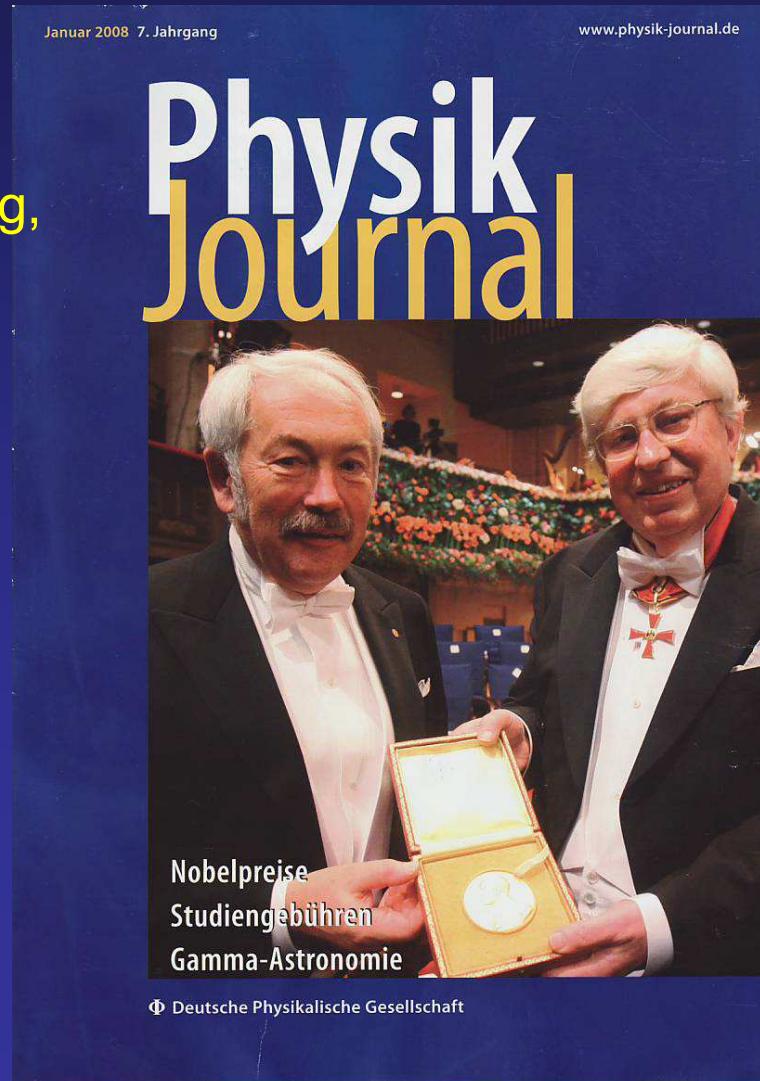


# Nobel Laureates 2007

Physics:  
Prof. Peter Grünberg,  
FZ Jülich  
and  
Prof. Albert Fert,  
Paris



Chemistry:  
Prof. Gerhard Ertl,  
Fritz Haber Institut der  
MPG, Berlin

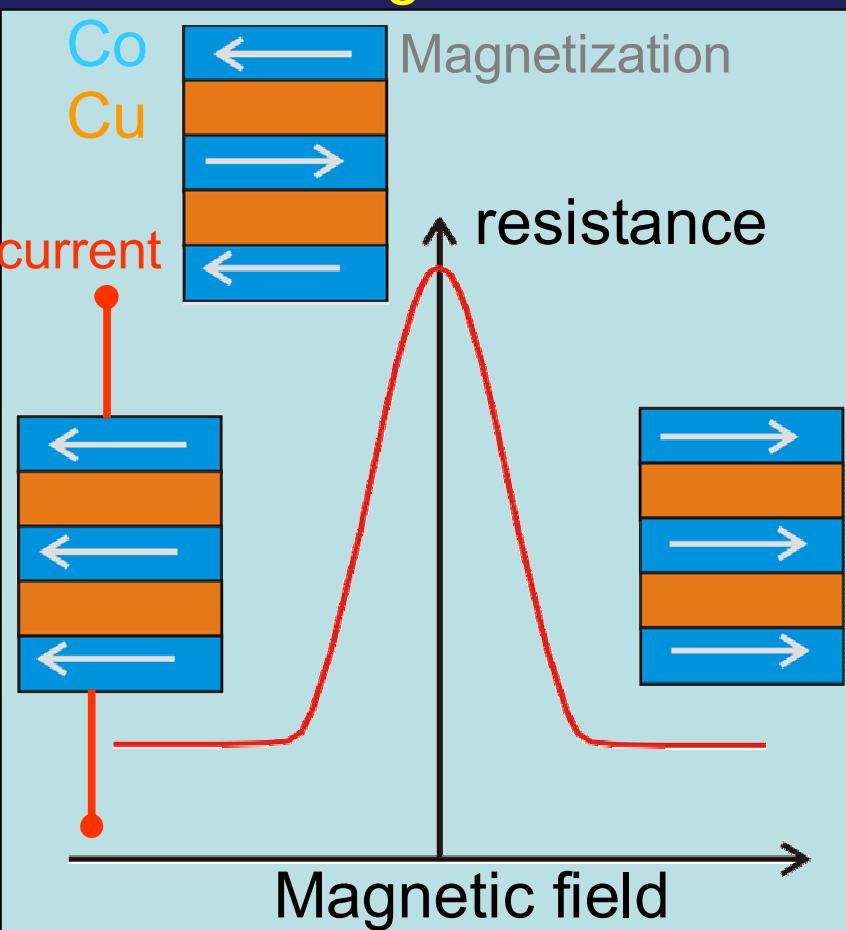
# Giant Magneto Resistance: GMR

Electrical resistance of stacked magnetic layers

FAST transition discovery - application



P. Grünberg,  
FZ Jülich  
US Patent 4,949,039  
1990

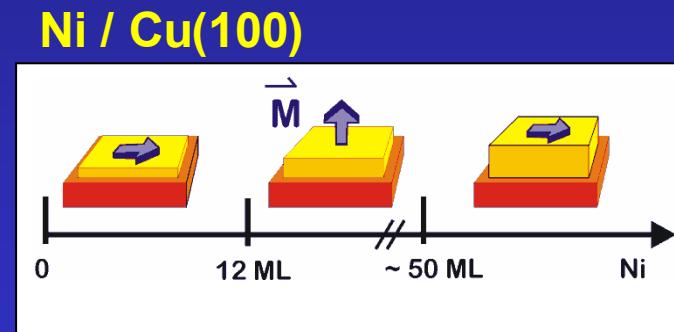
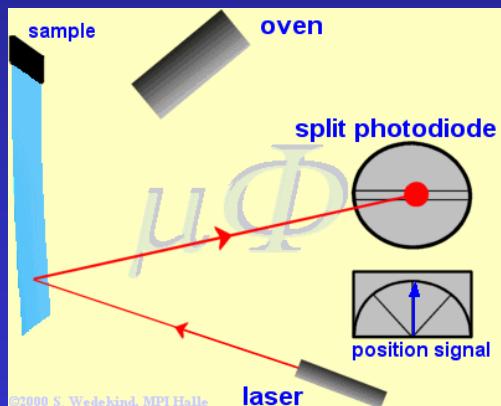


A. Fert,  
Paris

# Magnetic Anisotropy and How it can be controlled

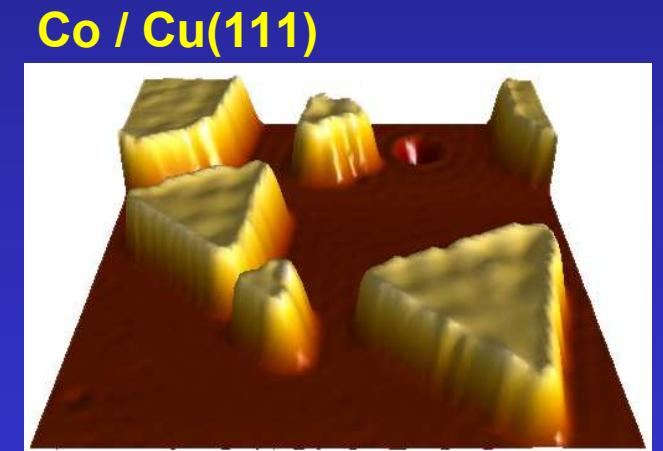
Dirk Sander

Max-Planck-Institut für Mikrostrukturphysik, Halle, Germany  
[www.mpi-halle.de](http://www.mpi-halle.de)



Stress and magnetism:  
Magnetic anisotropy

Surface stress,  
Film stress,  
magnetoelastic stress



Spin-STM  
Magnetic switching  
Spin-polarization

# Acknowledgment



**Max Planck Institute of Microstructure Physics  
Halle, Germany**



Jürgen  
Kirschner



Hirofumi  
Oka

Guillemin  
Rodary

Zhen  
Tian

Sebastian  
Wedekind

Nicole  
Kurowsky

# Magnetism is everywhere!

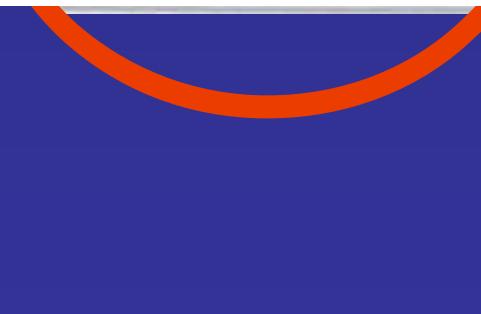


## Magnetic anisotropy

decisive for applications, and demanding for theory:

Easy magnetization direction

Remanent magnetization in view of temperature and stray fields



# What will be covered?

Experimental evidence for magnetic anisotropy  
and why do we worry...

