: ***ab initio theory for many-body problem***

4.1 Density Functional Theory - DFT

rigorous in principle

but: MA requires SOC, SOC $\leftrightarrow$ relativistic effect

$\Rightarrow$ ***Dirac*** equation, fully relativistic treatment !

instead: ***Pauli*** addition to Hamiltonian $H_{SO} = \vec{\sigma} \cdot (\vec{\nabla} V(\vec{r}) \times \vec{p})$

successful, predictive power!

e.g. spin reorientation in 1 ML Fe *Gay and Richter*

PMA in Co_1Ni_2 multilayers *Daalderop et al., PRL 68,682 (1992)*

problems: difficult/tedious for large sytems, defects;
structure models (lattice distortions, strain, relaxations),
disordered/ordered alloys, …

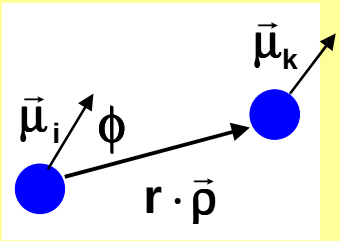
4.2 phenomenological theories

- single ion anisotropy: *energy of electric multipoles with crystal field*
  → MA of 4f magnets - strong SOC;
  less appropriate for 3d metals

- pair energy model L. Néel 1953: 3d metals with direct exchange interaction

$$\varepsilon_a = \sum_i \varepsilon_i ;$$

$$\varepsilon_i = \sum_k w_{ik}$$



$$w_{ik} = g_2(r_{ik})\cdot(\cos^2\phi - \tfrac{1}{3}) + g_4(r_{ik})\cdot(\cos^4\phi - \tfrac{6}{7}\cos^2\phi + \tfrac{3}{35}) + \ldots$$

$$\cos\phi = \vec{\rho}\cdot\vec{m} = \rho_x m_x + \rho_y m_y + \rho_z m_z ; \qquad \vec{m} = \frac{\vec{M}}{M};$$

$$g_2(r) = l + m\partial r ; \qquad g_4(r) = q + s\partial r$$

[pseudo-dipolar term + pseudo-quadrupolar term + …]

ε_a by summation over *suitable atomic pairs*

$\Rightarrow$ ratios between K_i (absolute values → ab initio theory), K_i and λ;
accounts for: different lattice symmetries, strain - magnetostriction, surfaces;
e.g. theory of PMA, induced UMA in Permalloy – $Ni_{81}Fe_{19}$, ...

5. how to measure the strength of MA

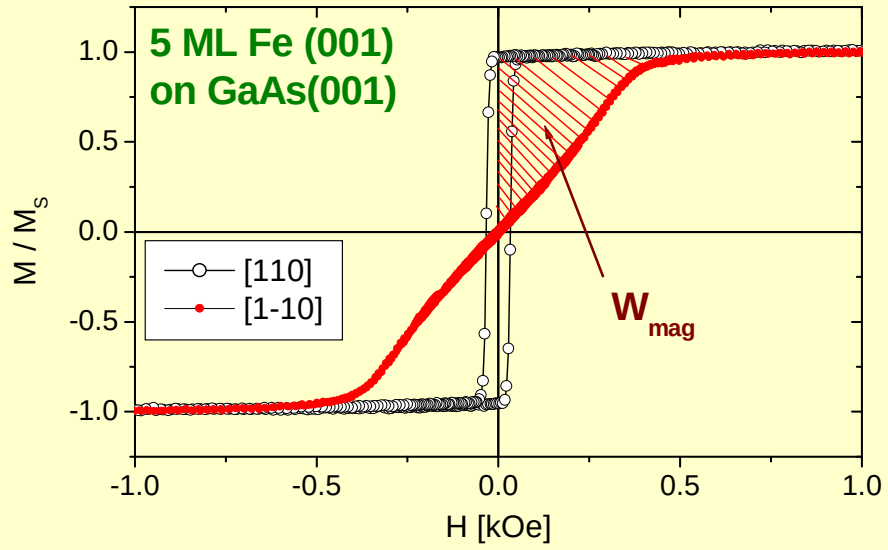
a)

magnetizing energy W_{mag}

$$w_{mag} = \int_0^{M_S} H dM$$

$$W_{mag}(\phi) - W_{min} = \varepsilon_a(\phi)$$

ε_a … MA energy density

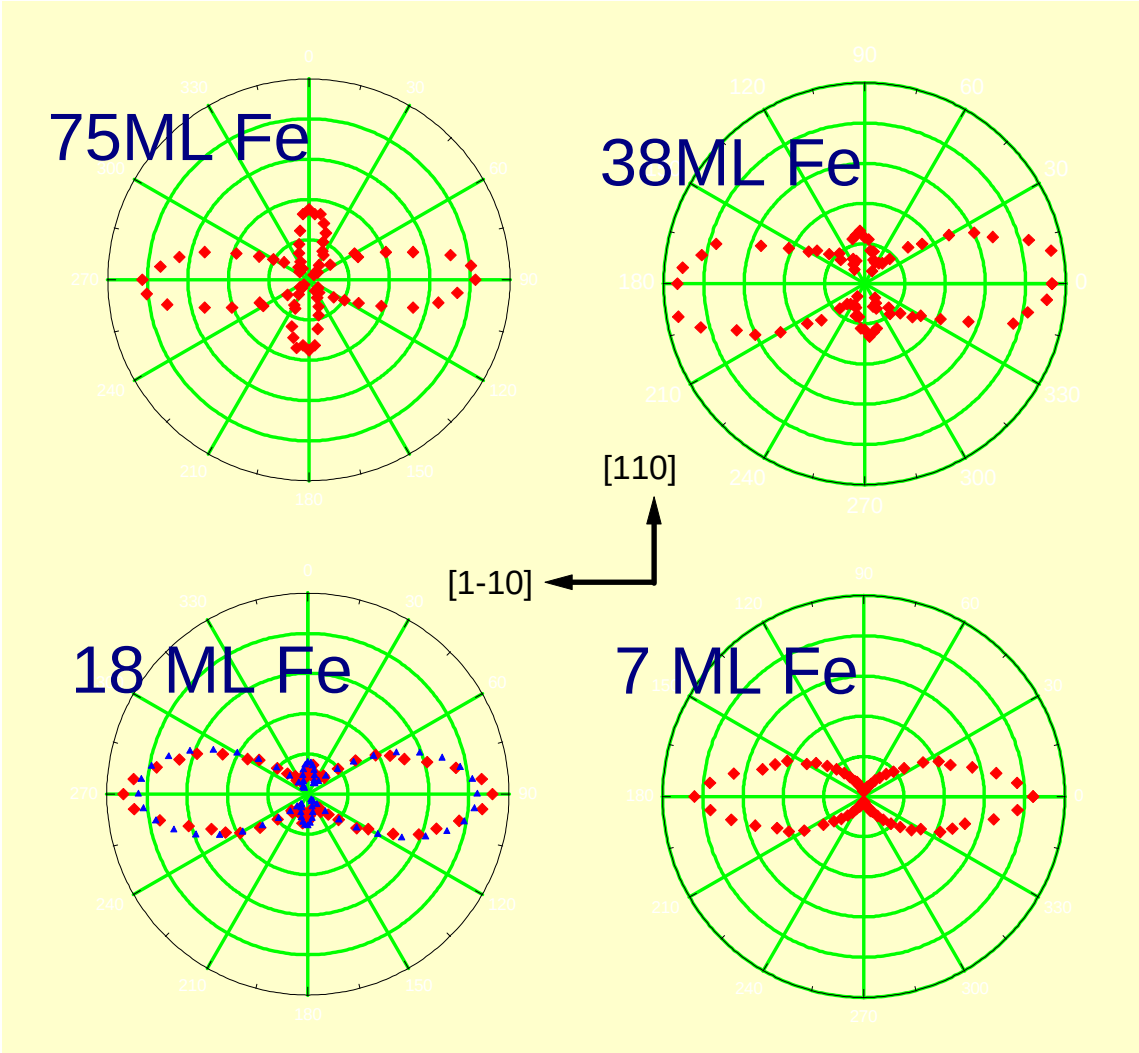


M(H) loops by

VSM, AGM, SQUID, MOKE + M_S, …

integration of anhysteretic M(H) loops

Fe (001) on GaAs(001)



