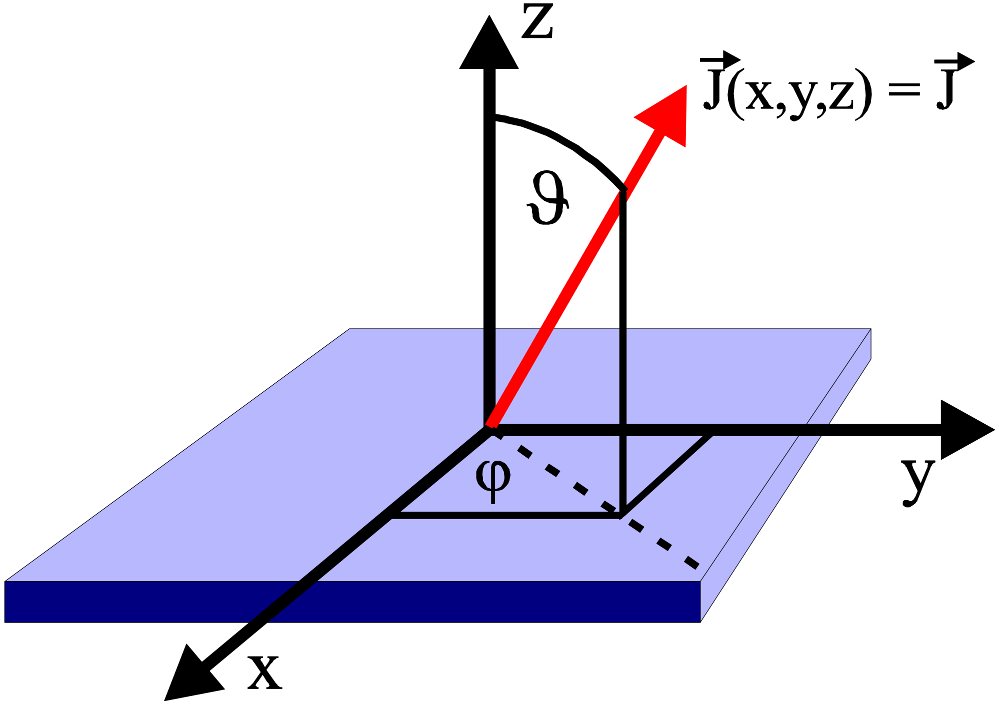
Magnetic anisotropies in ultrathin films



Assumptions:

1. homogeneous magnetization
2. ultrathin films with thickness

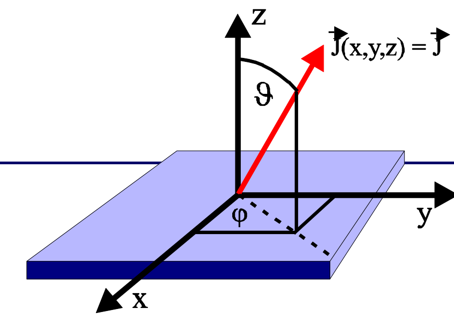
   $t < l$

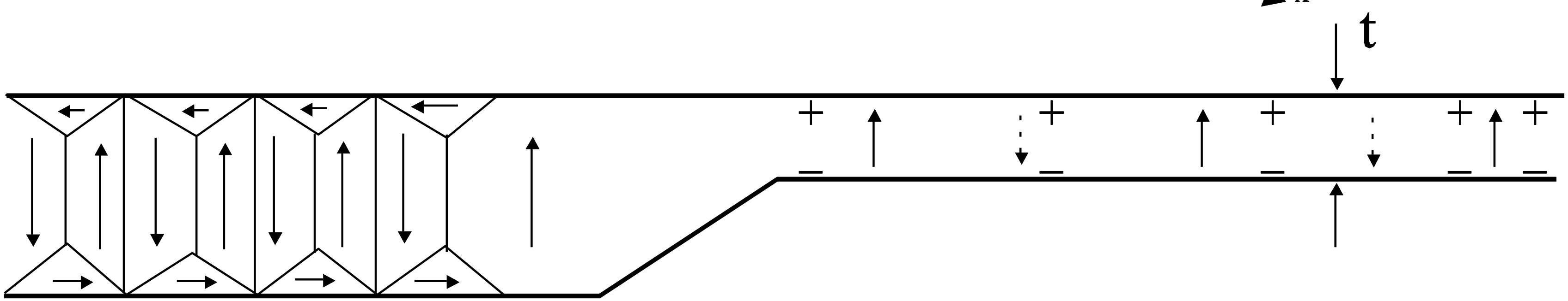
   $$l = \sqrt{A/K} \approx 10\text{nm}$$

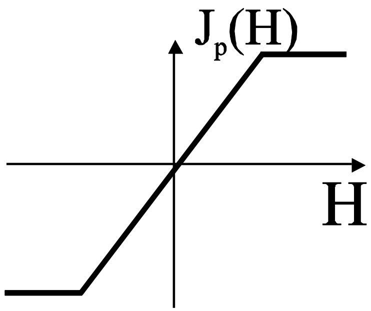
   A : Austauschkonstante 10^{-11} J/m

   K : Anisotropiekonstante 10^{5} J/m^3

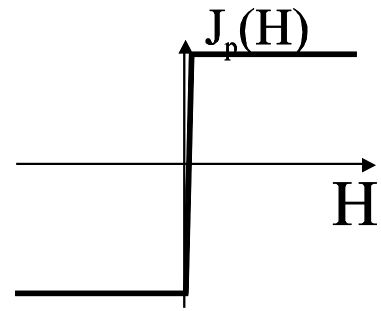
Magnetostatic Anisotropy







inhomogeneous state, no stray fields

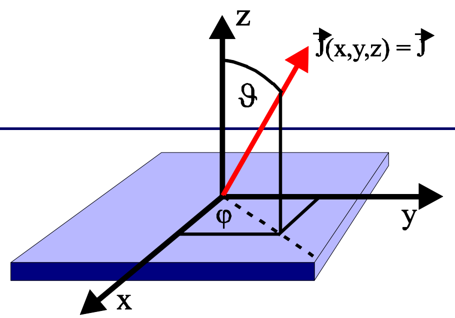


homogeneous state, stray field energy

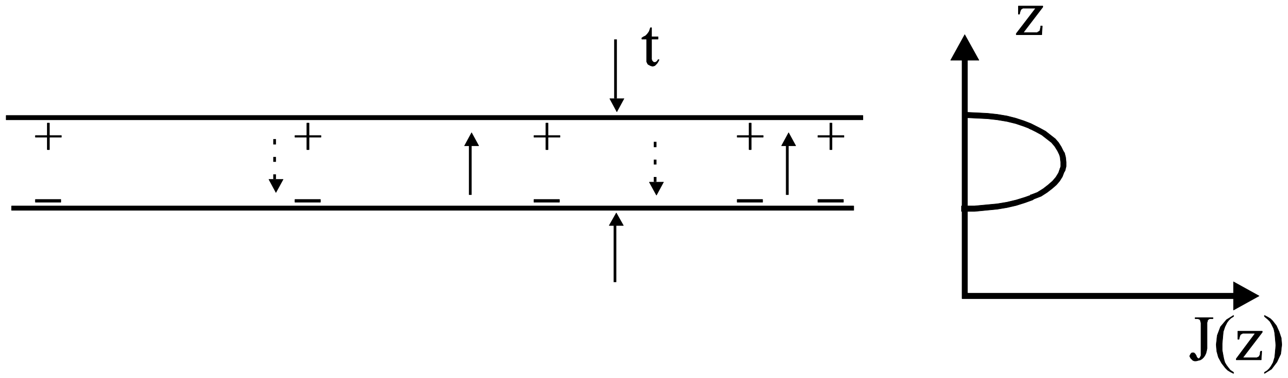
For homogeneous state the energy density

$$f^{sh} = \frac{F^{sh}}{V} = \frac{J_s^2}{2\mu_0} N \cos^2 \vartheta$$

becomes a local property



Magnetostatic Anisotropy

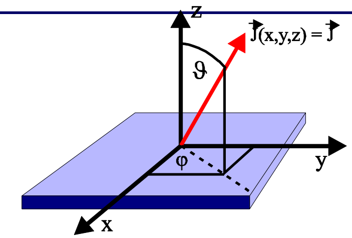


Magnetostat. anisotropy with magnetization depending on z

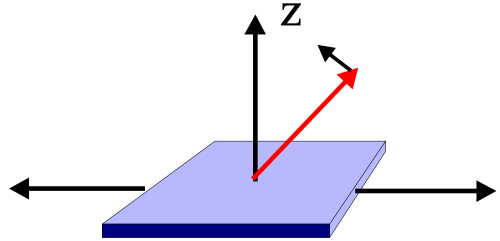
$$f^{sh} = \frac{1}{t}\int_0^t \frac{J_s^2(z)}{2\mu_0}\cos^2\vartheta \, dz$$