Typical energy scales involved

Contributions to the magnetic anisotropy  
dipolar interactions  
spin-orbit-coupling

How to quantify magnetic anisotropy

Hard-axis magnetization loops  
Magnetoelastic coupling  
Magnetic switching and thermal stability (?)

How to control the magnetic anisotropy

crystalline order  
film thickness, lattice strain  
adsorbate coverage, temperature

# Ferromagnetic nanostructures

- $L_{\text{sample}} \sim L_{\text{exch}} \sim L_{\text{domain wall}}$   
monodomain (Stoner-Wohlfarth switching ?)

Bonet et al., PRL 83, 4188 (1999)

- Temperature could overcome anisotropy  $kT \sim KV$   
superparamagnetism

Bean et al., JAP 30, 120S (1959)

Néel, Ann. Geophys. 5, 99 (1949)

- Atoms with low coordination

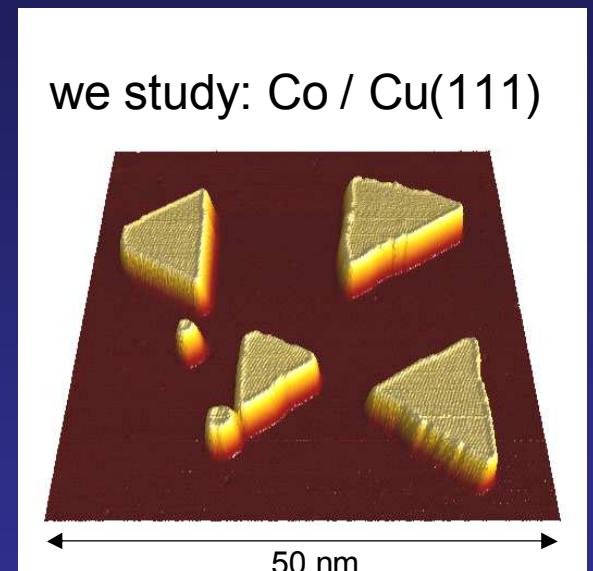
$K_{\text{surface}}$  and / or  $M$  could be very high

Gambardella et al.,  
Science 300, 1130 (2003)

- Quantum effects (discrete states, collective tunneling)

Bernand-Mantel et al., APL 89, 062502 (2006)

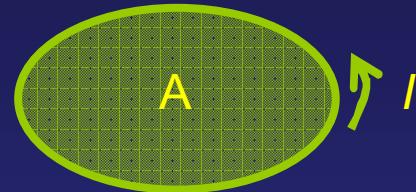
Wernsdorfer et al. ,PRL 79, 4014 (1997)



# Reminder about units: magnetic moment, magnetization, magnetic field

Current loop and its magnetic moment  $m$ :

$$m = I A \text{ [A m}^2\text{]}$$



microscopic view: electron orbit with orbital moment

Natural unit of  $m$ : Bohr magneton  $\mu_B$

$$m = \frac{e\ell}{2m_e} = \frac{e\hbar}{2m_e} = \mu_B \\ = 9.27 \times 10^{-24} \text{ A m}^2$$

Note:  $[\text{A m}^2] = [\text{J T}^{-1}]$

Magnetization  $M$ : total magnetic moment per volume

$$M: [\text{A m}^{-1}] = [\text{J m}^{-3} \text{ T}^{-1}]$$

Magnetic field  $B$  of induced by current  $I$  through wire:

Custom: x-scale of hysteresis loop:  $\mu_0 H$  [ $\text{T}$ ]

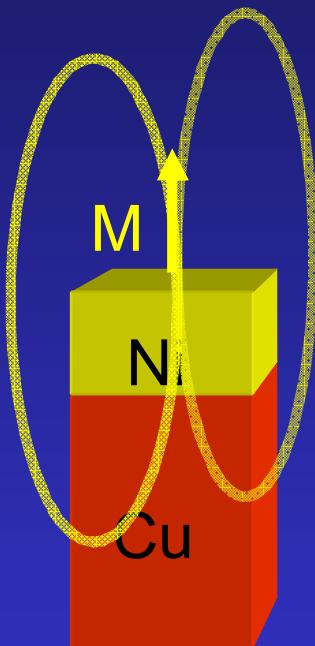
Note: energy density  $\int \mu_0 H \text{ d}M : [\text{J / m}^3]$

$$B = \frac{\mu_0 I}{2\pi r} \left( H = \frac{1}{\mu_0} B \text{ [A/m]} \right)$$

$$\mu_0 = 4\pi 10^{-7} \left[ \text{T} \frac{\text{m}}{\text{A}} \right] \\ 1 \text{ T} = 7.96 \times 10^5 \text{ A / m}$$

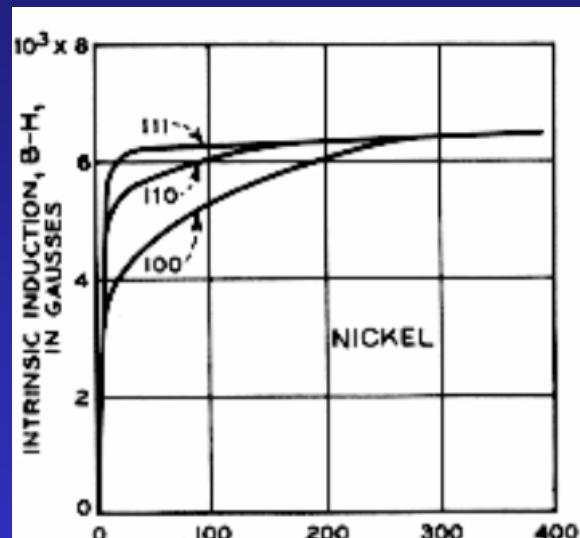
# Contributions to the magnetic anisotropy energy

dipolar origin:

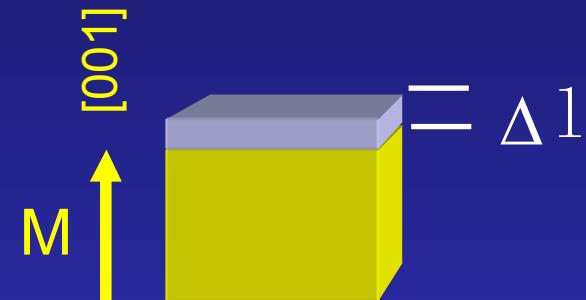


spin-orbit interaction:

magnetocrystalline anisotropy



magnetostriiction



contraction upon  
magnetization [001]

epitaxial lattice contraction [001]:  
polar magnetization

$$f_{\text{demag}} = \frac{1}{2} \mu_0 M^2$$

$11 \mu\text{eV} / \text{atom}$

$$K_1 = 0.4 \mu\text{eV} / \text{atom}$$

$$B_1 = 650 \mu\text{eV} / \text{atom}$$

lattice strain: decisive for anisotropy

# Physical origin of magnetic anisotropy

## spin-orbit interaction

Exchange energy refers only to the angle between spins, but  
NOT to the absolute orientation

$$H_{exchange} \sim J_{ij} S_i S_j$$

Relativistic quantum mechanics:

$$H_{SOC} \sim \xi \ell \cdot s$$

spin-orbit interaction:

Spin-orbit constant:  $\xi$  (3d: 50 – 100 meV)

electron spin  $s$  interacts with the magnetic moment of its own orbital motion /

the orbital motion interacts with the crystal structure by electrostatic fields

However, the orbital angular momentum is largely quenched in cubic crystals

Electrons: hybrids of wavefunction of opposite  $m_l$

Small magnetic anisotropy: cubic systems ( $\mu\text{eV} / \text{atom}$ ),

large anisotropy: reduced symmetry,

e.g. hexagonal or strained systems ( $\text{meV} / \text{atom}$ )

Dipolar crystalline anisotropy: (NOT shape anisotropy) hcp and strained cubic:  
negligible, as compared to SOC

# Energy scales in magnetism and magnetic anisotropy

Magnetic anisotropy energy scales are very small ( $\mu\text{eV}$ ) as compared to bond energies, elastic energies

$$f_{\text{cubic}} = K_1(\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_1^2 \alpha_3^2) + K_2(\alpha_1^2 \alpha_2^2 \alpha_3^2) + \dots$$

$$f_{\text{hex}} = K_1 \sin^2 \theta + K_2 \sin^4 \theta + \dots$$

		bcc-Fe 273 K	hcp-Co 275 K	fcc-Ni 296 K
$K_1$	(MJ m <sup>-3</sup> )	0.048	0.513	-0.006
	(meV/atom)	0.0035	0.035	-0.0004
$K_2$	(MJ m <sup>-3</sup> )	0.001	0.001	-0.003
	(meV/atom)	0.00007	0.00007	-0.0002
$T_C$	(K)	1044	1360	627
	(meV/atom)	90	117	54