magnetizing energy

$$w_{mag} = \int_0^{M_S} HdM$$

as a function of field orientation

b) fitting h.a. M(H) loops: faster alternative method

if symmetry of anisotropy is known from $\varepsilon_a(\phi)$

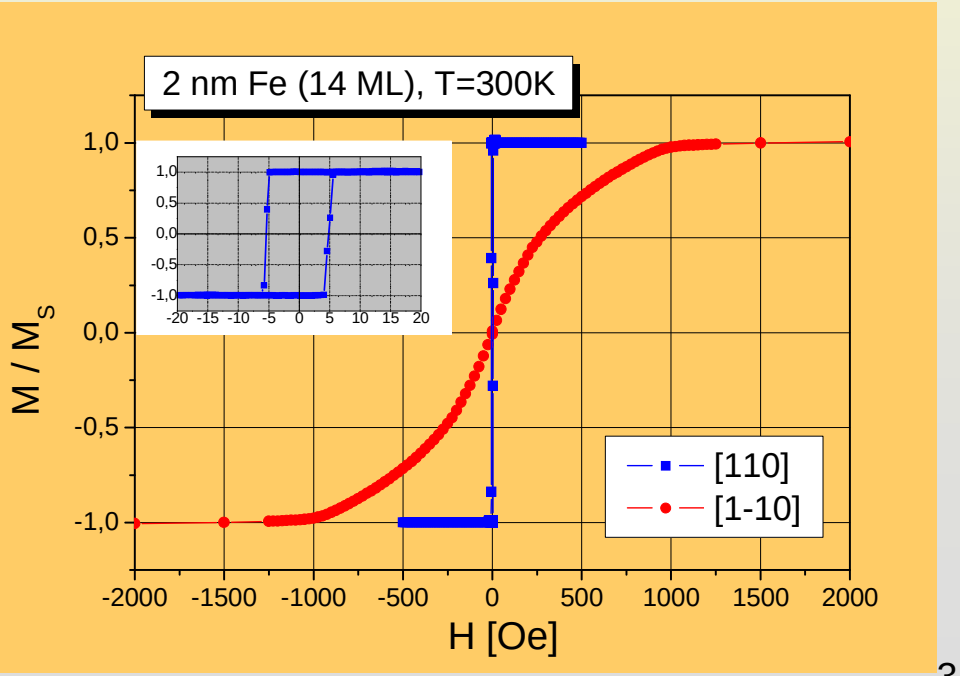
$$\varepsilon_m(\phi, H, \alpha) = -\frac{1}{4} K_1^{eff} \sin^2(2\phi) + K_u^{eff} \sin^2(\phi) - HM_s \cos(\phi - \alpha)$$

reversible magnetization loops *along hard axis* $\leftrightarrow$ equilibrium states

$$\frac{d\varepsilon_m}{d\phi} = 0 \quad \Rightarrow \quad H(m) = 2K_1^{eff}(2m^3 - m) / M_s + 2K_u^{eff} m / M_s$$

fit to experimental h.a. M(H) / H(m) loops
(here: [1-10])

$\Rightarrow$ **K_1^{eff}, K_U^{eff}**



c) K_i from torque:

$$T = \frac{dE_m}{d\phi}$$

- ***static*: torque magnetometer**
- ***dynamic*: FMR** **($H_{res} = H_{eff} = H_{ext} + H_K$** for H_{ext}//e.a. etc.**)**

main source of error: non-uniform $\vec{M}$,
domains, incomplete saturation

$\Rightarrow$ measurement at high field, e.g. FMR at highest frequency

best: $lim\ K_i(1/H)$
$1/H \rightarrow 0$

6. Symmetry and MA

example: single crystalline FM materials (e.g.epitaxially grown Fe films)

6.1 3D → 2D, **i.e. *reduced extension* in 1 dimension /** bulk → ultrathin film

⇔ enhanced fraction of surface moments
- lower coordination
- lower symmetry, e.g. *broken cubic symmetry*

basic idea: **MAE of surface atoms different from volume atoms;**

current practice: magnetic surface anisotropy = real MAE – ideal volume MAE

$$E_a^{eff} = E_a^{vol} + E_a^{surf\,/\,\mathrm{int}}$$

$$\frac{E_a^{eff}}{f(\phi_i)} = V \cdot K_{eff} = V \cdot K_V + A \cdot (K_{\mathrm{int}}^{(1)} + K_{\mathrm{int}}^{(2)})$$