Bei Abnahme um ΔJ_s an der Grenzfläche:

$$f^{sh} = f_v^{sh} + \frac{1}{t} f_s^{sh} = \left\{ \frac{J_s^2}{2\mu_0} + \frac{1}{t}\frac{J_s^2 d_z}{2\mu_0}\left[\frac{2\Delta J_s}{J_s} + \left(\frac{\Delta J_s}{J_s}\right)^2\right]\right\}\cos^2\vartheta$$



Magnetoelastic Anisotropy



mechanical strain
due to epitaxial growth

example: bcc-(110) - plane

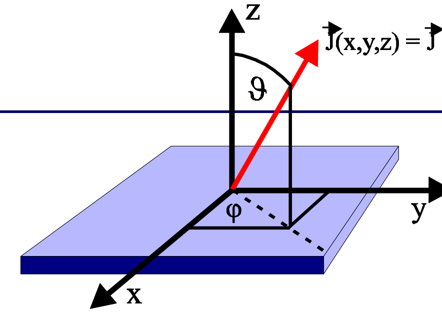
$$f^{me}(\vartheta, \pi/2) = B_2(\varepsilon_3 - \varepsilon_2)\cos^2\vartheta$$

$$B_2 = -3c_{44}\lambda_{111}$$ (magneto-elastic coupling constant)

Fe: $B_2 = 8\ 10^6\ \mathrm{J/m^3}$

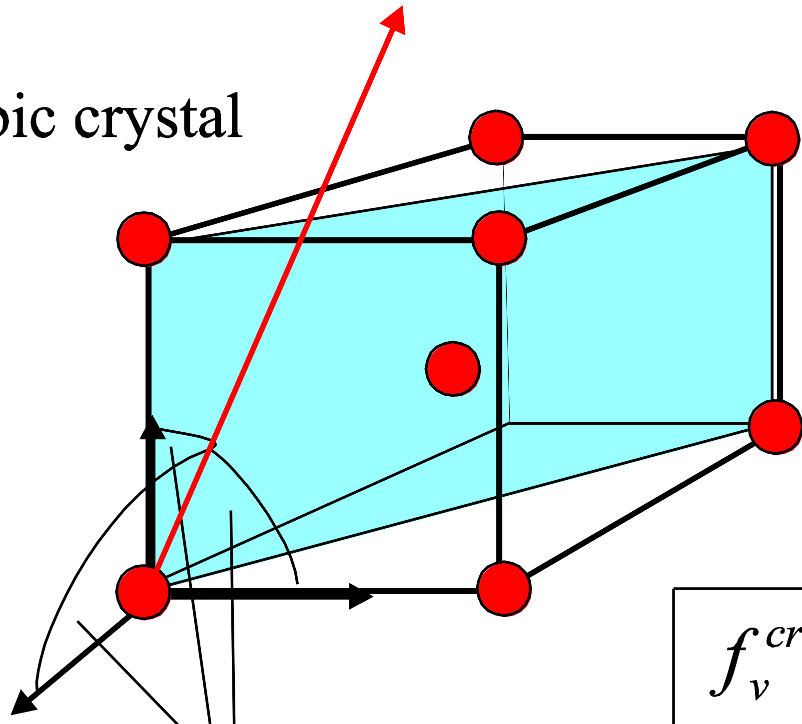
Attention: epitaxial strain often t-dependent $\varepsilon(t) = \varepsilon_v + (1/t)\,\varepsilon_s$

resulting in: $$f = f_v^{me} + \frac{1}{t} f_s^{me}$$



Magnetocrystalline Anisotropy

cubic crystal



$$F/V = K_1(\alpha_1^2\alpha_2^2+\alpha_2^2\alpha_3^2+\alpha_1^2\alpha_3^2)$$

transformation into sample-coordinates (i.e. (110))

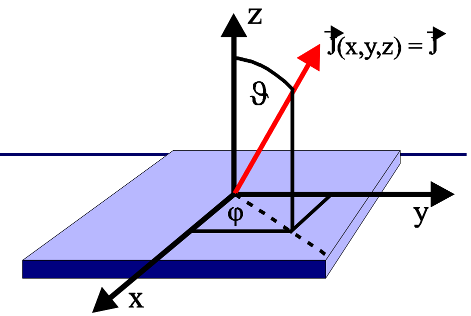
$$f_v^{cr}(\vartheta,\pi/2) = -K_1 \sin^2\vartheta \cos^2\vartheta$$

$$\alpha_i = \cos(e_i;J)$$

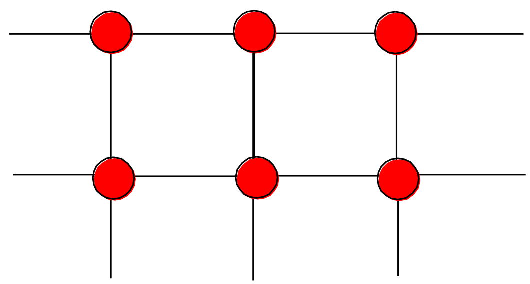
hexagonal crystal

$$f_v^{cr}(\vartheta,\varphi) = -(K_1+K_2)\cos^2\vartheta - K_2 \sin^2\vartheta\cos^2\vartheta$$

Surface - Anisotropy



$$F(\vartheta,\varphi) = f_v(\vartheta,\varphi)\cdot V + f_s(\vartheta,\varphi)\cdot A$$



Symmetry-Breaking
at an interface

Volume-Anisotropy := f_v proportional to the volume of the film

Surface-Anisotropy := f_s proportional to the surface

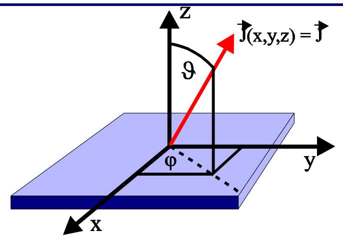
Energydensity: $$\frac{1}{V}F(\vartheta,\varphi) = f_v(\vartheta,\varphi) + \frac{1}{t} f_s(\vartheta,\varphi)$$

The part of f_s, due to symmetry-breaking is called:

Néel - type surface - anisotropy f_s^{Ne}

Magnetice Anisotropies

Surface-Anisotropy

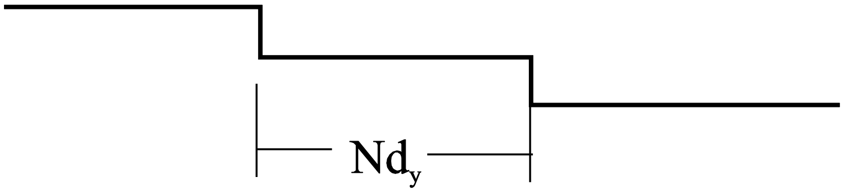


Néel - type Surface-Anisotropy as a function of polarangle

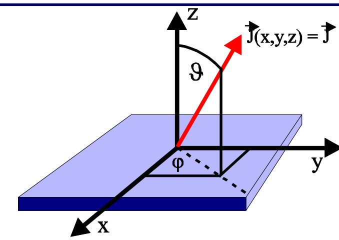
$$f_s^{Ne}(\vartheta, \pi/2) = K_{s,2}^{Ne} \cos^2\vartheta + K_{s,4yz}^{Ne} \sin^2\vartheta \cos^2\vartheta$$