$\alpha_i$  : Direction cosine  
with respect to cubic axes

$\theta$  : Angle M, c-axis

# Dipole-dipole interactions

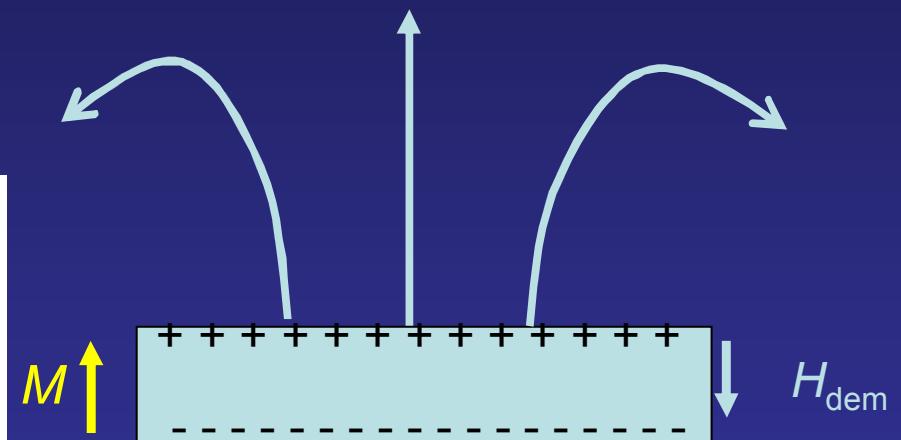
Shape anisotropy and demagnetizing field

Phenomenological picture:

magnetic surface charges, *outside*: sources of stray field

*Inside*:  $H_{\text{dem}}$  oriented antiparallel to  $M$   
*demagnetizing field*

		bcc-Fe	hcp-Co	fcc-Ni
		286 K	287 K	287 K
$M_s$	(kA m <sup>-1</sup> )	1717	1447	493
$\mu_0 M_s$	(T)	2.16	1.82	0.62
$\frac{1}{2} \mu_0 M_s^2$	(MJ m <sup>-3</sup> )	1.85	1.32	0.15
	(meV/atom)	0.14	0.09	0.012



$H_{\text{dem}}$  : constant only for ellipsoids

$$\mu_0 H_{\text{dem}} = -N M$$

$N$ : demagnetizing tensor, here  $N=1$

$$f_{\text{shape}} = - \int_0^{M_s} \mu_0 H_{\text{dem}} \, dM = \frac{1}{2} \mu_0 M_s^2$$

D. Sander

JPCM 16 (2004) R603

# Stress: from films to surfaces

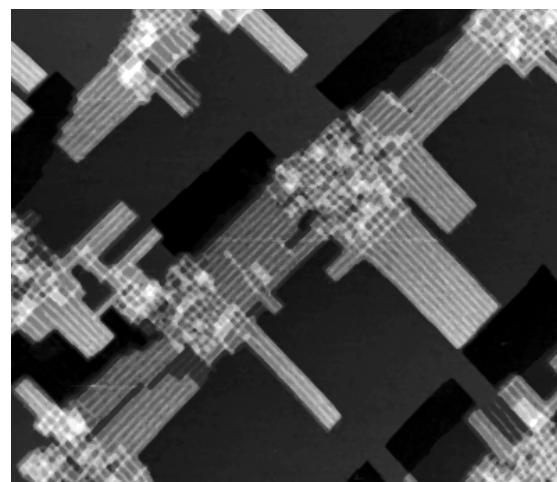
900 nm Cr / glass



1.2 mm

Hu et al.,  
Acta Metall. 36 (1988)1301

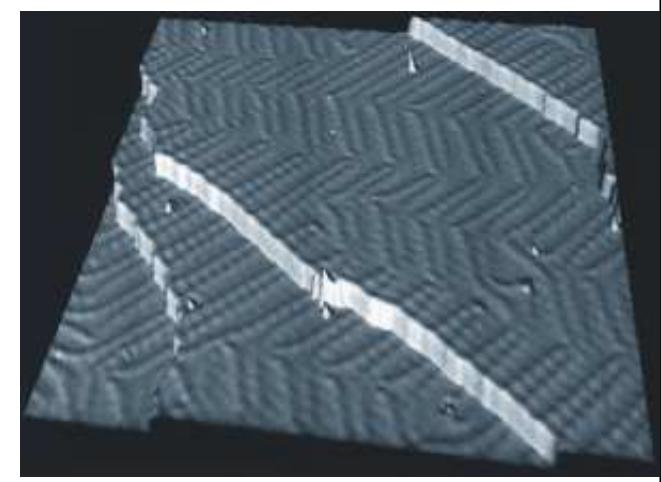
5 atomic layers Fe / W(100)



200 nm

W. Wulfhekel et al.,  
EPL 49(2000)651

Au(111)



80 nm

Crommie et al.,  
PRL 80 (1998) 1469

delamination

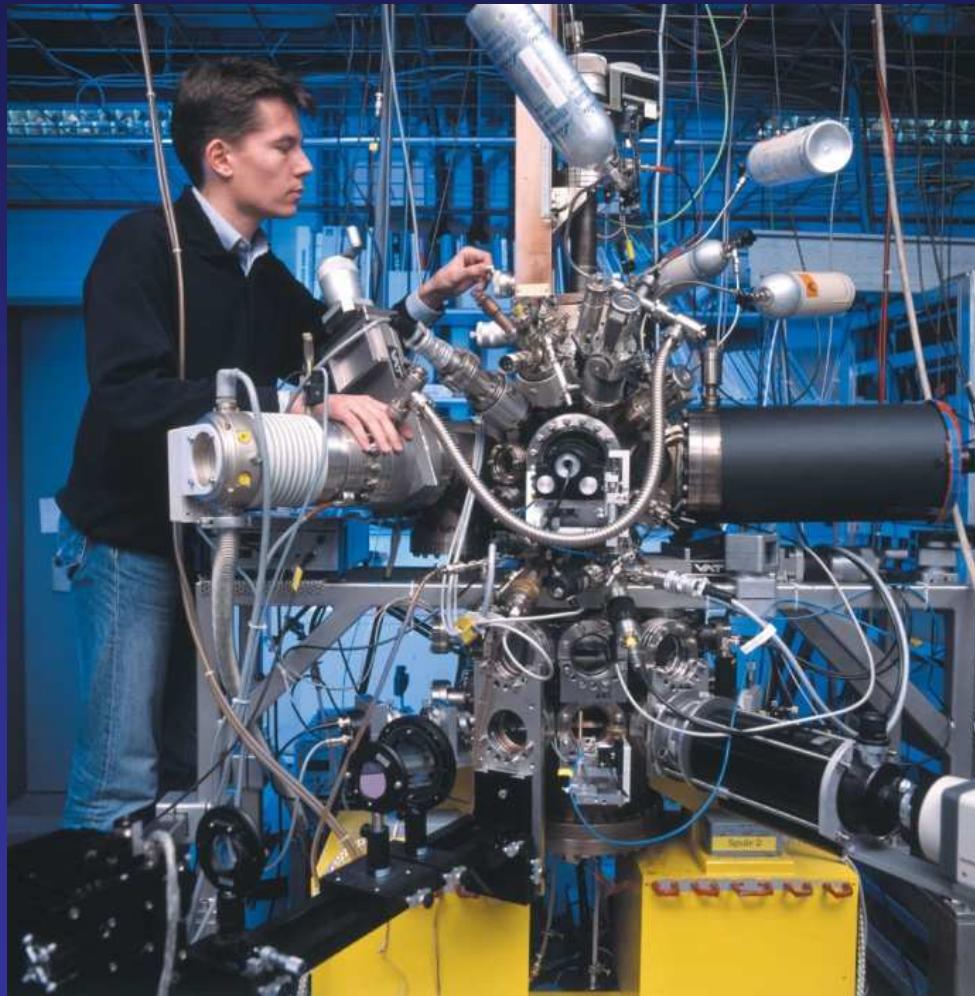
nano-patterning of  
magnetic anisotropy

surface stress

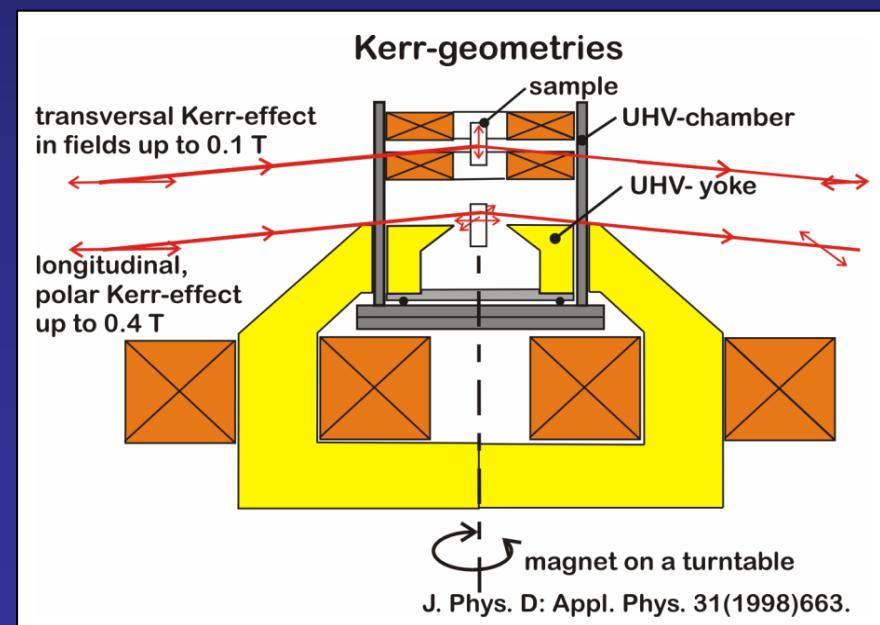
*Strain and its impact on magnetic anisotropy needs to be considered*

# Specific experimental equipment at the MPI Halle

In-situ preparation and magnetic measurements (separate: spin-STM)