$$K_{eff} = K_V + \frac{1}{t}(K_{\mathrm{int}}^{(1)} + K_{\mathrm{int}}^{(2)})$$

test: K_{eff} vs. 1/t
or **$K_{eff} \cdot t$ vs. t**

6.1.1 Perpendicular MA - PMA

predicted by L. Néel in 1953 ;
exp. confirmed by Gradmann et al. 1968

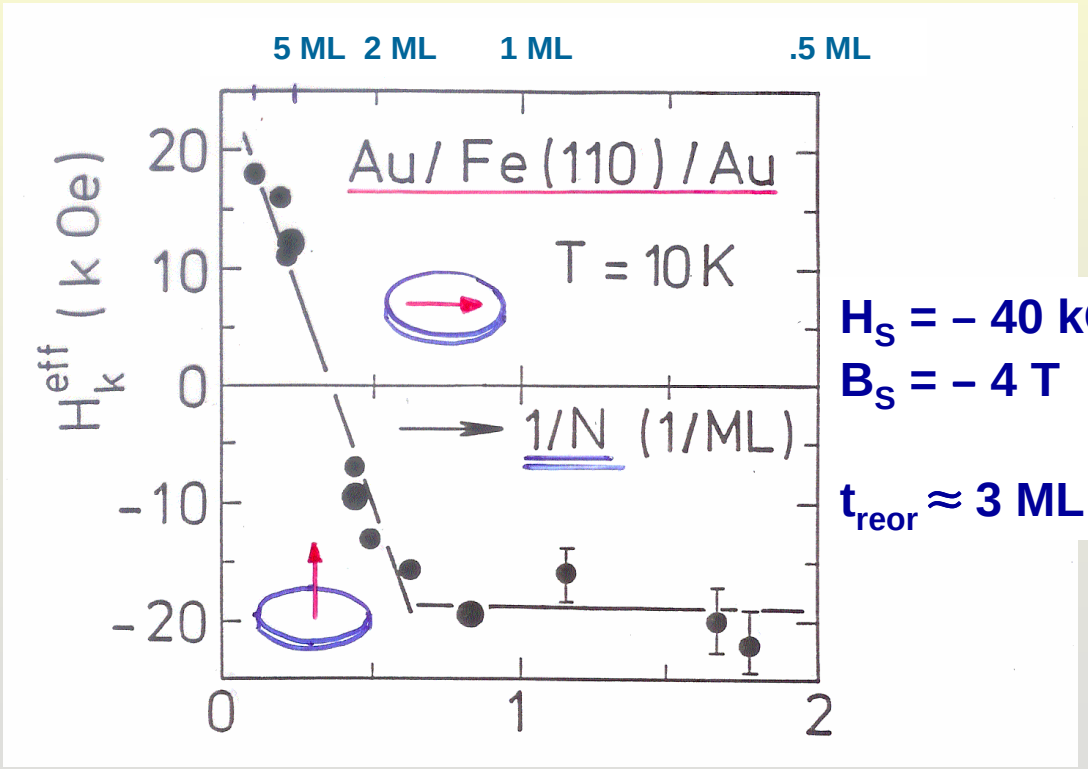
film normal = symmetry axis

$$K_{eff} = \frac{1}{2}\mu_0 M_S^2 + K_V^{'} + \frac{1}{t}(K_{\text{int}}^{(1)} + K_{\text{int}}^{(2)})$$

Fe(110) on Au(111)

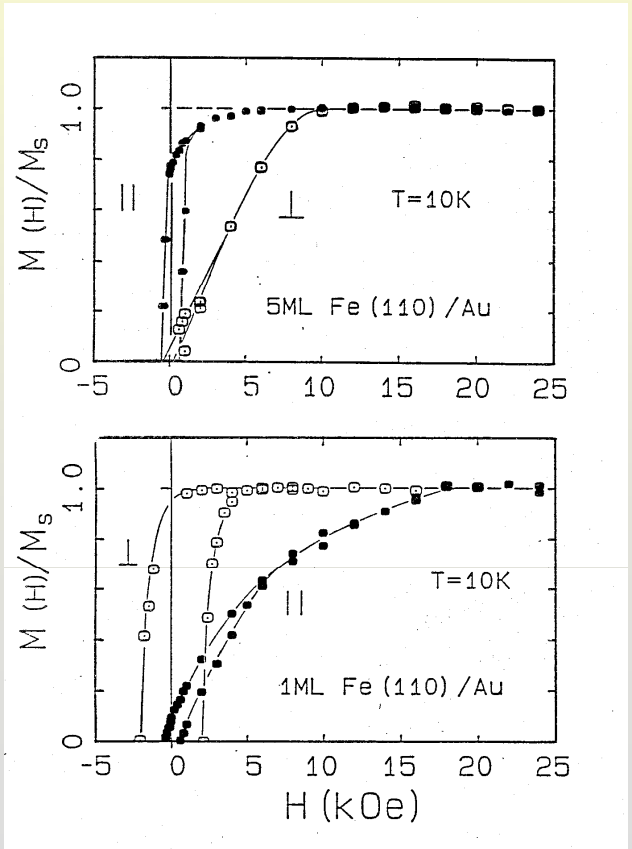
1 ML ↔ 0.2 nm

$$H_K^{eff} = 4\pi M_S + H_K^{vol} + \frac{1}{t}(H_S^{(1)} + H_S^{(2)}) \quad \text{(cgs)}$$



H_S = – 40 kOe
B_S = – 4 T

$t_{reor} \approx$ 3 ML

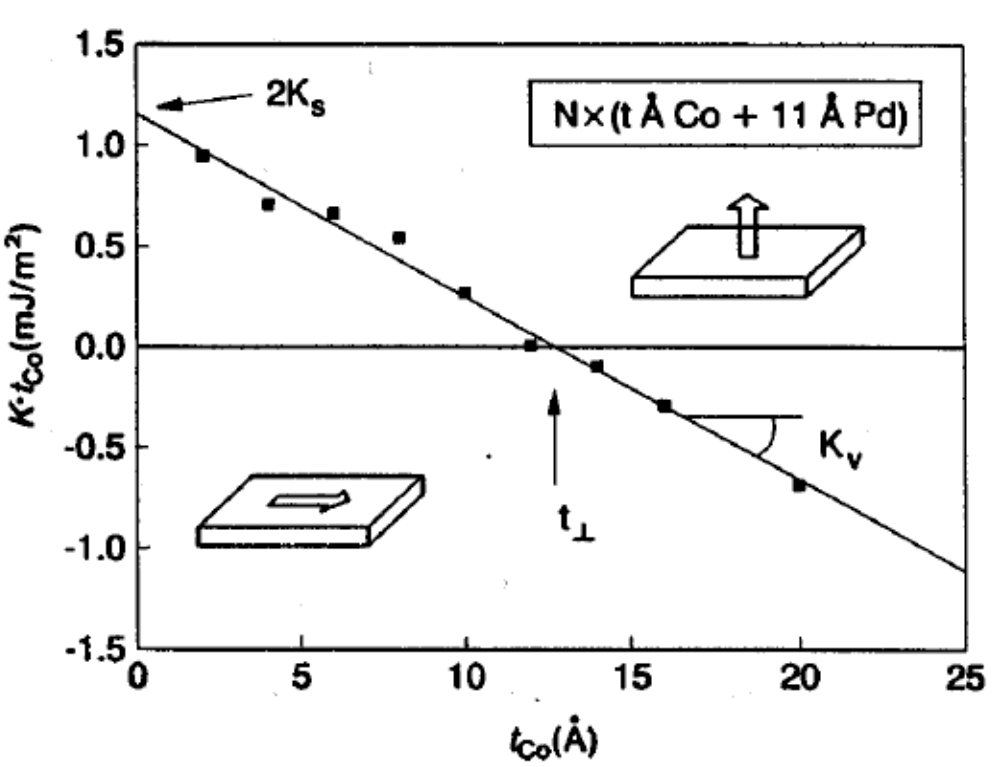


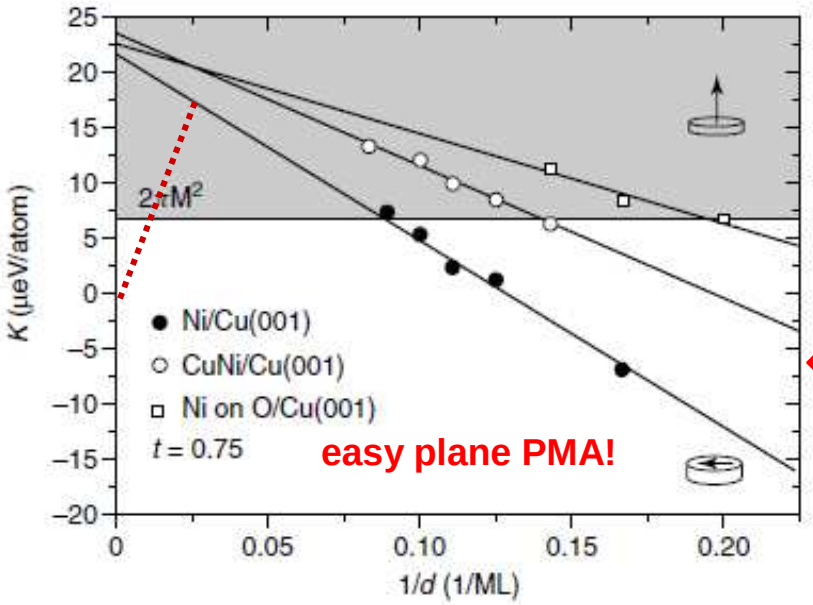
G. Lugert and G. Bayreuther
Thin Solid Films 175 (1989) 311