Step-Anisotropy due to symmetry-breaking at a step

$$f^{step}(\vartheta, \varphi) = \frac{1}{t}\frac{1}{Nd_y}\left(K_{step}\cos^2\vartheta + K_{step,p}\cos^2\varphi \sin^2\vartheta\right)$$



Magnetic Anisotropies



Summary of all contributions:

$$f = f_v^{cr} + f_v^{sh} + f_v^{me} + f_v^{step} + \frac{1}{t}\left(f_s^{Ne} + f_s^{sh} + f_s^{me} + f_s^{step}\right)$$

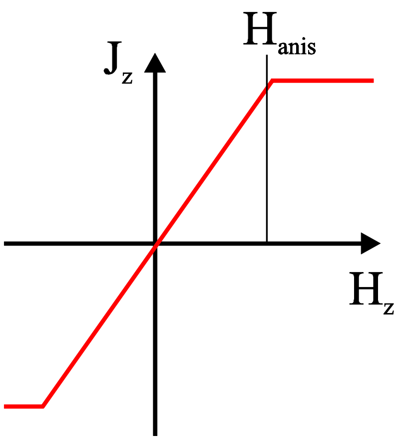
Out-of-plane Anisotropy $f(\vartheta,\pi/2)$:

$$f(\vartheta,\pi/2) = \left\{\left(\frac{J_s^2}{2\mu_0} + K_{v,2\perp}\right) + \frac{1}{t}K_{s,2\perp}\right\}\cos^2\vartheta + \left\{K_{v,4yz} + \frac{1}{t}K_{s,4yz}\right\}\sin^2\vartheta\cos^2\vartheta$$

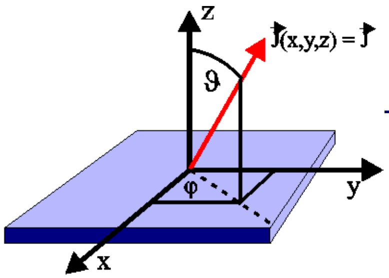
Definition of the anisotropy field H_{anis}:

$$f_{\vartheta\vartheta}(\vartheta_0,\pi/2) = H_{anis}(\vartheta_0,\pi/2)J_s$$

$$H_{anis} = \pm\frac{2L}{J_s} = \pm\frac{2}{J_s}\left\{\left(\frac{J_s^2}{2\mu_0} + K_{v,2\perp}\right) + \frac{1}{t}K_{s,2\perp}\right\}$$



Magnetic Anisotropies

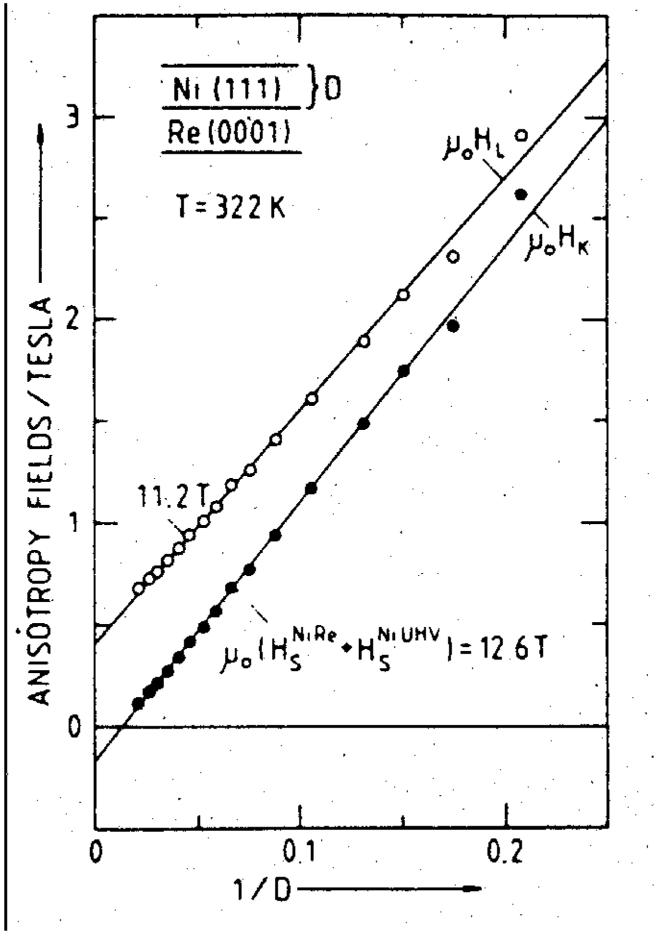


$$\mu_0 H_{anis} = J_s + \mu_0 \frac{2K_{V,2\perp}}{J_s} + \underline{\frac{1}{D}\mu_0 \frac{2K_{s,2\perp}}{t_1 J_s}}$$

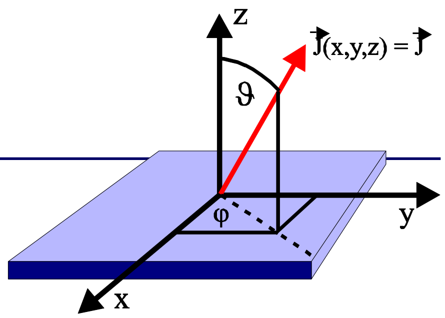
$$\mu_0 H_{anis} = J_s + \mu_0 H_K + \underline{\frac{1}{D}}\mu_0 H_s$$