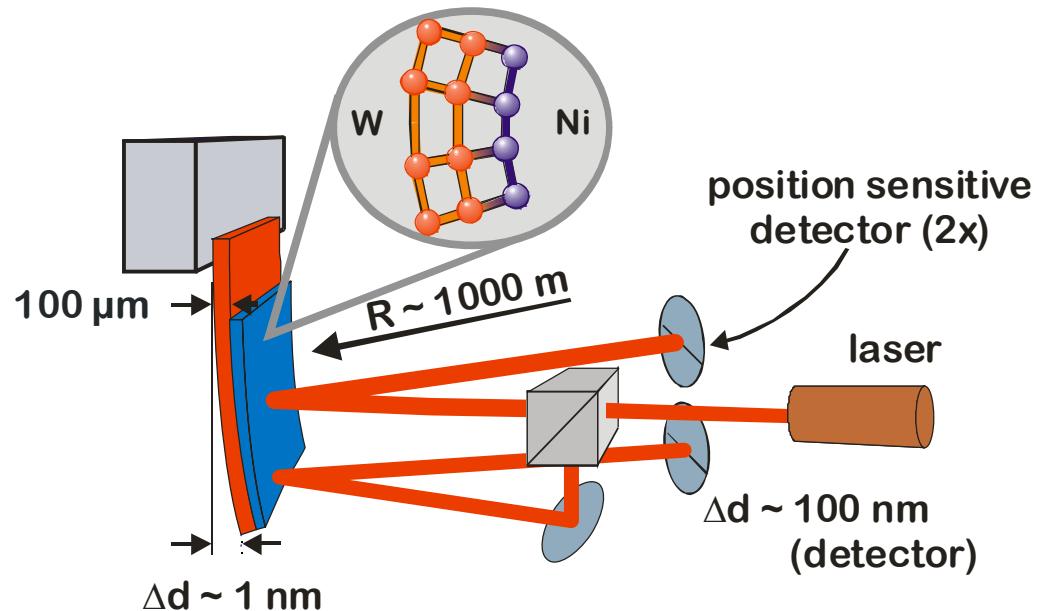


Auger electron spectroscopy  
Low energy electron diffraction  
Ion gun  
Evaporators  
Magneto-optical Kerr-effect  
Crystal curvature stress measurements



# Stress measurements

film growth:



limits of static measurements:

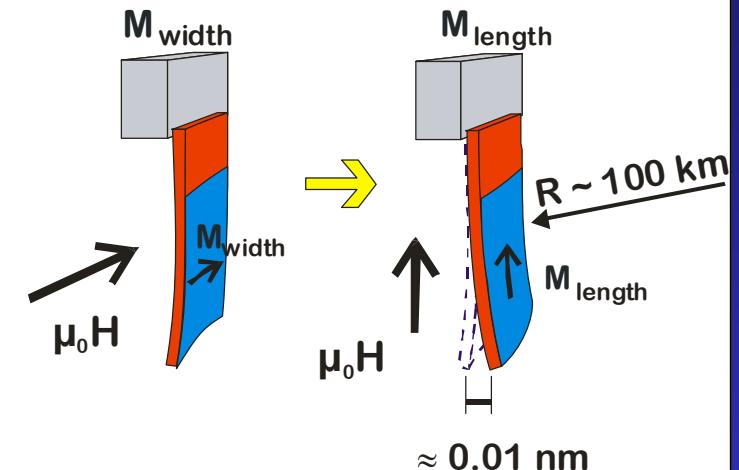
**0.01 N / m**  
**50 MPa in one ML**  
**1 meV / surface atom**

$$\Delta\tau_S = \Delta(\tau_F t_F) = \frac{Y_S t_S^2}{6(1-v_S)} \Delta\left(\frac{1}{R}\right)$$

typical stress: GPa

magneto-elastic stress:

magnetization reversal



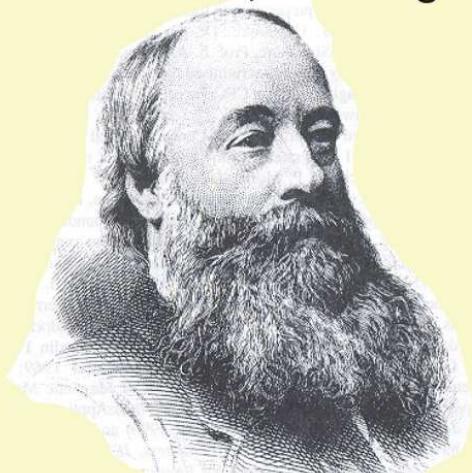
typical stress: MPa

factor 1000

- Rep. Prog. Phys. 62 (1999) 809  
 J. Phys.: Cond. Matter 16 (2004) R603  
 Appl. Phys. A 87 (2007) 419  
 Sensors 8 (2008) 4466  
 J. Phys. : Cond. Matter 21 (2009) 134015

# Magnetostriction

On the Effect of Magnetism  
upon the  
Dimension of Iron and Steel Bars  
J. P. Joule, Phil. Mag. 30 (1847) 225

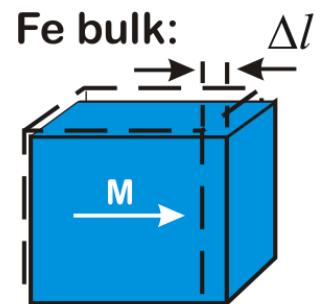


James Prescott Joule  
(1818 - 1889)

... the experiments were very troublesome...  
the experiments had to be carried out  
after eight o'clock P.M.

It was impossible to make an observation  
when a cart was passing ...  
nor could anything be done when  
wind was blowing...

## Magnetostriction and magneto-elastic stress



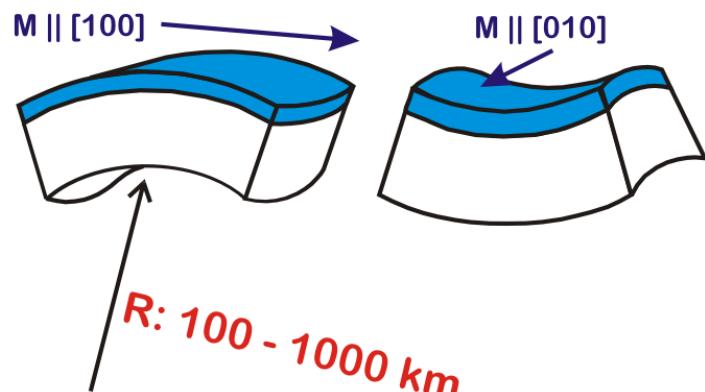
$$\lambda_{100} = \frac{\Delta l}{l} = 2 \times 10^{-5}$$

$$\lambda \sim B_1, B_2$$

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

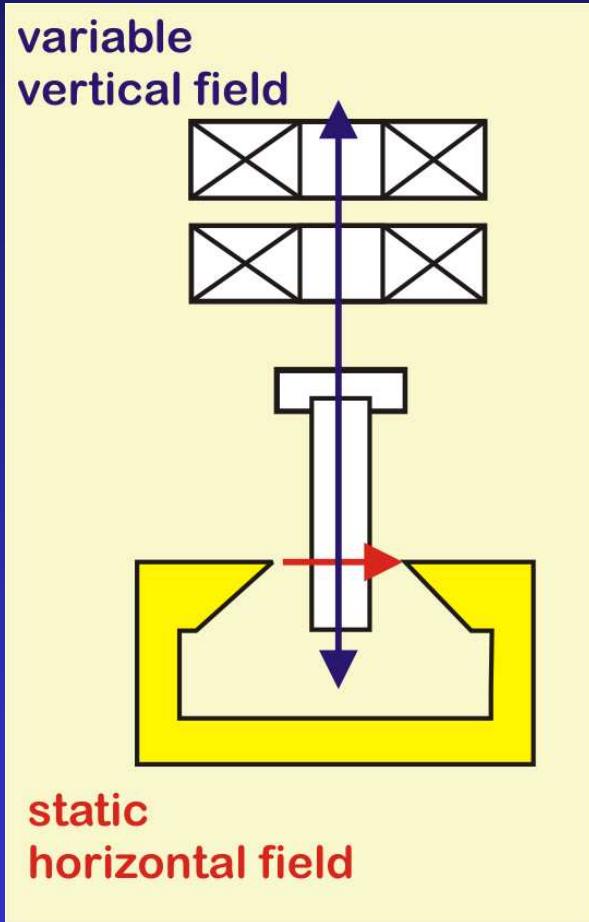
$$B_1(\text{Fe}) = -3.43 \text{ MJ m}^{-3} (\text{MPa!})$$