other examples with perpendicular e.a.: **Co/Au, Co/Pt, Co/Pd, Fe/Pt !**

Co/Pd polycrystalline multilayer

F. J. A. den Broeder et al.,
J. Magn. Magn. Mater. 93, 562 (1991)





← **Ni/Cu: surface anisotropy with perpendicular hard axis !**

general mechanism: SOC + crystal field

applications: magnetic recording media, spin torque oscillators, …

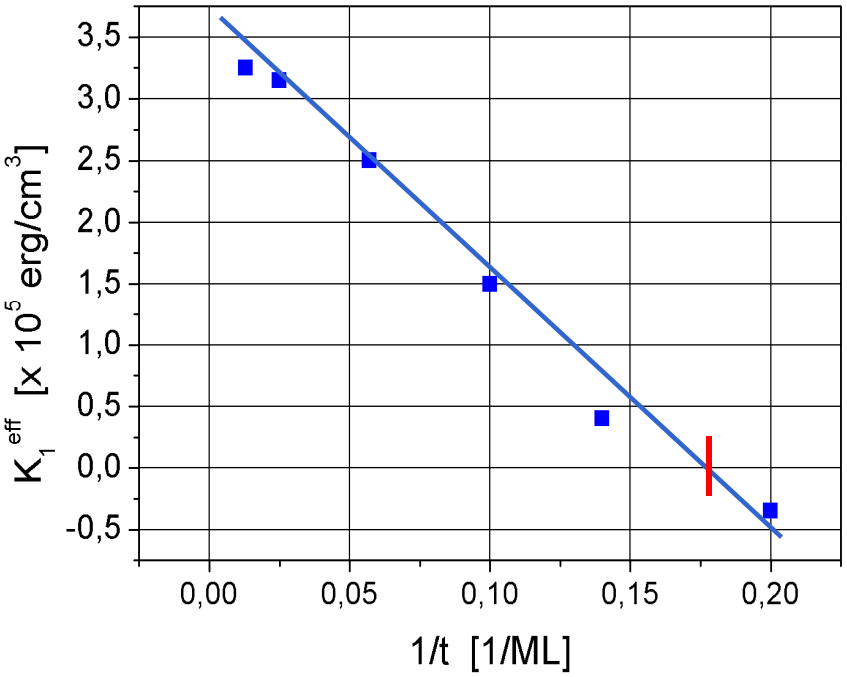
6.1.2 In-plane interface anisotropy - fourth order

Fe(001) epitaxial films

B. Heinrich et al., 1989
M. Brockmann et al., 1997

$$\varepsilon_a = K_0 + K_1 \cdot (\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + K_2 \cdot \alpha_1^2\alpha_2^2\alpha_3^2 + ...$$

25 ML Au/ ***t*** Fe/GaAs(001); *t = 5 ML …. 75 ML*



K_1^{eff} from M(H) loops

$K^{eff} = K^{vol} + 1/t \cdot K^{int}$

$\Rightarrow K_1^{vol}$ and K_1^{int} of opposite sign !

strong thickness dependence,
change of sign of K_1:
e.a. [100] → [110]

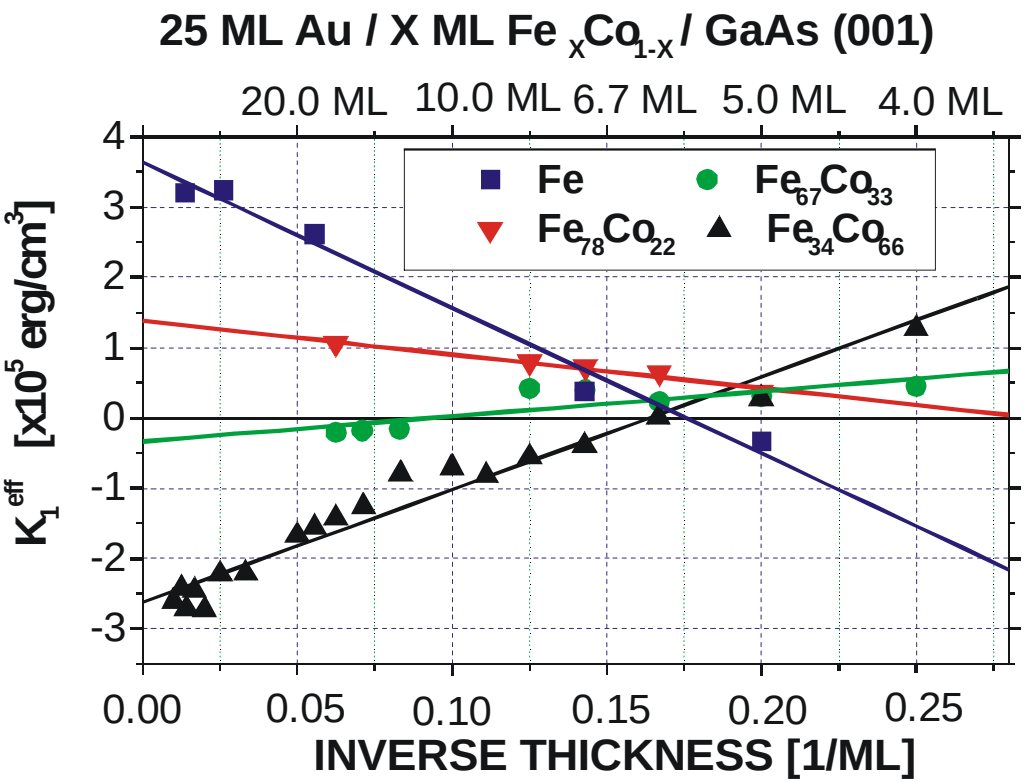
origin ?

G. Bayreuther et al., J. Appl. Phys. 93, 8230 (2003)

single crystalline $Fe_{1-x}Co_x$(001) films, $0 \leq x \leq 0.7$

MBE-grown on GaAs(001), Ag(001), Au(001)

stable bcc structure,
$a_0 \approx$ const.