Shape anisotropy depends on thickness

$K_{s,2\perp} = 0.6$ mJ / m²

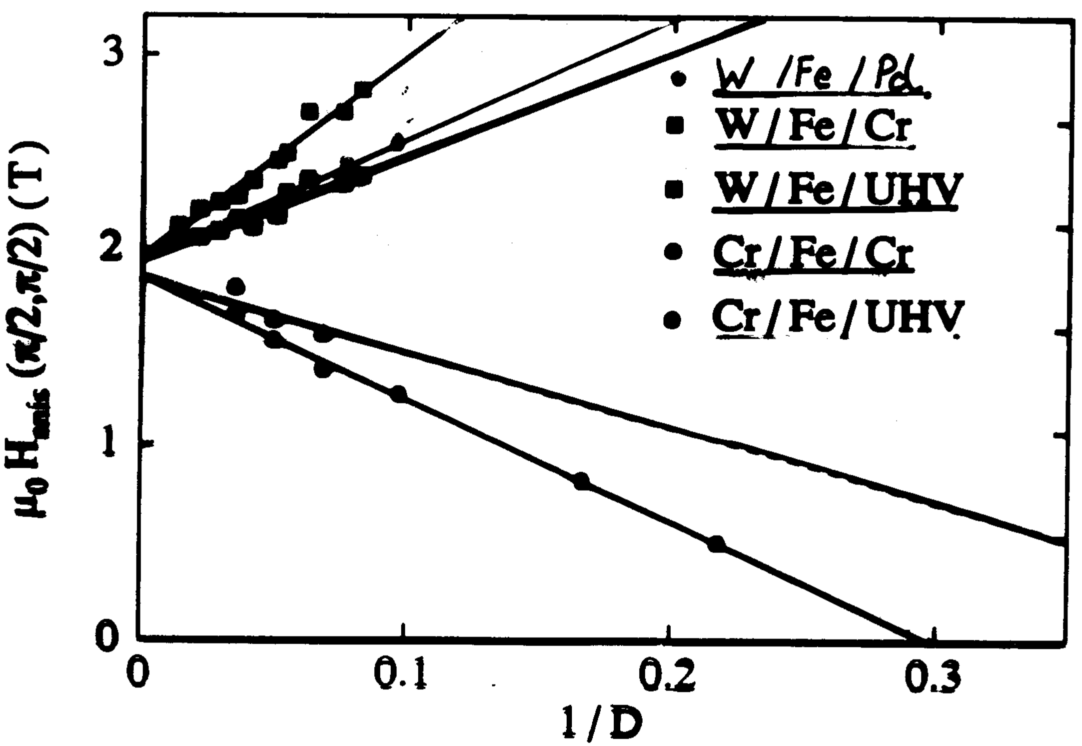


Magnetic Anisotropies

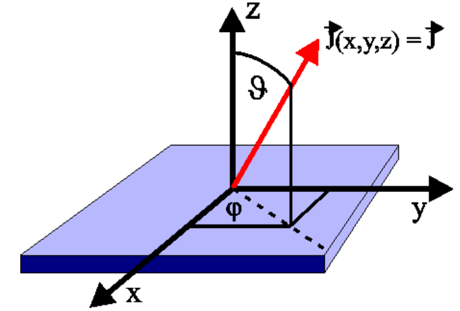


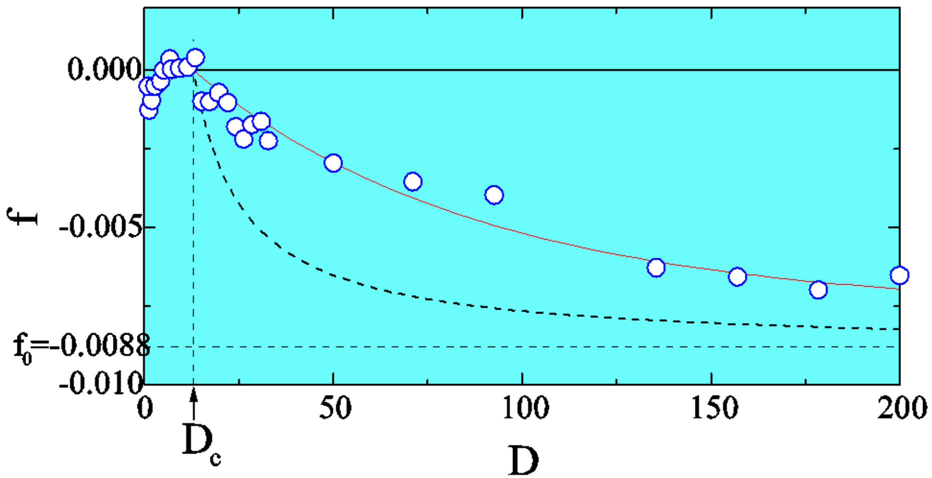
Determination of single interface anisotropies

$$H_{anis} = \frac{1}{\mu_0} J_s + \frac{1}{D}\left(H_s^{(1)} + H_s^{(2)}\right)$$

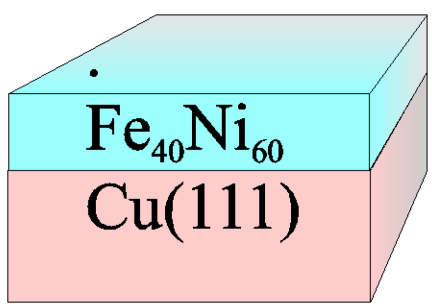


Magnetic Anisotropies



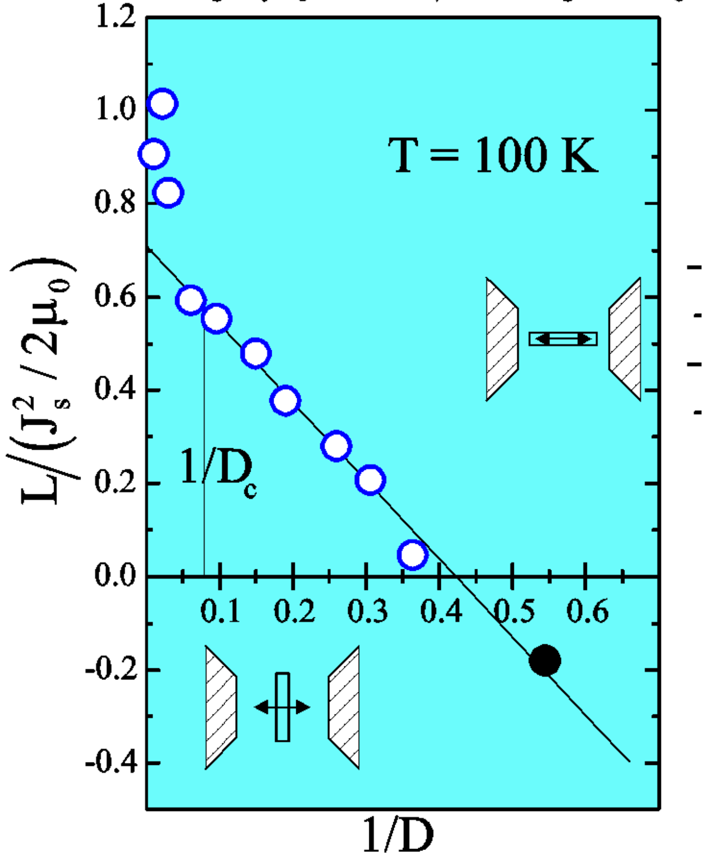


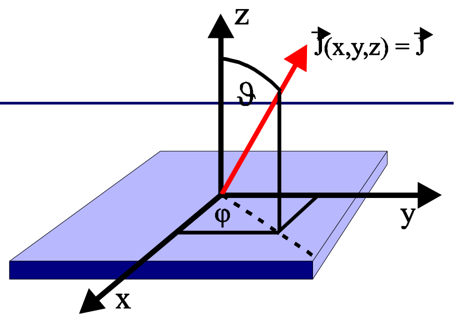
Misfit $(a_{FeNi}-a_{Cu})/a_{Cu}$ vs. film thickness



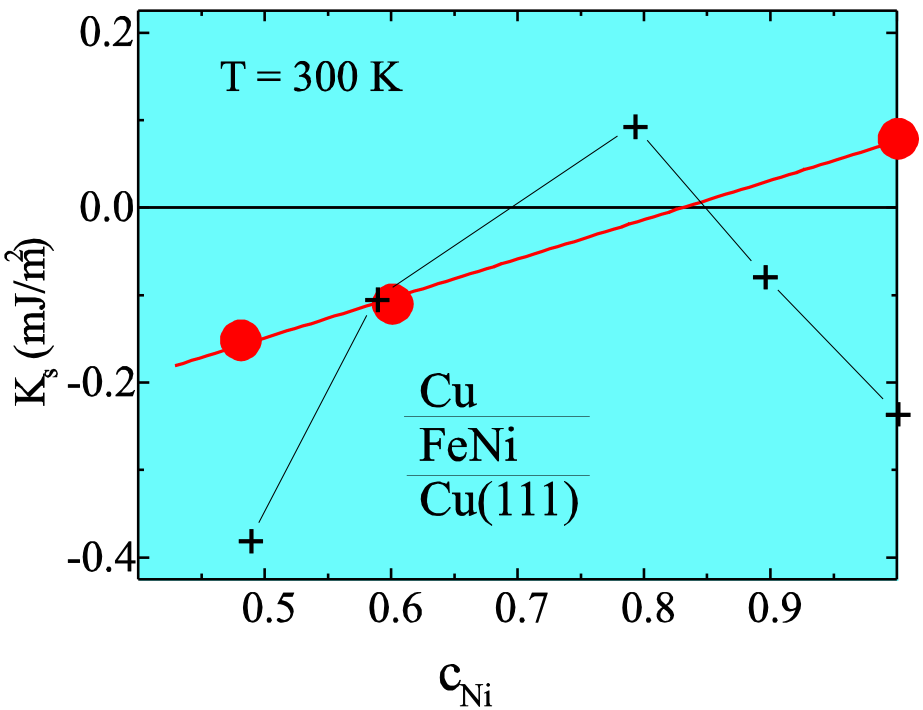
Anisotropy constant L

$$L = J_s^2/\mu_0 + K_V + K_s/Dd_0$$





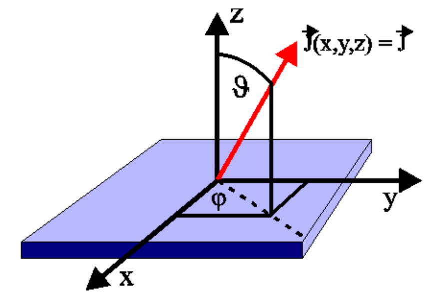
Anisotropy constant changes with Ni concentration