Fe epitaxial film:  $\tau(\rightarrow) - \tau(\downarrow) = B_1$

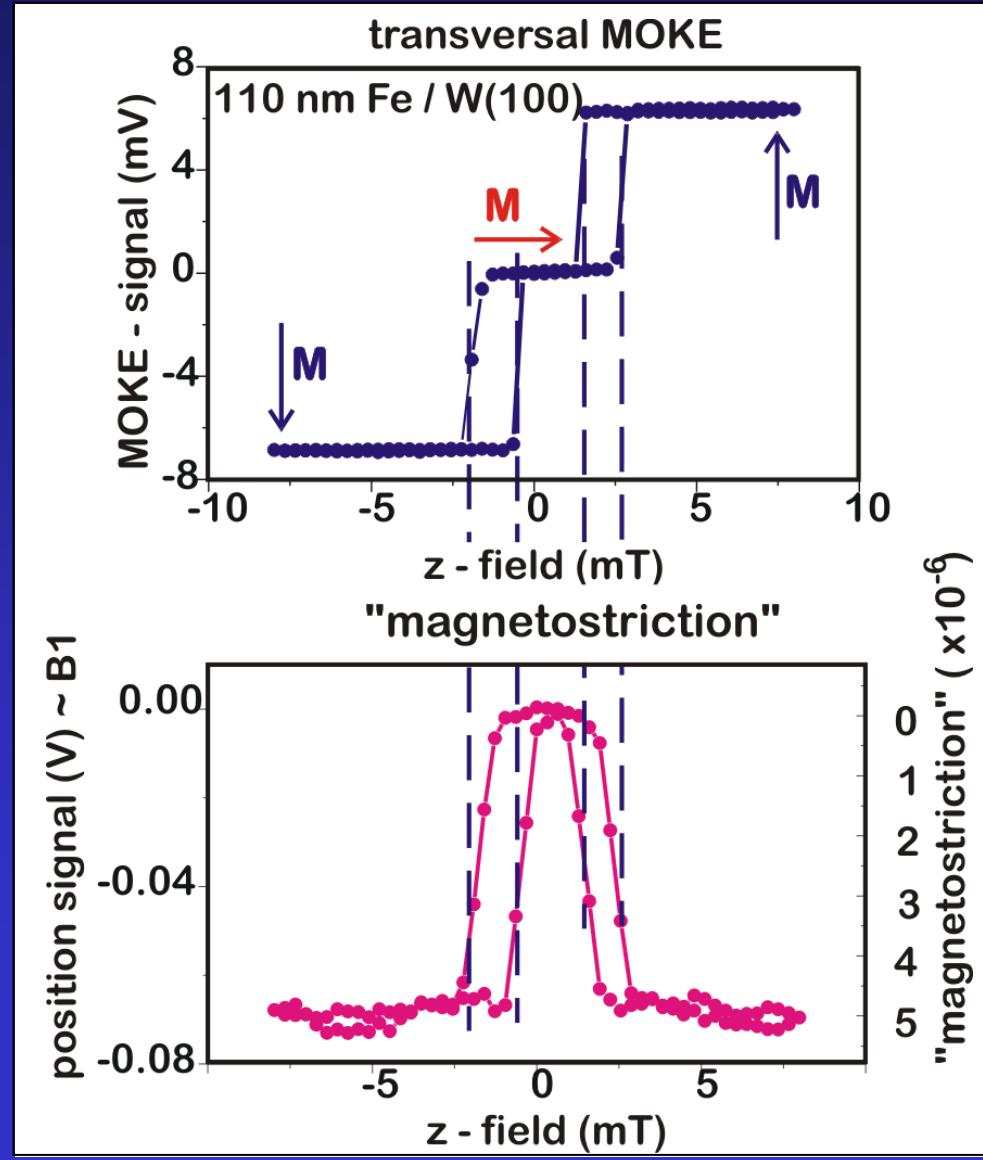


R: 100 - 1000 km

# Simultaneous “magnetostriiction” and MOKE

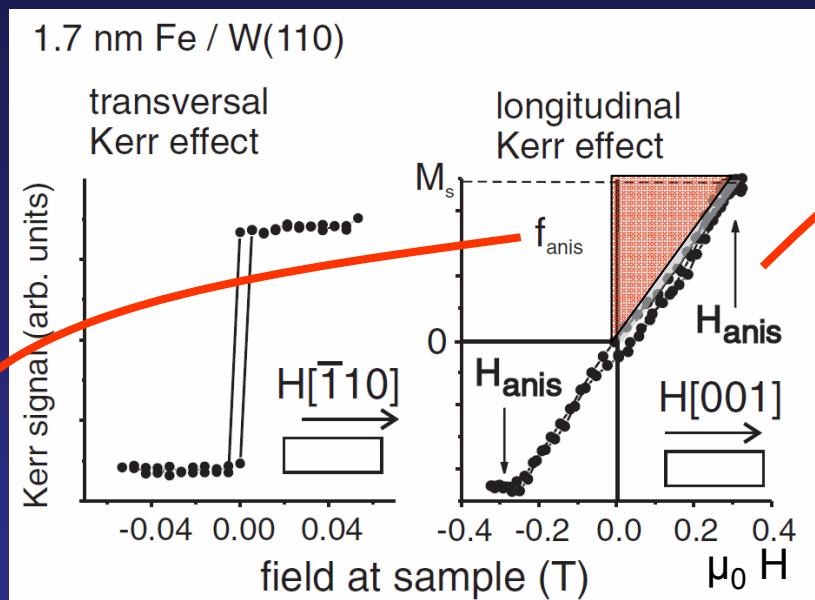


$$\lambda_{100} = -\frac{2B_1}{3c_{11}}$$



# Experimental evidence of magnetic anisotropy

## Hard-axis magnetization loops (1)



Alternative description:  
Anisotropy field  $H_{\text{anis}}$

$$K_{\text{eff}} = \frac{1}{2} \mu_0 H_{\text{anis}} M_s$$

Quantitative analysis of  $K_{\text{eff}}$  possible

$$f_{\text{anis}} = K_{\text{eff}} = \int_0^{M_s} \mu_0 H \, dM$$

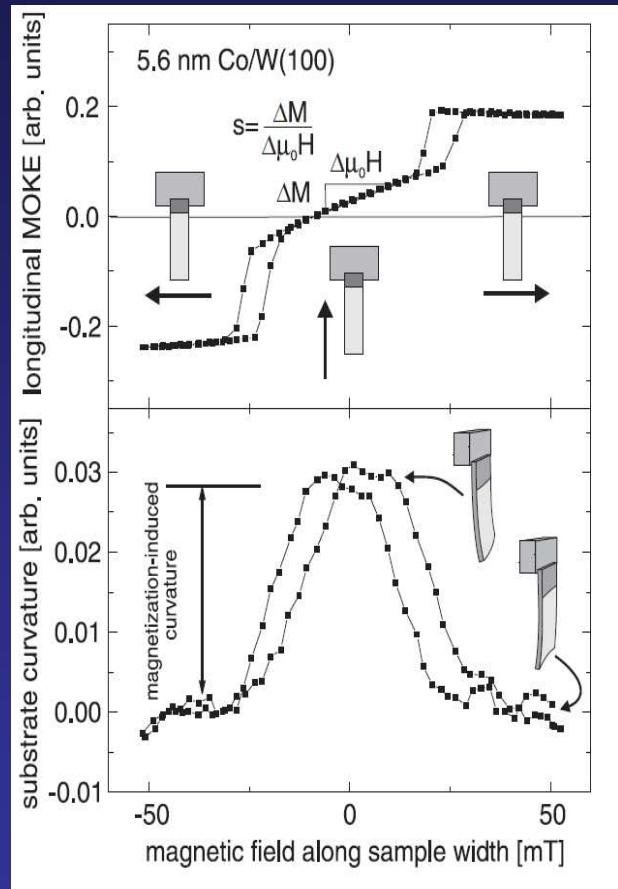
Here:  
 $K_{\text{eff}} = 0.26 \text{ MJ/m}^3$   
 $\mu_0 H_{\text{anis}} = 0.3 \text{ T}$

Compare bulk Fe:  $0.048 \text{ MJ/m}^3$   
( $3.5 \mu\text{eV/atom}$ )

D. Sander  
JPCM 16 (2004) R603

*Change of  $K$ : Fe thickness, temperature*

# Quantitative analysis: hard-axis magnetization loops (2)



Trick:  
small constant field (2 mT) along easy direction  
(e.g. sample length)  
small magnetizing field along sample width  
Weber et al., APL 70 (1997) 520.  
„hard-axis loop“ can be obtained

Here: 2 mT along sample length  
Hysteresis loops with H along sample width

$$\text{Slope: } s = \frac{\Delta M}{\Delta \mu_0 H}$$

$$\mu_0 H_{\text{anis}} = M_s / s$$

$$K_{\text{eff}} = \frac{1}{2} \mu_0 M_s^2 / s = 58 \text{ kJ/m}^3$$

# Experimental determination of magnetic anisotropy

## (1)

Fe / W(001): a combined MOKE and stress study

Total energy density:

$$\begin{aligned} F = & K_4(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_1^2\alpha_3^2) + 2K_2\alpha_3^2/t_F \\ & + 1/2c_{11}(\epsilon_1^2 + \epsilon_2^2 + \epsilon_3^2) + c_{12}(\epsilon_1\epsilon_2 + \epsilon_2\epsilon_3 + \epsilon_1\epsilon_3) \\ & + 1/2c_{44}(\epsilon_4^2 + \epsilon_5^2 + \epsilon_6^2) + B_1(\epsilon_1\alpha_1^2 + \epsilon_2\alpha_2^2 + \epsilon_3\alpha_3^2) \\ & + B_2(\epsilon_4\alpha_1\alpha_2 + \epsilon_5\alpha_2\alpha_3 + \epsilon_6\alpha_1\alpha_3) + 1/2\mu_0M_s^2\alpha_3^2 \end{aligned}$$

Stress and magnetoelastic coupling:

$$\begin{aligned} \partial F / \partial \epsilon_i &= c_{11}\epsilon_{\parallel} + c_{12}(\epsilon_{\parallel} + \epsilon_{\perp}) + B_1\alpha_i^2 = \tau_i, \quad i = 1, 2 \\ \partial F / \partial \epsilon_3 &= c_{11}\epsilon_{\perp} + 2c_{12}\epsilon_{\parallel} + B_1\alpha_3^2 = 0. \end{aligned}$$