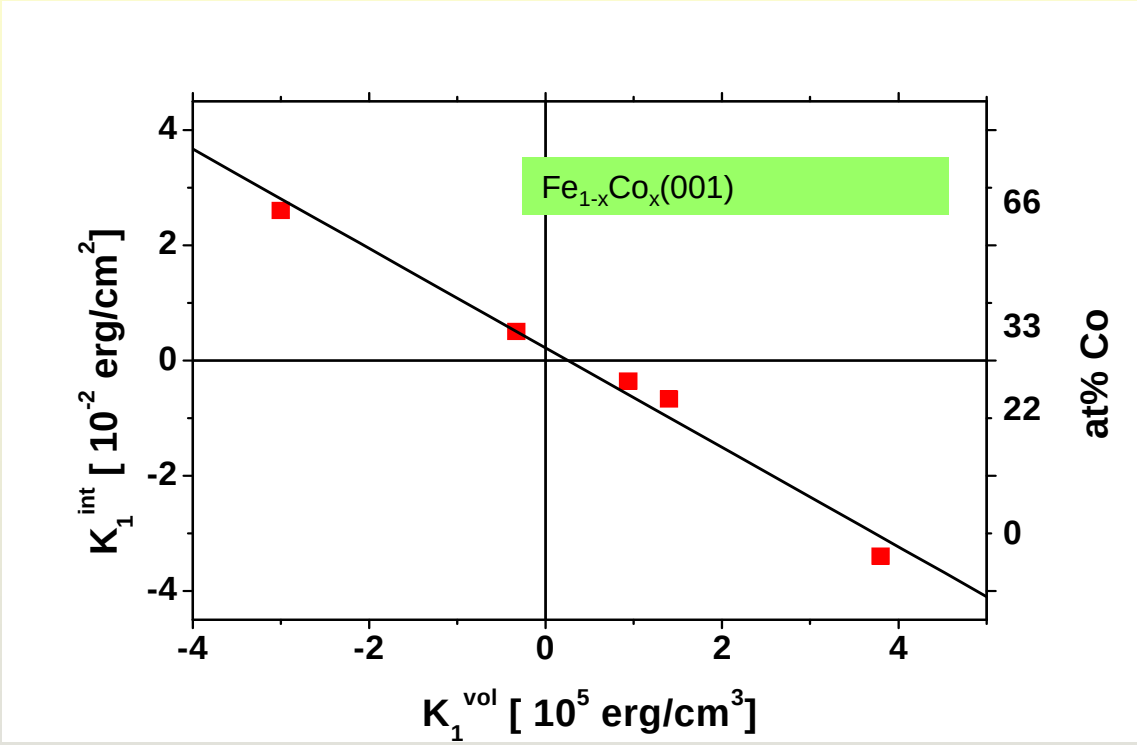


$K^{eff} = K^{vol} + 1/t \cdot K^{int}$

$\Rightarrow K_1^{vol}$ and K_1^{int} always of opposite sign !

G. Bayreuther et al., J. Appl. Phys. 93 (2003) 8230

fourth-order volume and interface anisotropy constants of epitaxial $Fe_{1-x}Co_x$ (001) films on GaAs(001)



$$K^{eff} = K^{vol} + 1/t \cdot K^{int}$$

universal critical thickness

t_{crit} for $K_1^{eff}=0$;

universal proportionality between K_1^{vol} and K_1^{int}

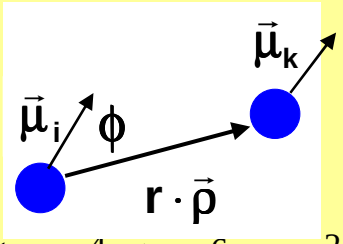
$$t_{crit} = - K_1^{int}/K_1^{vol}$$

how to explain?

L. Nèel's pair energy model of magnetic anisotropy

$$\varepsilon_a = \sum_i \varepsilon_i ;$$

$$\varepsilon_i = \sum_k w_{ik}$$



$\vec{M}$ **uniform**

$$w_{ik} = g_2(r_{ik}) \cdot (\cos^2\phi - \tfrac{1}{3}) + g_4(r_{ik}) \cdot (\cos^4\phi - \tfrac{6}{7}\cos^2\phi + \tfrac{3}{35}) + \ldots$$

$$\cos\phi = \vec{\rho} \cdot \vec{m} = \rho_x m_x + \rho_y m_y + \rho_z m_z ; \qquad \vec{m} = \frac{\vec{M}}{M} ;$$

$$g_2(r) = l + m\partial r ; \qquad g_4(r) = q + s\partial r$$

E_a by summation over *suitable atomic pairs*

here: **summation over nn and nnn pairs** $\Rightarrow$

2nd order term = 0

4th order term ≠ 0

fourth-order in-plane anisotropy in unstrained (001) bcc film

$$K_1^{vol} = \frac{2}{a^3}\left(\frac{16}{9}q^{nn} - 2q^{nnn}\right)$$

$$K_1^{\text{int}} = -\frac{8}{9a^2}q^{nn}$$

$$\frac{K_1^{\text{int}}}{K_1^{\text{vol}}} = -\frac{2q^{nn}a}{8q^{nn} - 9q^{nnn}} = -t_{crit}$$

pure Fe: $K_1^{int} < 0 \Rightarrow q^{FeFe} > 0$

$Fe_{1-x}Co_x$: q^{nn} = average of q^{FeFe}, q^{FeCo} and q^{CoCo} $\leftrightarrow$ ***chemical order?***

q^{FeCo}, q^{CoCo} $\leftrightarrow$ $\langle q^{nn} \rangle < 0$ for $x > 0.3$

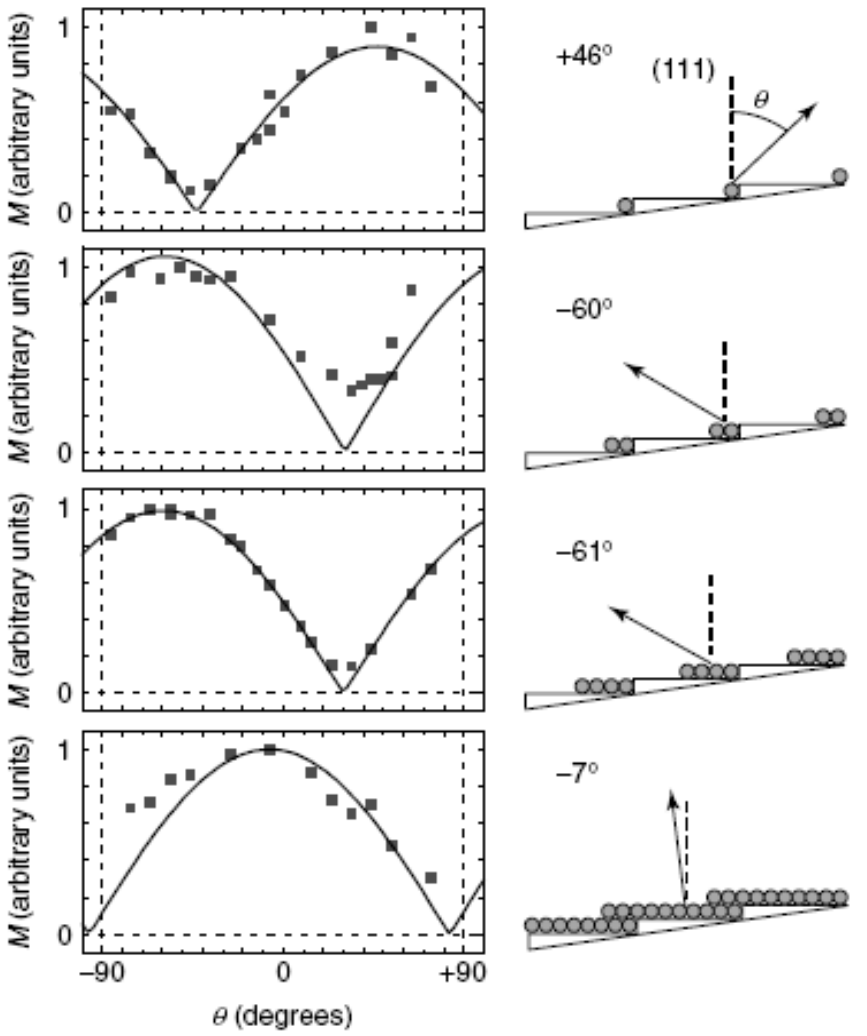
random alloy: q^{nn}/q^{nnn} independent of x $\Rightarrow$ <u>universal</u> t_{crit}

prediction: no effect of substrate (Au, Ag, GaAs) or covering material (vacuum, Au) is experimentally observed!