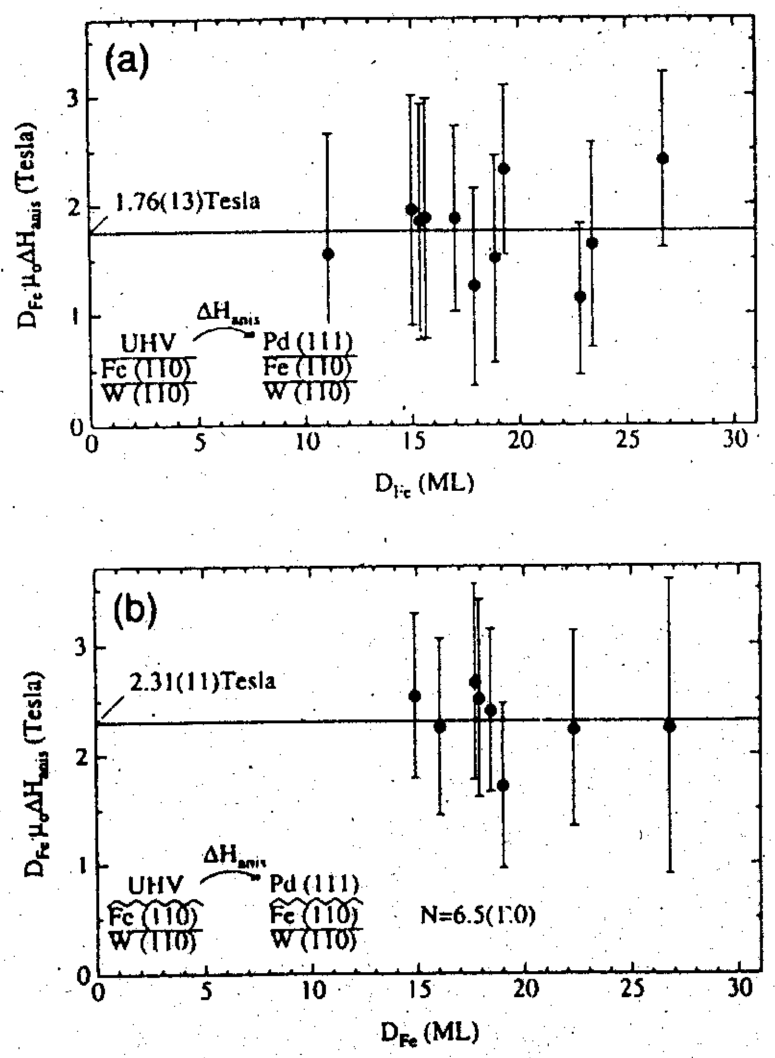


Interface anisotropy changes sign at $Fe_{20}Ni_{80}$

Magnetic Anisotropies

Step Anisotropies





ΔH_{anis}

UHV / Fe(110) / W(110) → Pd(111) / Fe(110) / W(110)

$$D\Delta H_{anis} = \Delta H_s(Pd)$$

ΔH_{anis}

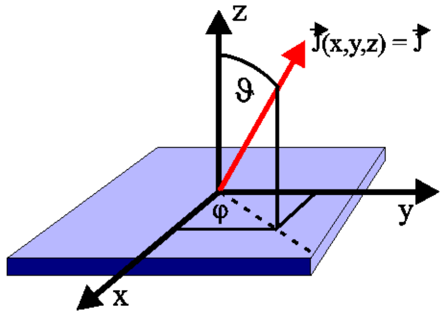
UHV / Fe(110) / W(110) → Pd(111) / Fe(110) / W(110)

$$D\Delta H_{anis} = \Delta H_s(Pd) + (1/N)\Delta H_{step}(Pd)$$

$$\Delta H_{step}(Pd) = 1.6(9)\text{ Tesla}$$

Magnetic Anisotropies

Higher Order Anisotropies

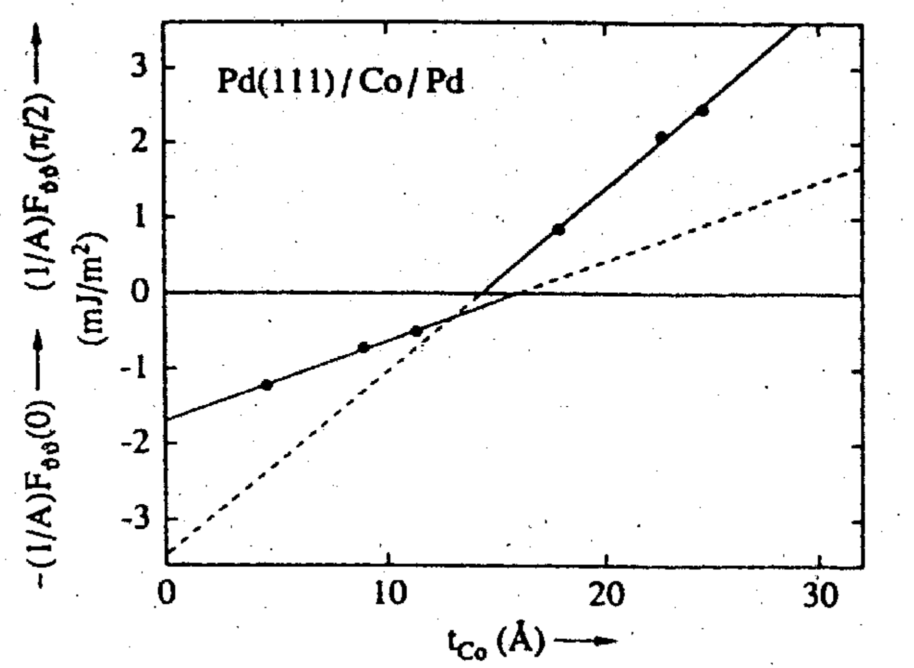


$$\frac{F(\vartheta,\varphi)}{V} = \kappa_2(t)\cos^2(\vartheta) + \kappa_4(t)\cos^2(\vartheta)\sin^2(\vartheta)$$

$$\frac{F_{\vartheta\vartheta}(\pi/2,\pi/2)}{A} = \left\{\frac{J_s^2}{\mu_0} + 2\left(K_{V,2\perp} + K_{V,4yz}\right)\right\}t + 2\left(K_{s,2\perp} + K_{s,4yz}\right)$$