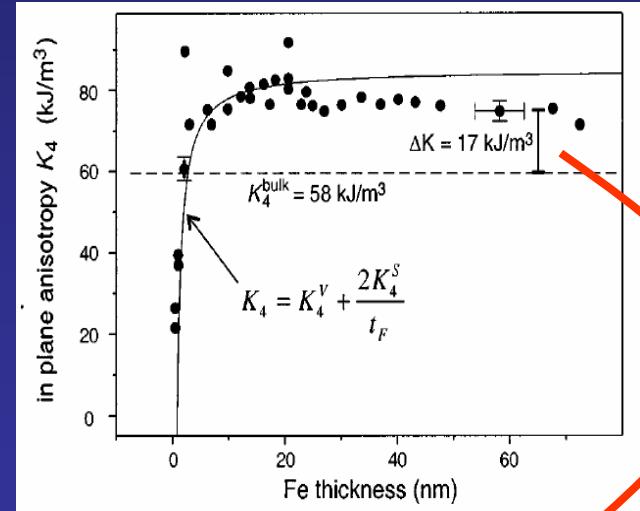
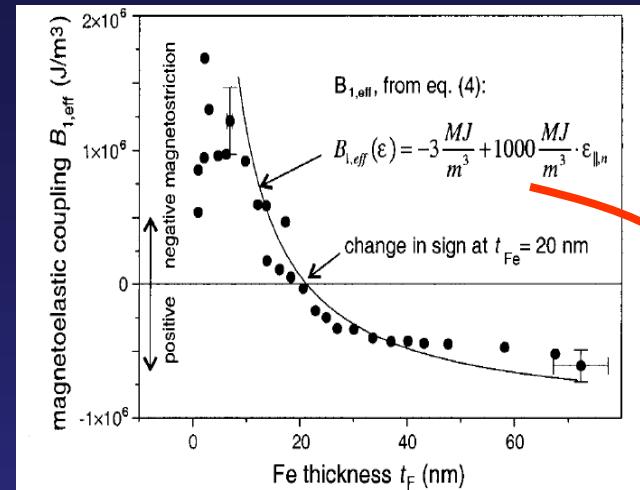
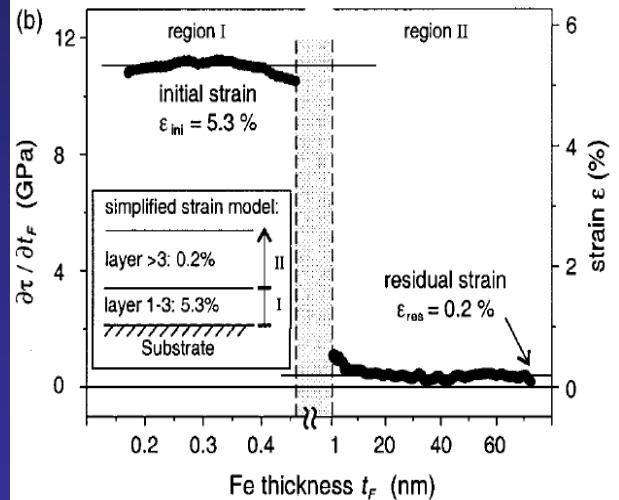
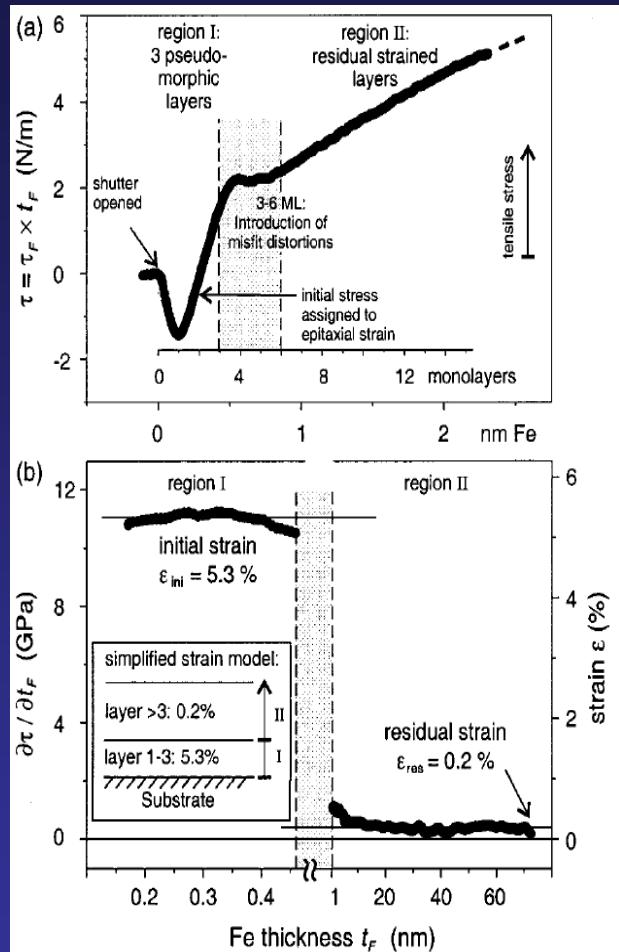
$$f_{\parallel} = K_4/4 \quad \text{From in-plane measurements with small field}$$

$$f_{\perp} = -B_1\epsilon_0(1 + 2c_{12}/c_{11}) + 2K_2/t + \mu_0M_s^2/2 \quad \text{For info}$$

Enders, Sander, Kirschner, JAP 85 (1999) 5279.

# Fairly complete extraction of magnetic anisotropy

(2)



Enders, Sander, Kirschner  
JAP 85 (1999) 5279

Lattice strain in thicker films: deviation of  $K_4$  from bulk  
Magnetoelastic coupling changes with strain

# Stranski-Krastanov layers of Fe: in-plane SRT

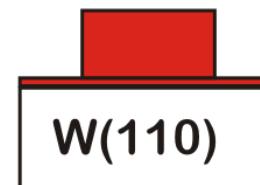
10 ML Fe / W(110)

layer growth  
at 300 K



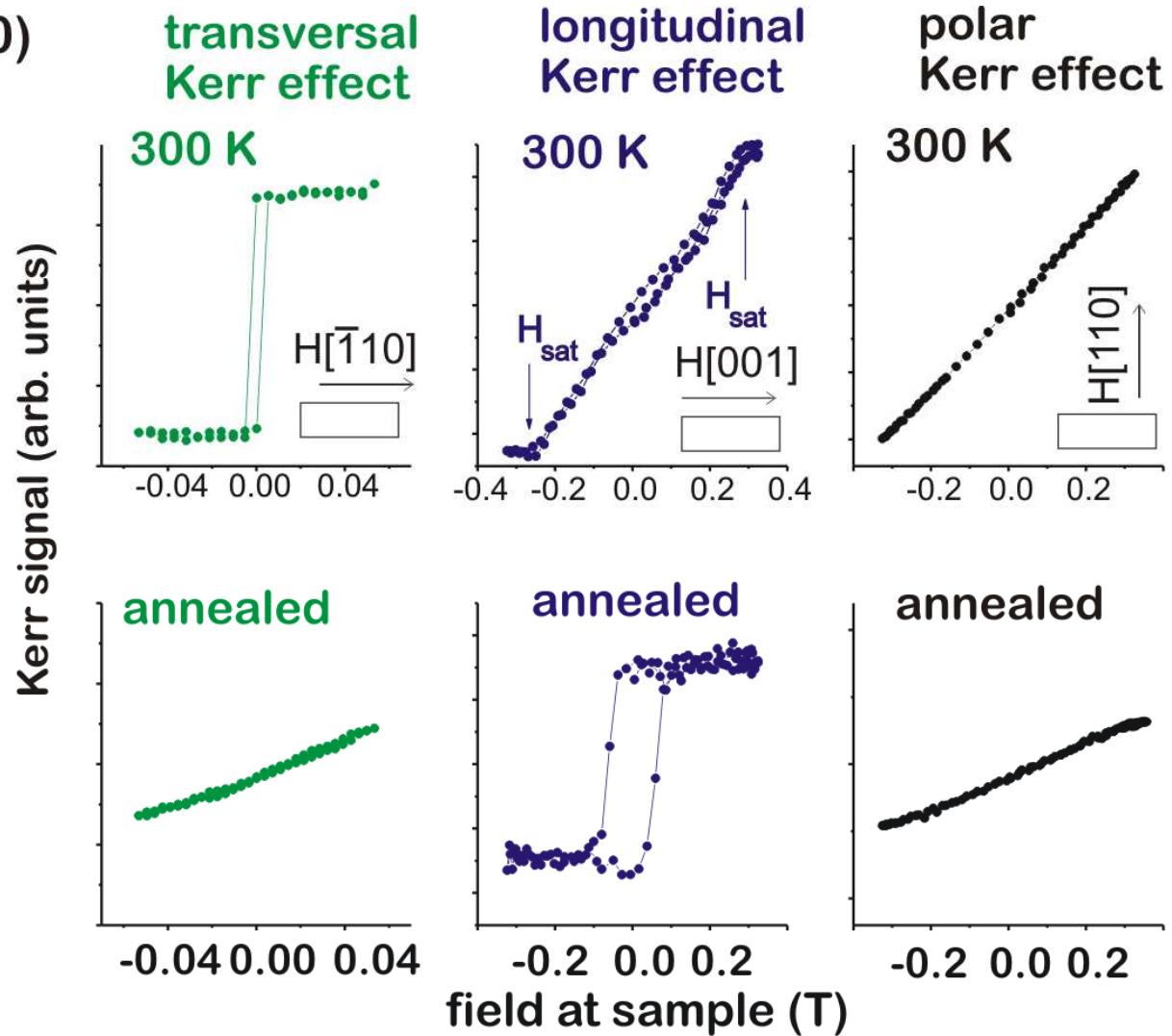
after annealing:

island formation

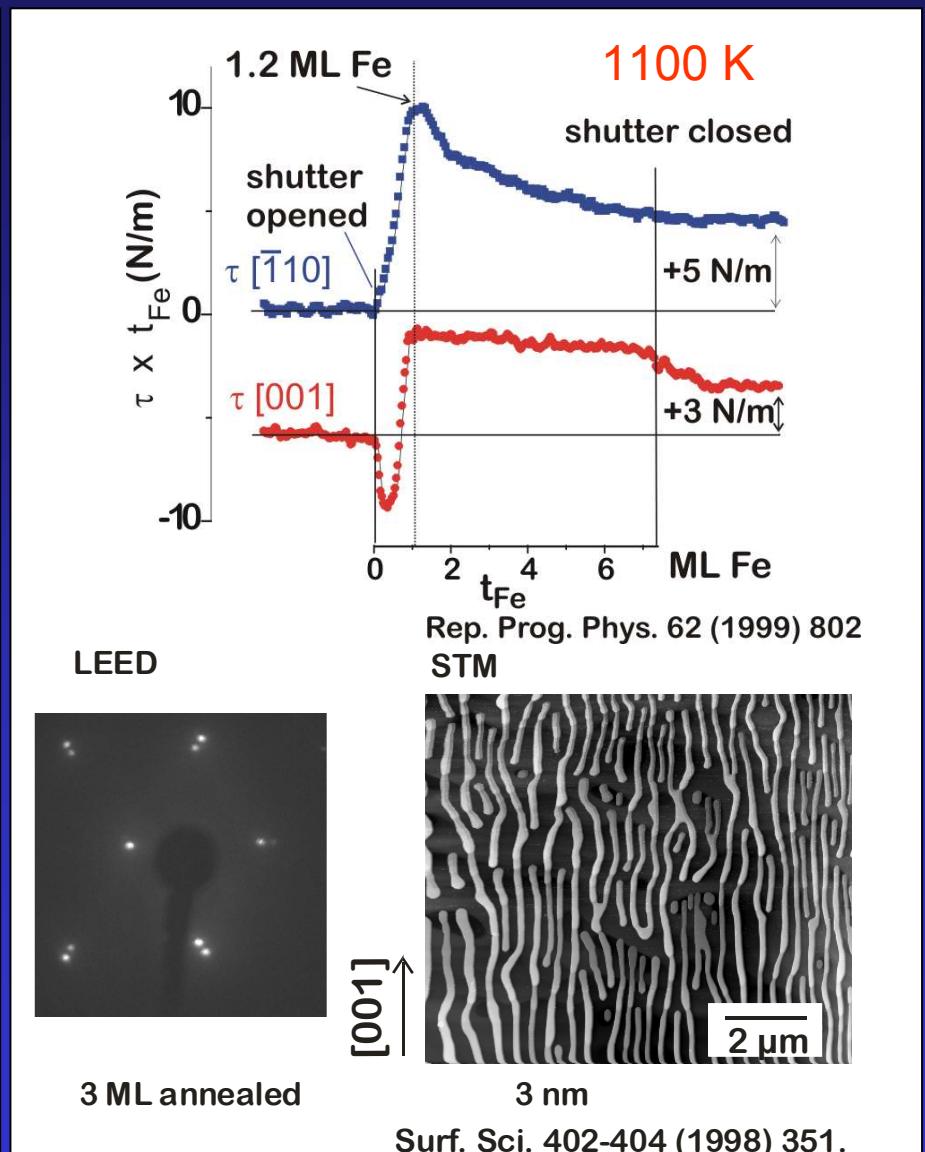
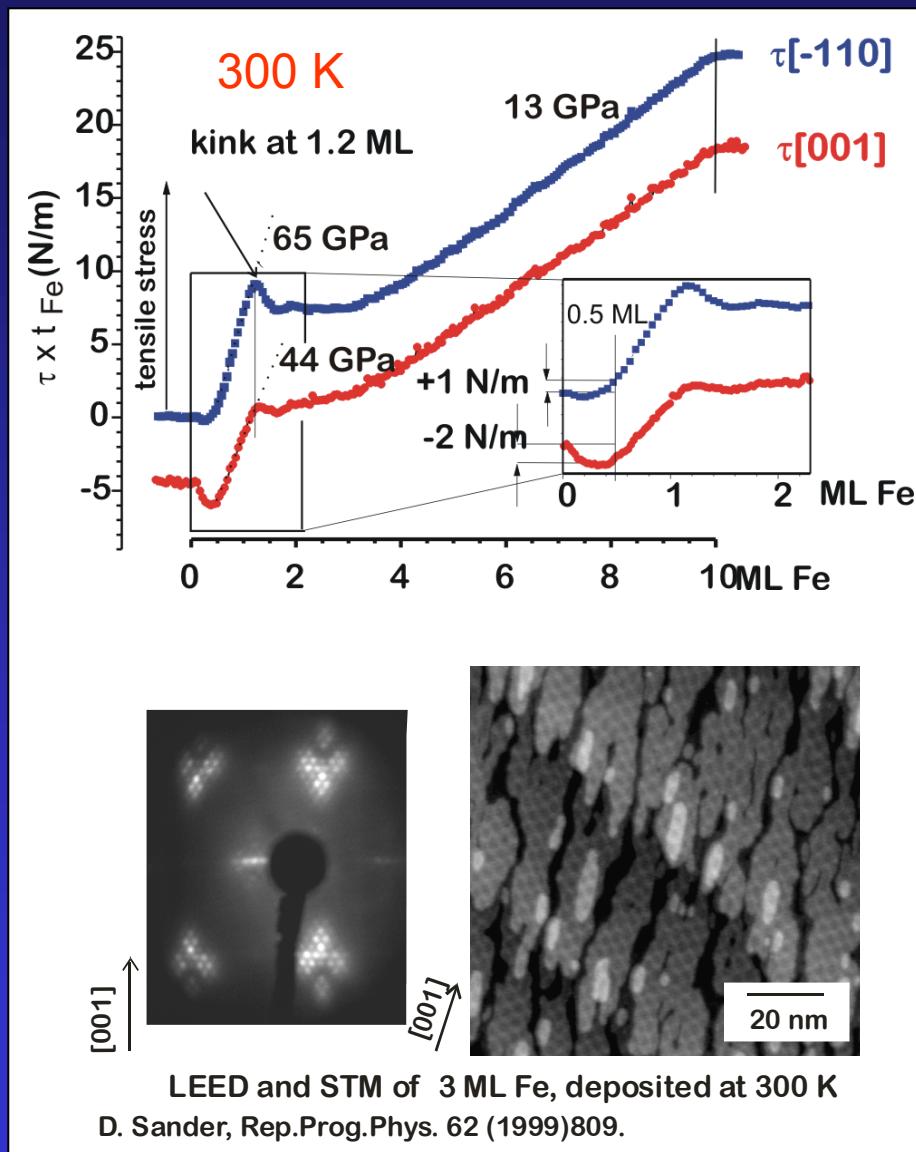


$$N_{\text{width}} = 0.12$$

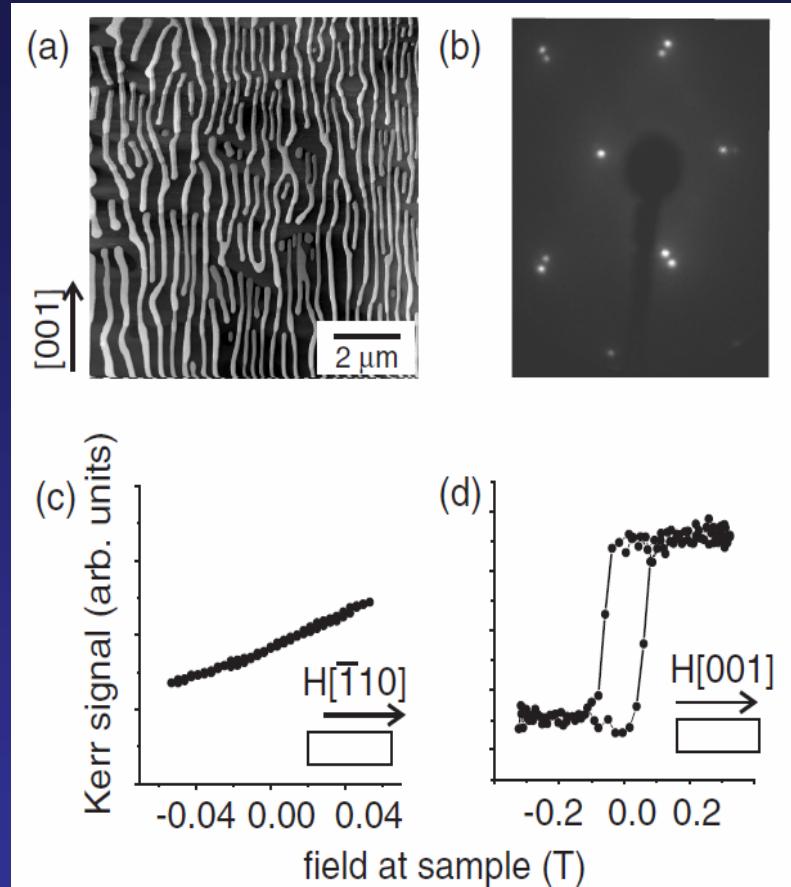
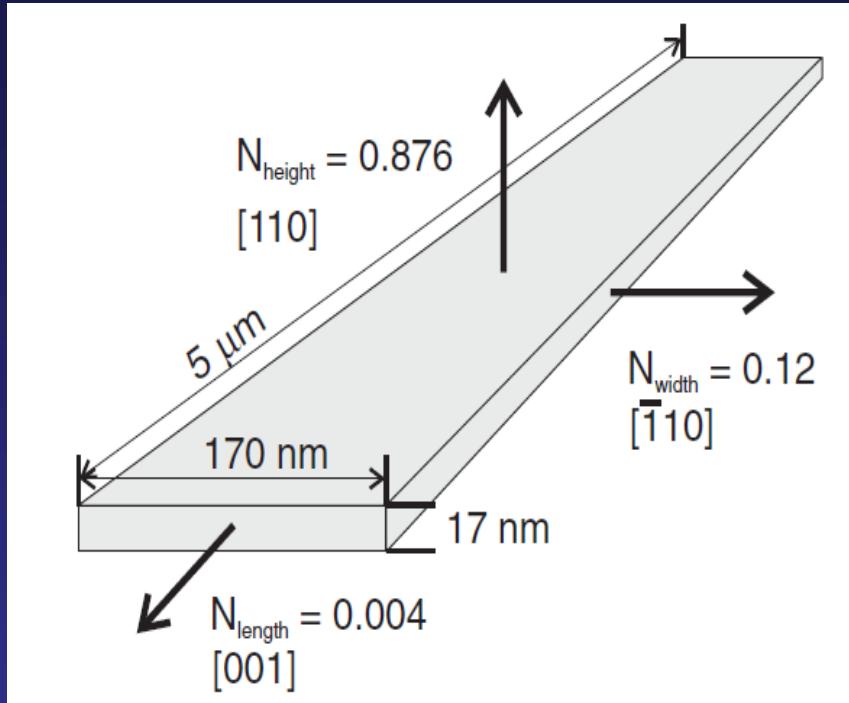
$$N_{\text{length}} = 0.004$$