6.2 2D → 1D: FM chains / wires

Co chains on vicinal Pt(9 9 7)

XMCD data from Co L_3 edge;
$\theta = \angle(\mathbf{k},[111])$; lines: UMA



Gambardella, P., Dallmeyer, A., Maiti K., *et al.* (2004). Oscillatory magnetic anisotropy in one-dimensional atomic wires. *Physical Review Letters*, **93**, 077203.

partially explained by DFT calc.

see **Handbook of Magnetism and Advanced Magnetic Materials, H. Kronmüller and S. Parkin, edts. Vol. 1, p. 575 ff**

6.2 further symmetry breaking mechanisms

- **orientational (chemical) order: induced UMA in Permalloy - $Ni_{81}Fe_{19}$ by oriented Ni-Fe, Ni-Ni, Fe-Fe pairs**

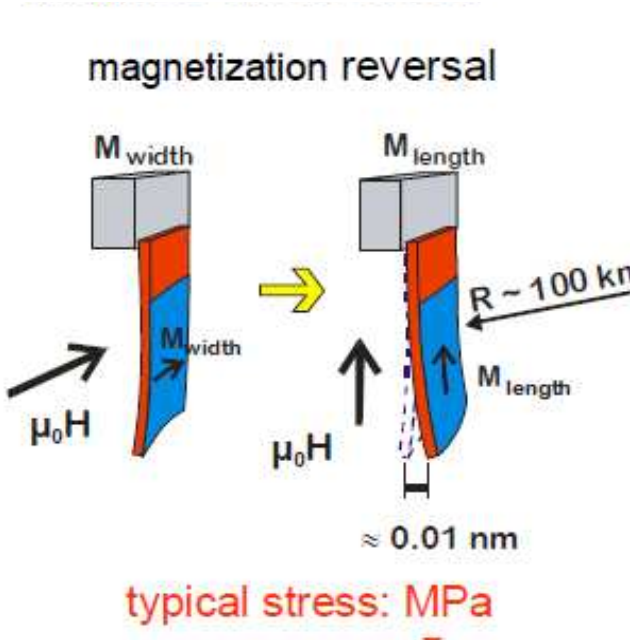
  L. Néel 1953

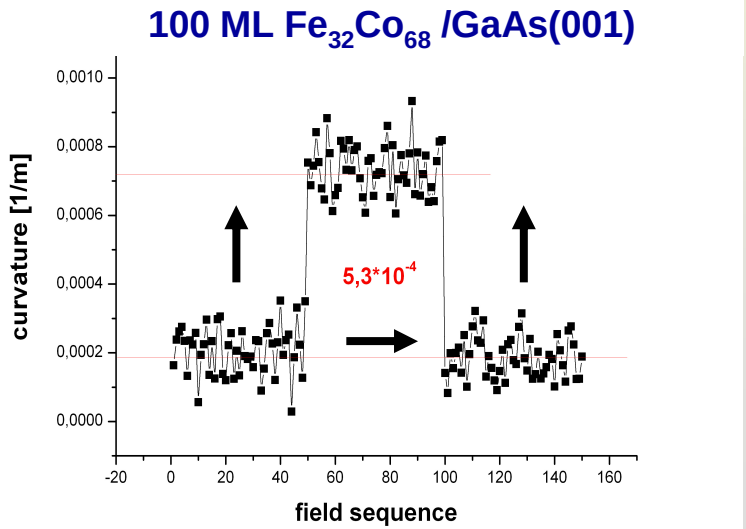
- **strained lattice: magneto-elastic anisotropy ↔ *magnetostriction***

  e.g. cubic → tetragonal

$$f_{ME}(\varepsilon,\alpha) = B_1(\alpha_1^2\varepsilon_1 + \alpha_2^2\varepsilon_2 + \alpha_3^2\varepsilon_3) + B_2(\alpha_1\alpha_2\varepsilon_6 + \alpha_1\alpha_3\varepsilon_5 + \alpha_2\alpha_3\varepsilon_4) + \ldots$$

curvature measured by double laser beam





D. Sander, Rep. Prog. Phys. 62, 809 (1999)

6.2 further symmetry breaking mechanisms

- **orientational (chemical) order: induced UMA in Permalloy - $Ni_{81}Fe_{19}$ by oriented Ni-Fe, Ni-Ni, Fe-Fe pairs**

  L. Néel 1953

- **strained lattice: magneto-elastic anisotropy $\leftrightarrow$ *magnetostriction***

  e.g. cubic $\rightarrow$ tetragonal

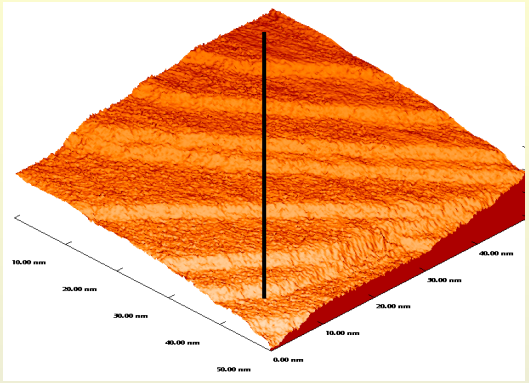
- **atomic steps**

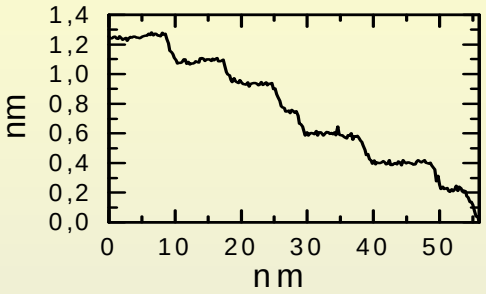
- **…..**

7. Tailoring and manipulating MA

7.1 controlled local symmetry: *monoatomic steps*

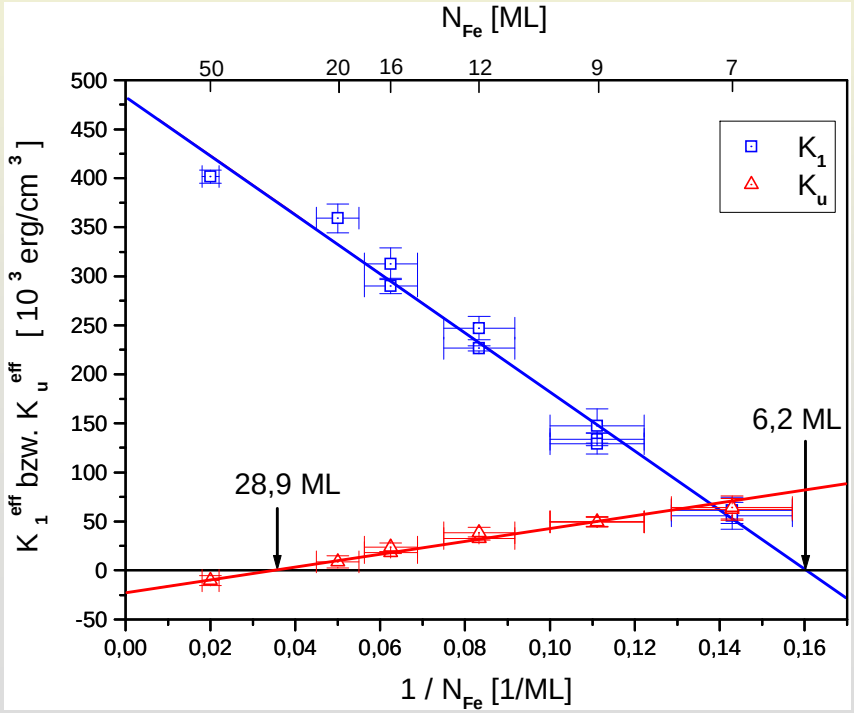
Fe / Ag/GaAs(1 0 29) T. Leeb et al., J. Appl. Phys. 85, 4964 (1999)