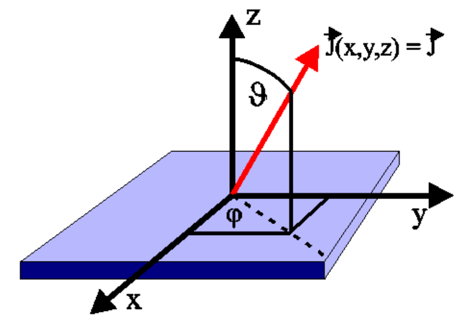
$$\frac{F_{\vartheta\vartheta}(0,\pi/2)}{A} = \left\{\frac{J_s^2}{\mu_0} + 2\left(K_{V,2\perp} - K_{V,4yz}\right)\right\}t + 2\left(K_{s,2\perp} - K_{s,4yz}\right)$$

Determination of higher order anisotropies from measurements in thickness regimes of different easy axis

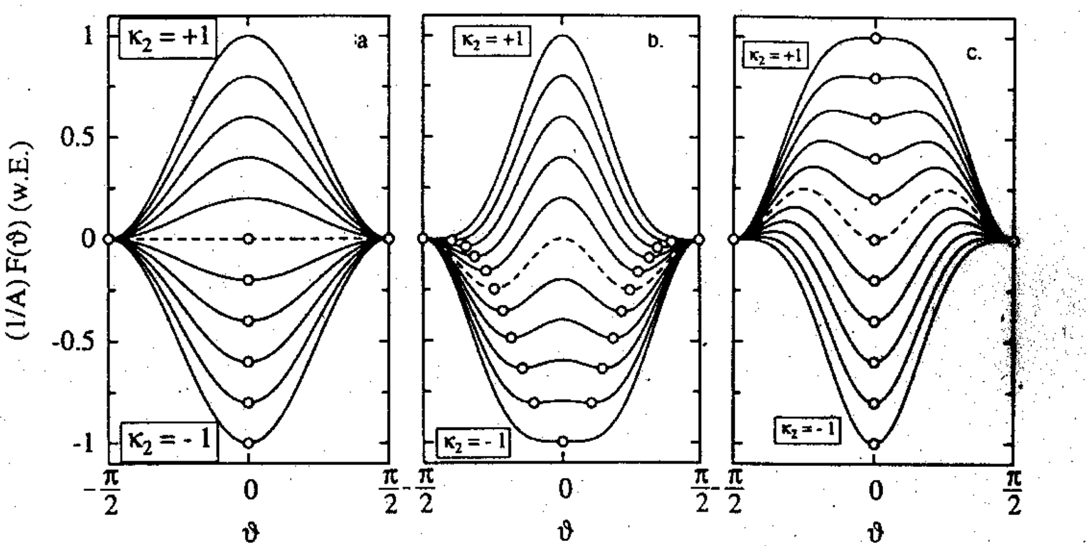


Magnetic Anisotropies

Spin reorientation transition with anisotropies of higher order

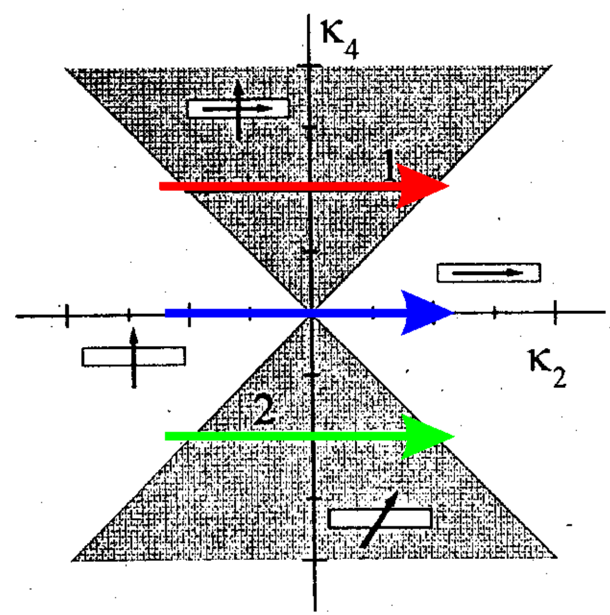


$$f(\vartheta) = \kappa_2 \cos^2(\vartheta) + \kappa_4 \cos^2(\vartheta)\sin^2(\vartheta)$$



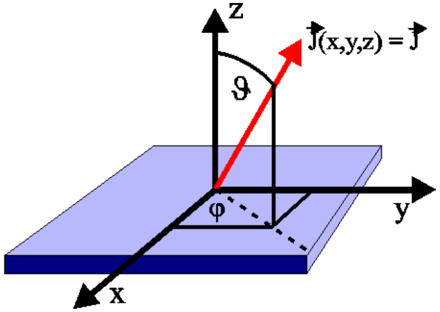
$\kappa_4 = 0$ $\kappa_4 = -1$ $\kappa_4 = +1$

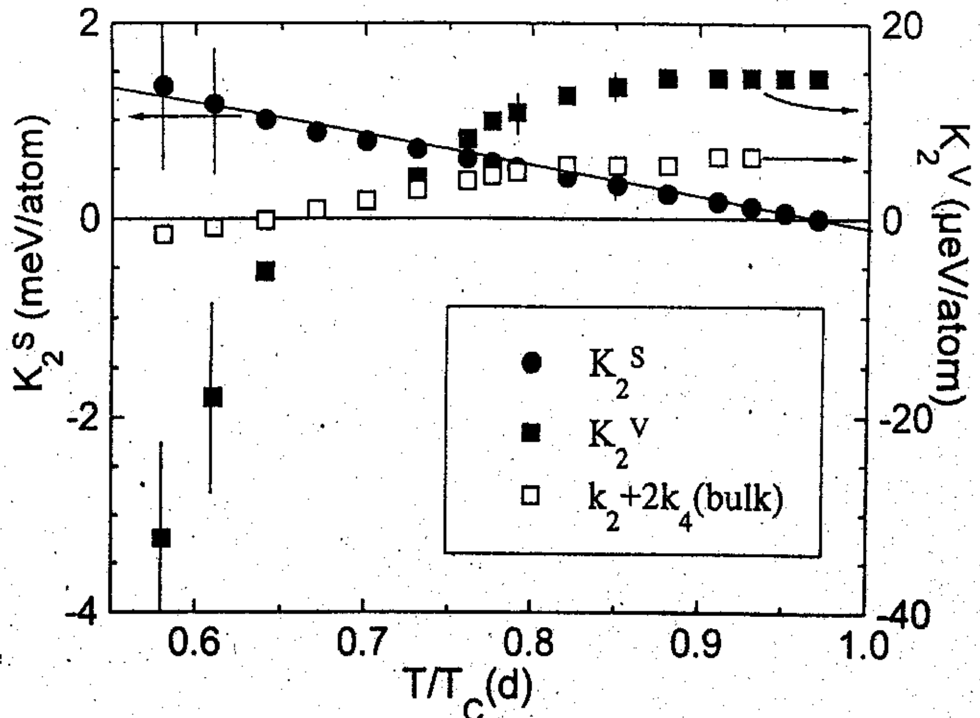
special | continuous rotation | metastable states