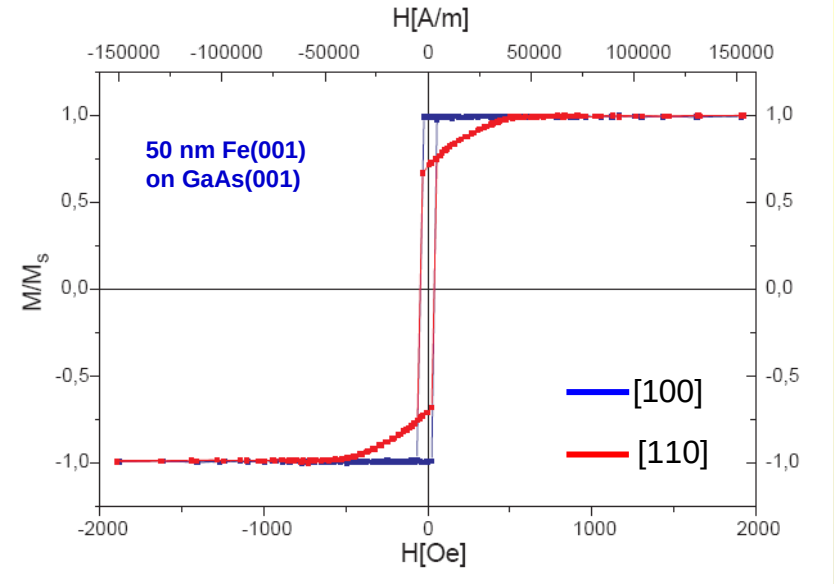


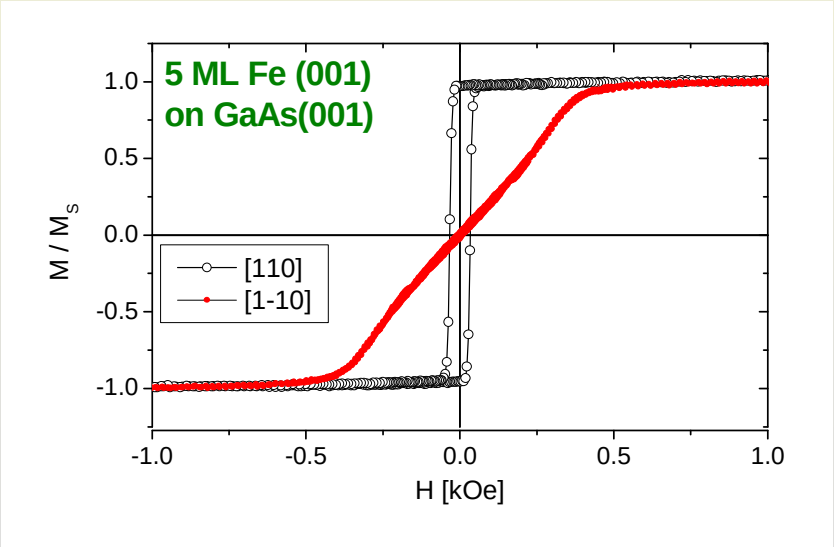
superposition of in-plane 4-fold and UMA

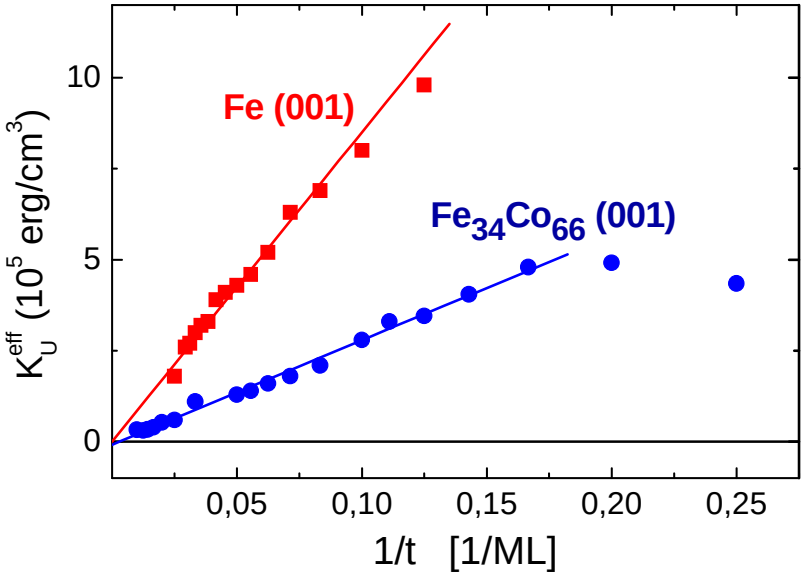
uniaxial e.a. ⊥ step edges



7.2 oriented chemical bonds - Fe(001)/GaAs(001)







uniaxial interface MA
by oriented Fe-As bonds;
K_U dominating for ultrathin films

7.3 MA modified by electric field

Nature Nanotechnology 4, 158 (2009)

Large voltage-induced magnetic anisotropy change in a few atomic layers of iron

T. Maruyama[1], Y. Shiota[1], T. Nozaki[1], K. Ohta[1], N. Toda[1], M. Mizuguchi[1†], A. A. Tulapurkar[1], T. Shinjo[1], M. Shiraishi[1], S. Mizukami[2], Y. Ando[3] and Y. Suzuki[1*]

NATURE NANOTECHNOLOGY DOI: 10.1038/NNANO.2008.406 LETTERS

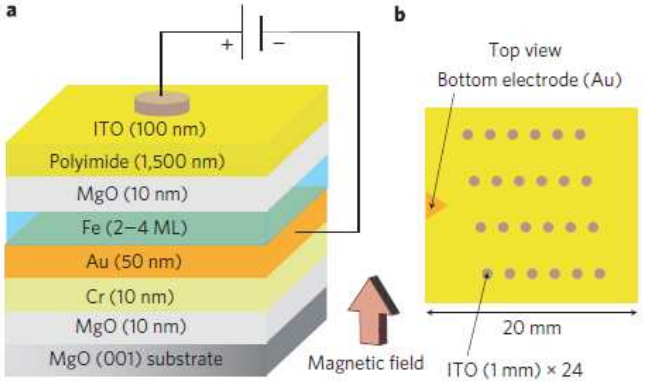


Figure 1 | Schematic of the sample used for a voltage-induced magnetic anisotropy change. a, A positive voltage is defined as a positive voltage on the top electrode with respect to the bottom electrode. A perpendicular magnetic anisotropy was induced by a negative voltage. The magnetic field was applied perpendicular to the film plane for Kerr ellipticity measurements. **b**, We fabricated the wedge-shaped Fe layer, incorporating 24 samples on the substrate, to investigate the dependence of the effect on Fe thickness.

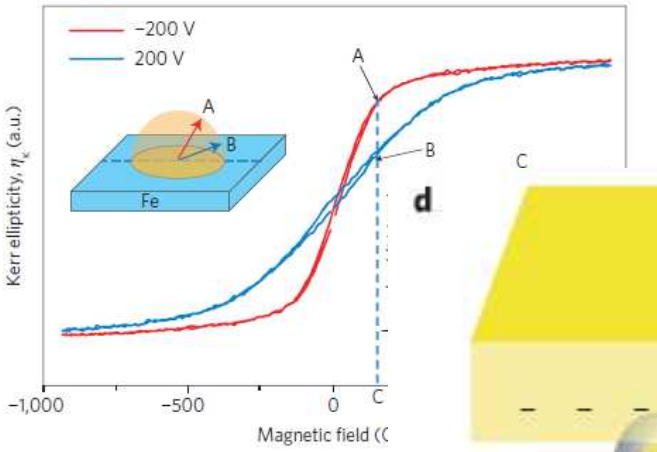
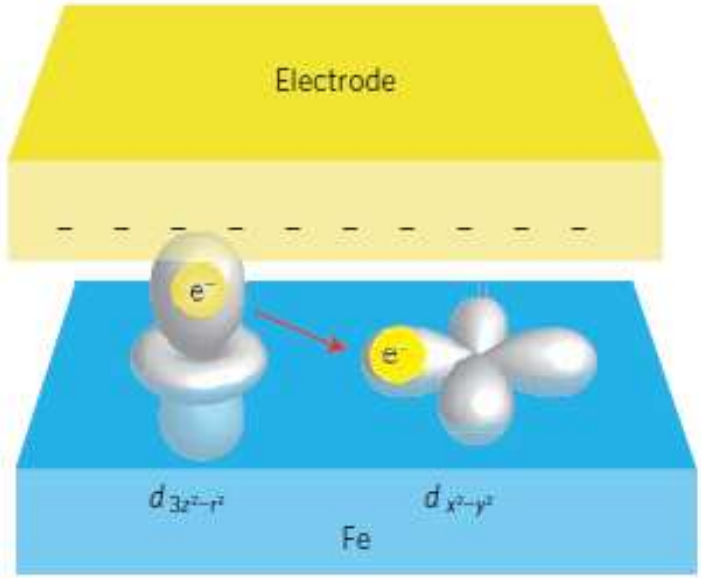


Figure 2 | Magneto-optical Kerr ellipticity η_K as a function of applied field. The thickness A significant change in the hysteresis curve i perpendicular anisotropy following applicatior inset shows the voltage modulation response The left inset illustrates the magnetization dir hysteresis curves.

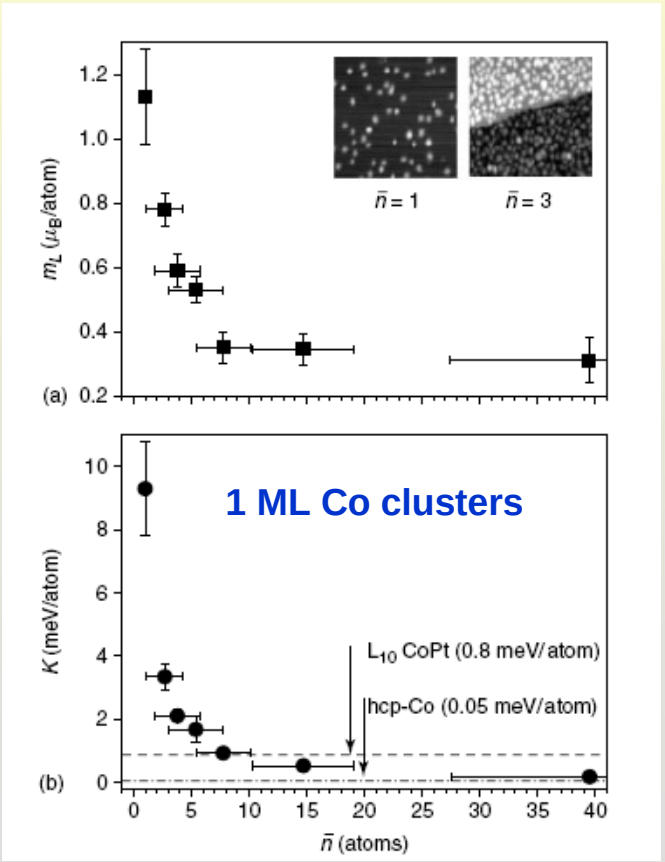


electric field induced / modified MA

- strong current activities
- FE/FM hybrid structures $\leftrightarrow$ magneto-elastic coupling
- multiferroic materials
- …..

8. Summary

- MA is essential for most applications of FM materials
- MA originates from dipolar and S-O interaction
- any symmetry breaking process creates additional MA
- MAE: .01 MJ/m^3 . . . . > 20 MJ/m^3
  1 μeV/atom . . . . > 10 meV/atom

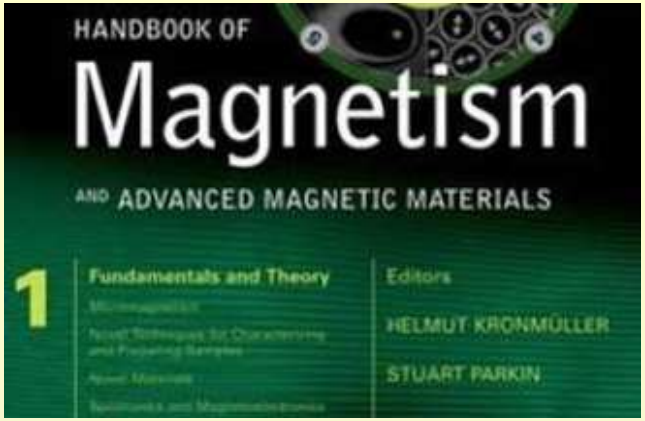


Gambardella et al.

8. Summary

- MA is essential for most applications of FM materials
- MA originates from dipolar and S-O interaction
- any symmetry breaking process creates additional MA
- MAE: .01 MJ/m^3 . . . . > 20 MJ/m^3
  1 μeV/atom . . . . > 10 meV/atom
- theory: (relativistic) DFT, but useful phenomen. theories
- many ways to manipulate MA (strength and orientation)
- many opportunities for future research and applications

Further reading



Handbook of Magnetism and Advanced Magnetic Materials, H. Kronmüller and S. Parkin, eds., Vol. 1, different chapters

Ruqian Wu (p. 423 ff), A. Enders et al.(p. 575 ff), Blügel and Bihlmayer (p. 598 ff)

Ultrathin Magnetic Structures
J.A.C. Bland and B. Heinrich, eds., Vol. I, ch. 2

Simple Models of Magnetism
R. Skomski, Oxford University Press, 2008; ch. 3

Heinrich, B. (1994). Ferromagnetic resonance in ultrathin film structures. In *Ultrathin Magnetic Structures II*, Bland, J.A.C. and Heinrich, B. (Eds.), Springer-Verlag: Heidelberg, pp. 195–222.

Sander, D. (2004). The magnetic anisotropy and spin reorientation of nanostructures and nanoscale films. *Journal of Physics. Condensed Matter*, **16**, R603–R636.