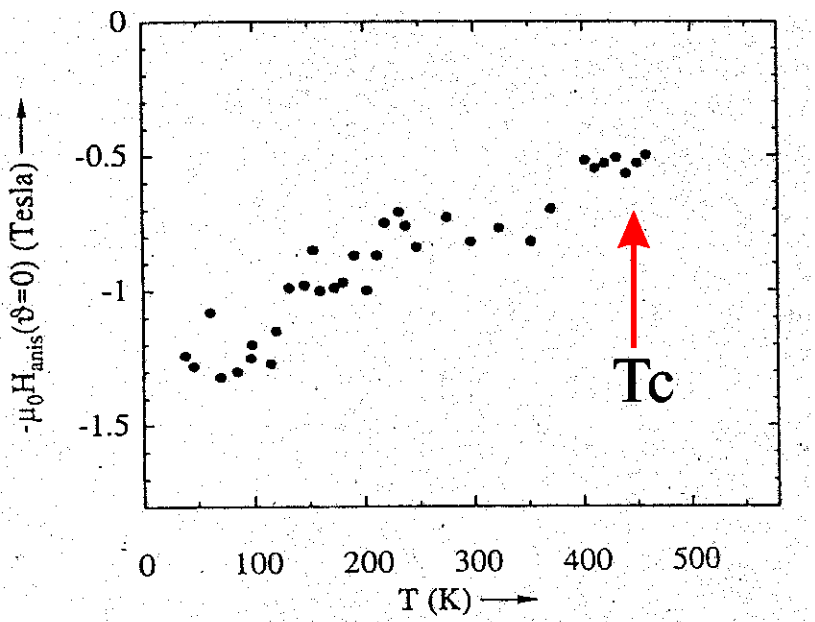


Magnetic Anisotropies

Temperature dependence





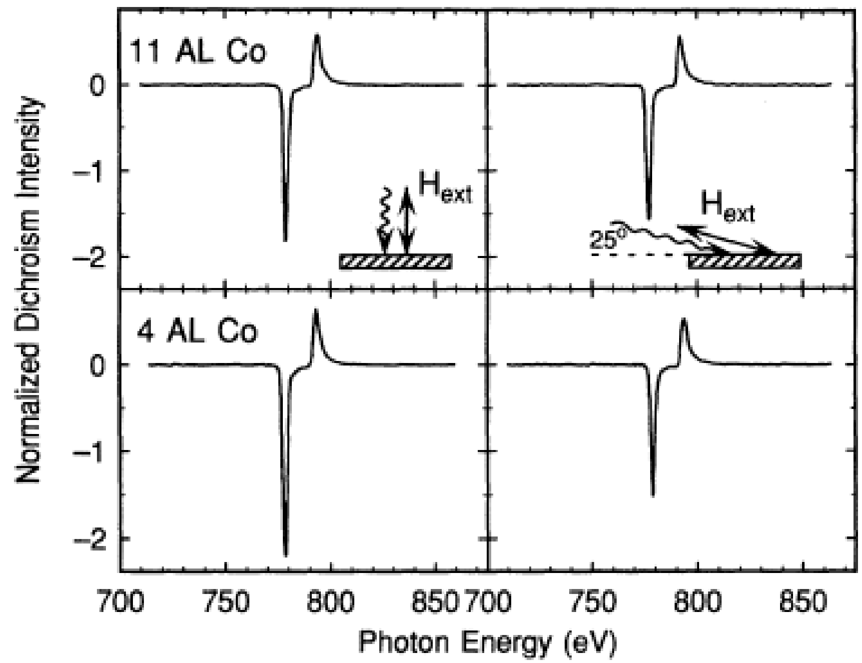


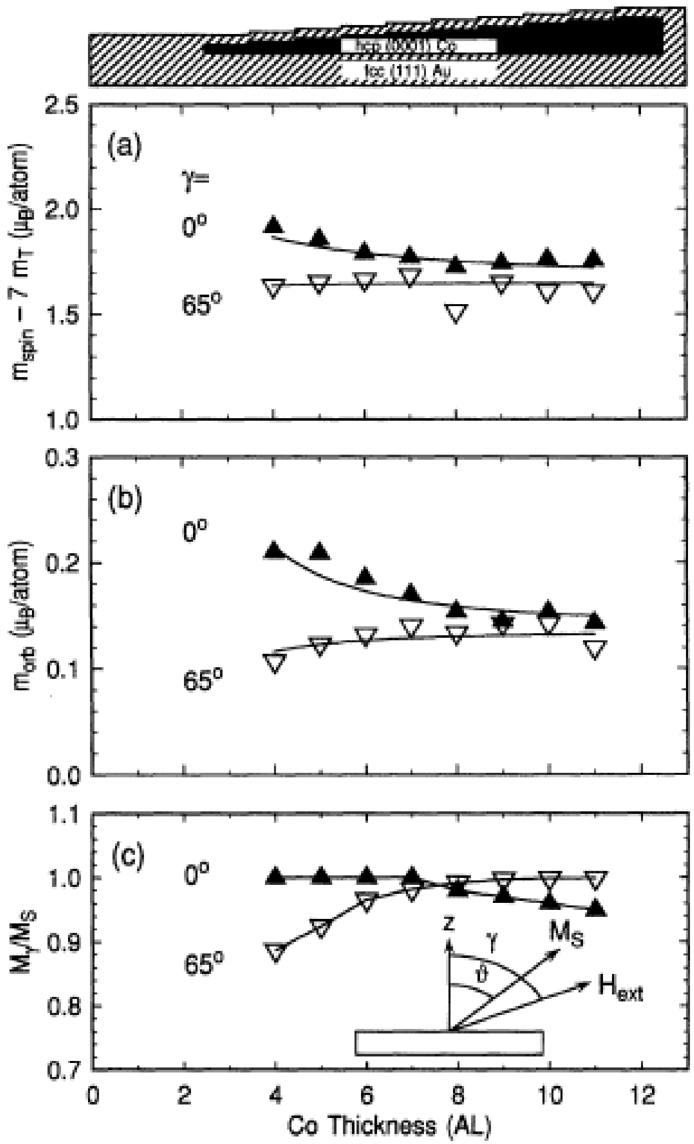
Gd(0001) on W(110) M. Farle, Rep. Progr. Phys. 61, 755 (1998)

1 ML Co on Cu(111)

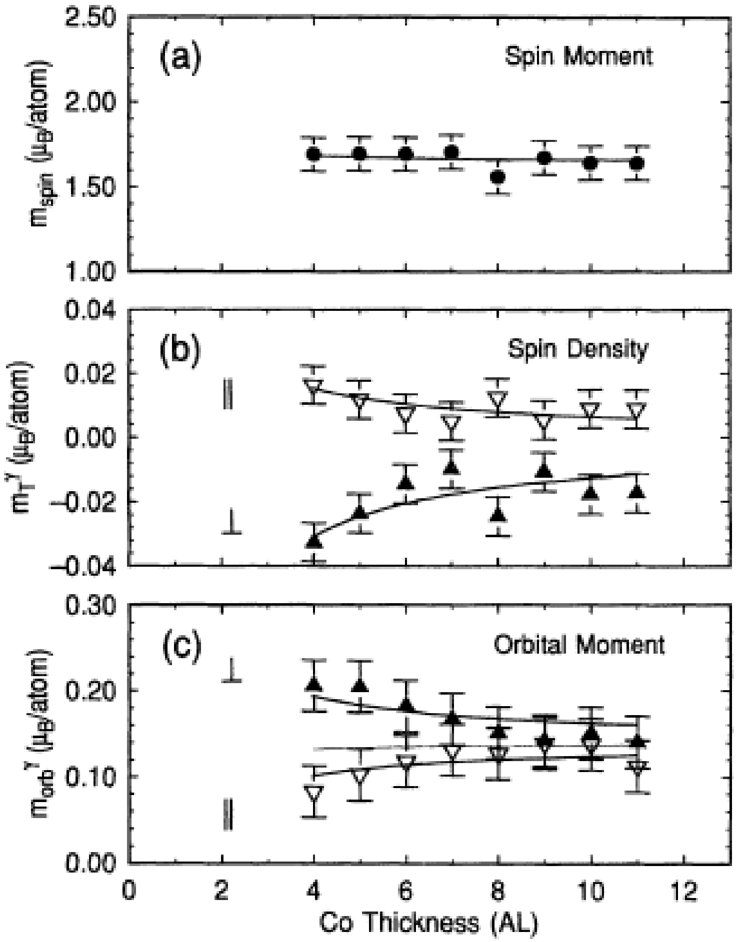
Microscopic Origin of Magnetic Anisotropy in Au/Co/Au Probed with X-Ray Magnetic Circular Dichroism

D. Weller,[1] J. Stöhr,[1] R. Nakajima,[2] A. Carl,[1,*] M. G. Samant,[1] C. Chappert,[3] R. Mégy,[3]
P. Beauvillain,[3] P. Veillet,[3] and G. A. Held[4]





hcp (0001) Co
fcc (111) Au
(a)
γ=
0°
65°
$m_{spin} - 7\,m_T$ (μ_B/atom)
(b)
0°
65°
m_{orb} (μ_B/atom)
(c)
0°
65°
M_γ/M_S
z
γ
ϑ
M_S
H_{ext}
Co Thickness (AL)

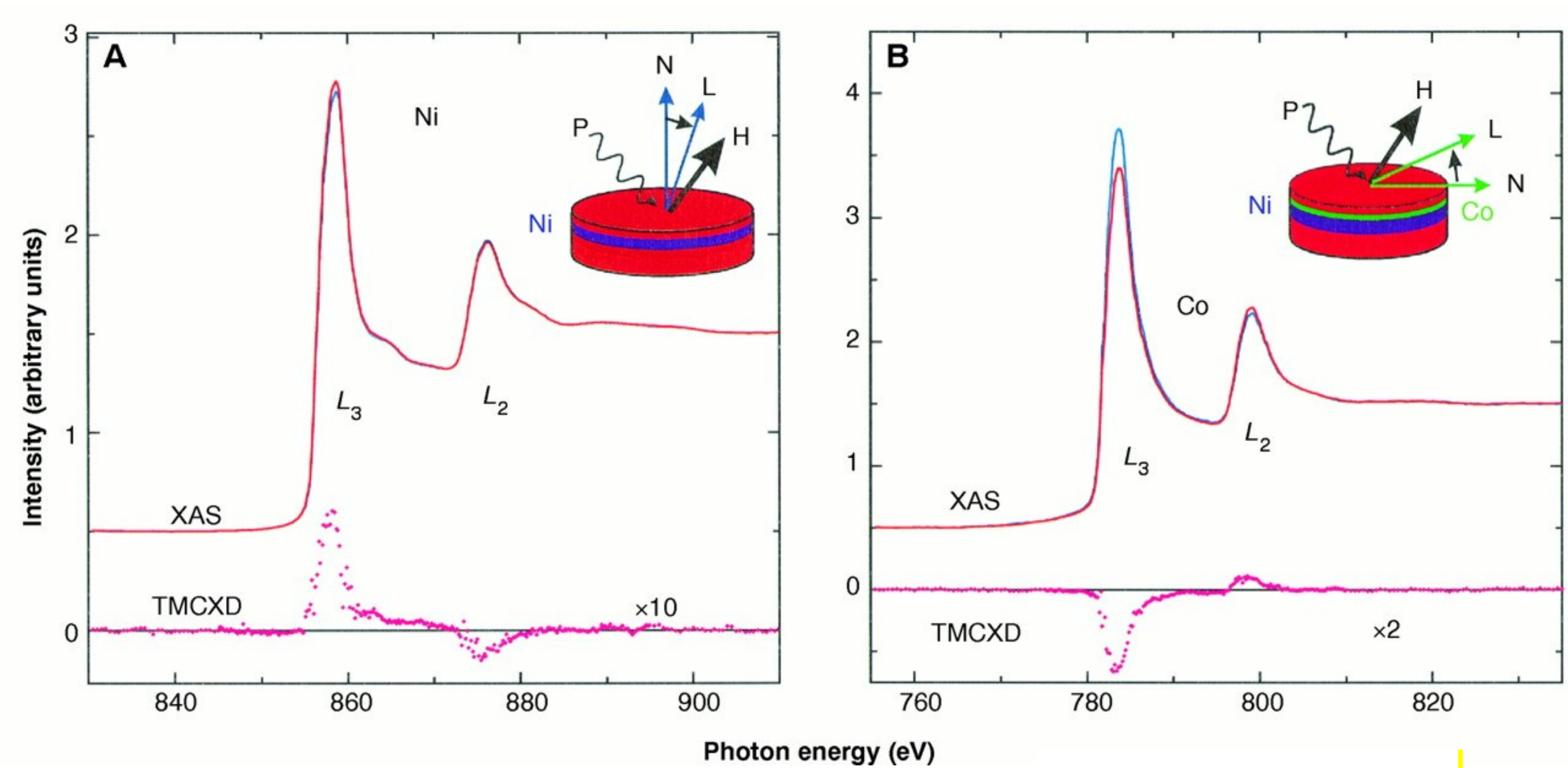


(a)
Spin Moment
(b)
Spin Density
(c)
Orbital Moment
Co Thickness (AL)

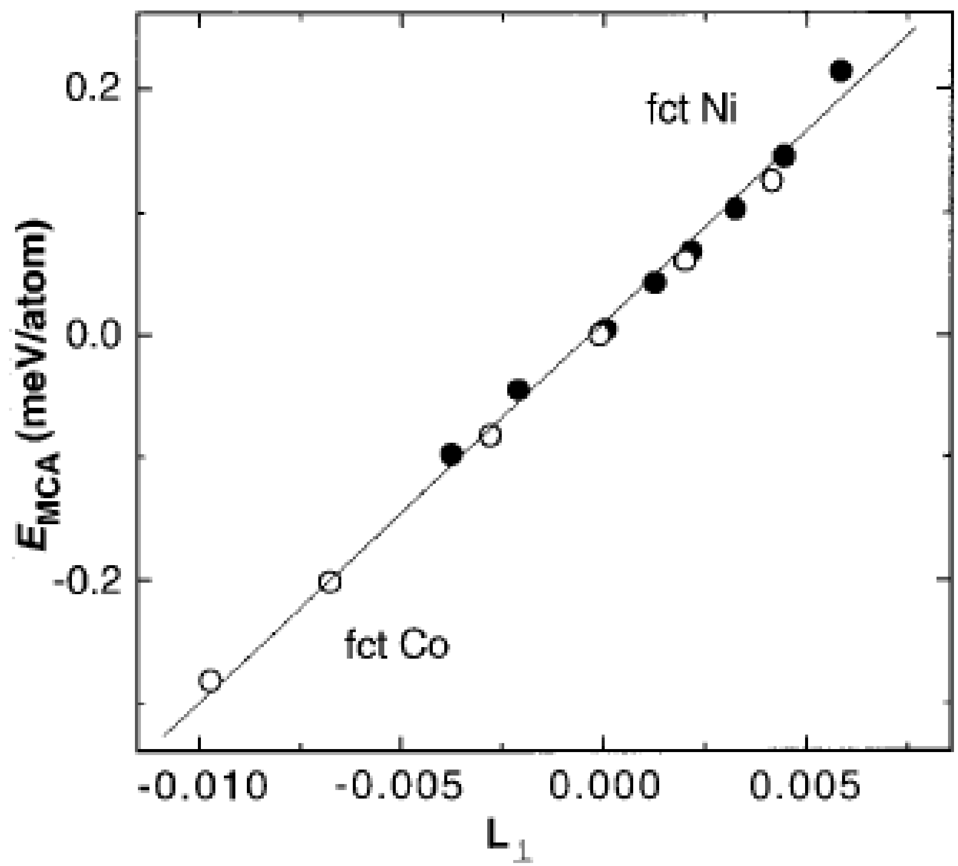
Durr HA, Guo GY, vanderLaan G, et al.

Element-specific magnetic anisotropy determined by transverse magnetic circular x-ray dichroism

SCIENCE 277 (5323): 213-215 JUL 11 1997



$$\mathbf{L}\cdot\mathbf{P} = -n_h \frac{4}{3}\frac{\Delta A}{A}$$



0.2
0.0
-0.2
E_{MCA} (meV/atom)
fct Ni
fct Co
-0.010
-0.005
0.000
0.005
$L_\perp$