# Film morphology, structure and stress: Fe / W(110)



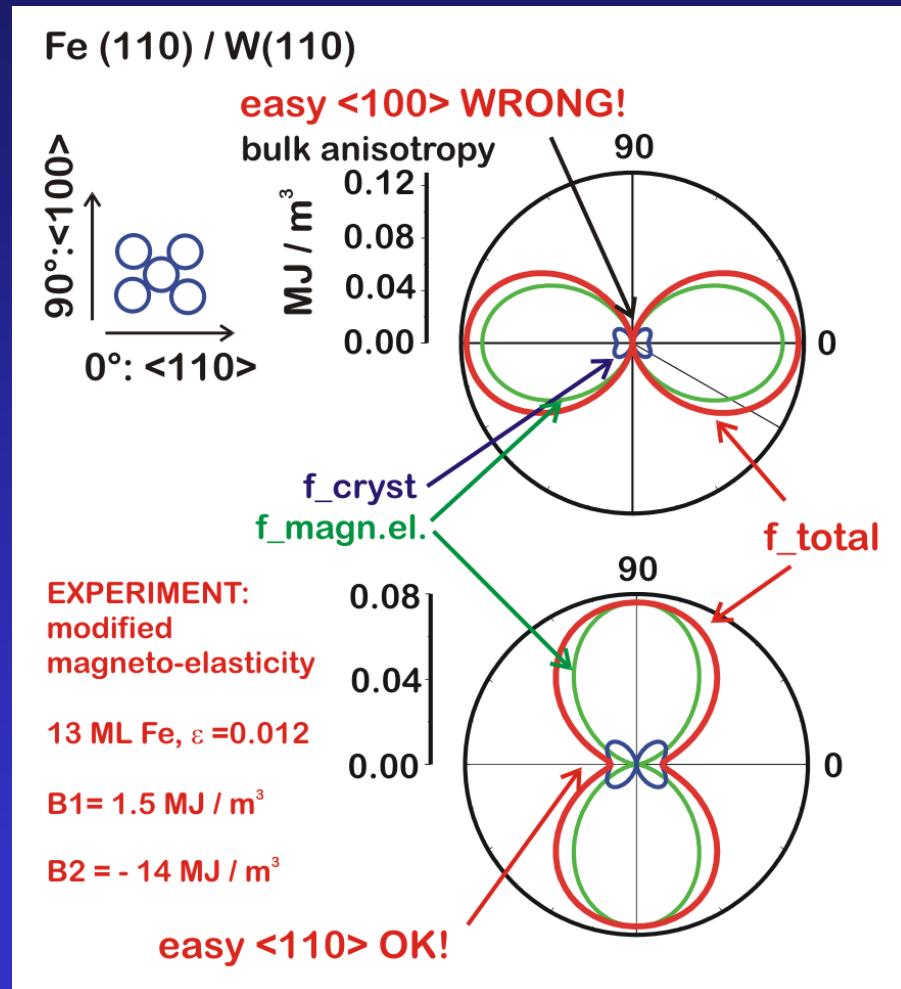
# Shape matters, but strain also ...



Shape favors M along [001]  
Strain reduction also favors M along [001],  
in-plane SRT from [110] to [001] also for flat films

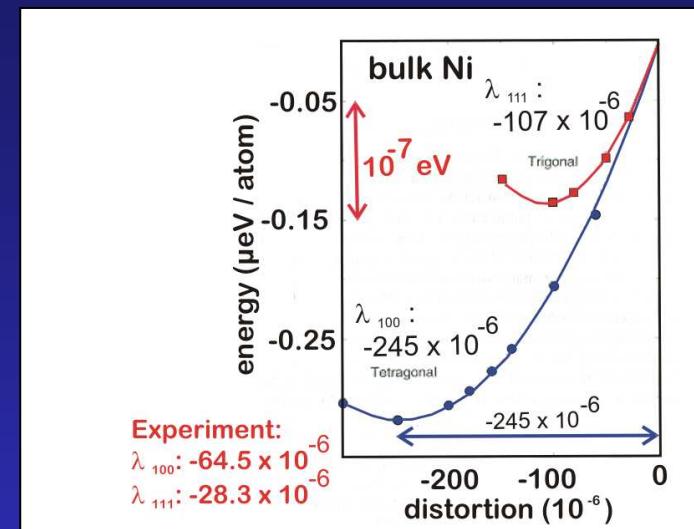
# Strain-modified magneto-elastic coupling

Implication for magnetic anisotropy



PRB 68 (2003) 155421

What about theory?



Hjorstam, Baberschke et al.  
PRB 55 (1997) 15026

theoretical justification of  

$$\Delta\tau_{\text{magnetostriction}} = \tilde{B}_1 + D^{\text{eff}} \varepsilon_0$$

Komelj, Fähnle

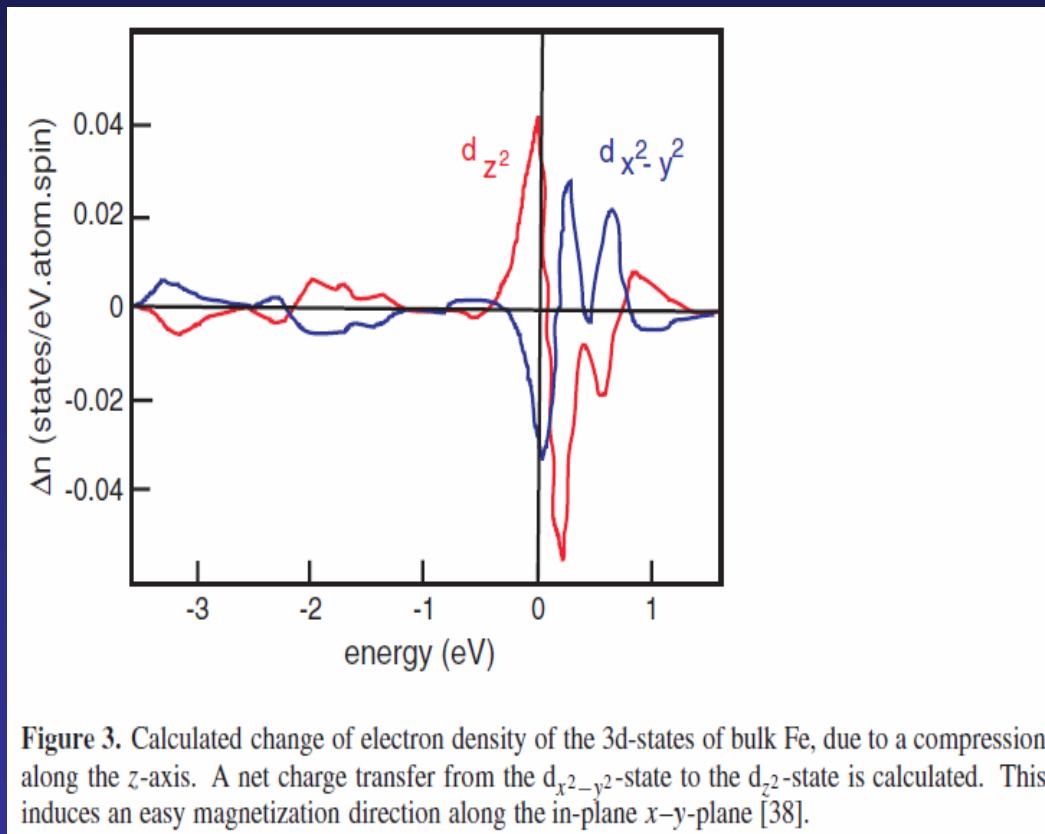
Jmmm 220(2000)L8  
Jmmm 220(2000)L13  
Jmmm 222(2000)L245  
PRB 65 (2002)212410

# Orbital occupation vs. lattice strain

Calculations for distorted bcc Fe:

Strain induced change  
of occupation of different  
d orbitals of Fe, driven  
by the strain-induced shift of  
energy positions of d-states

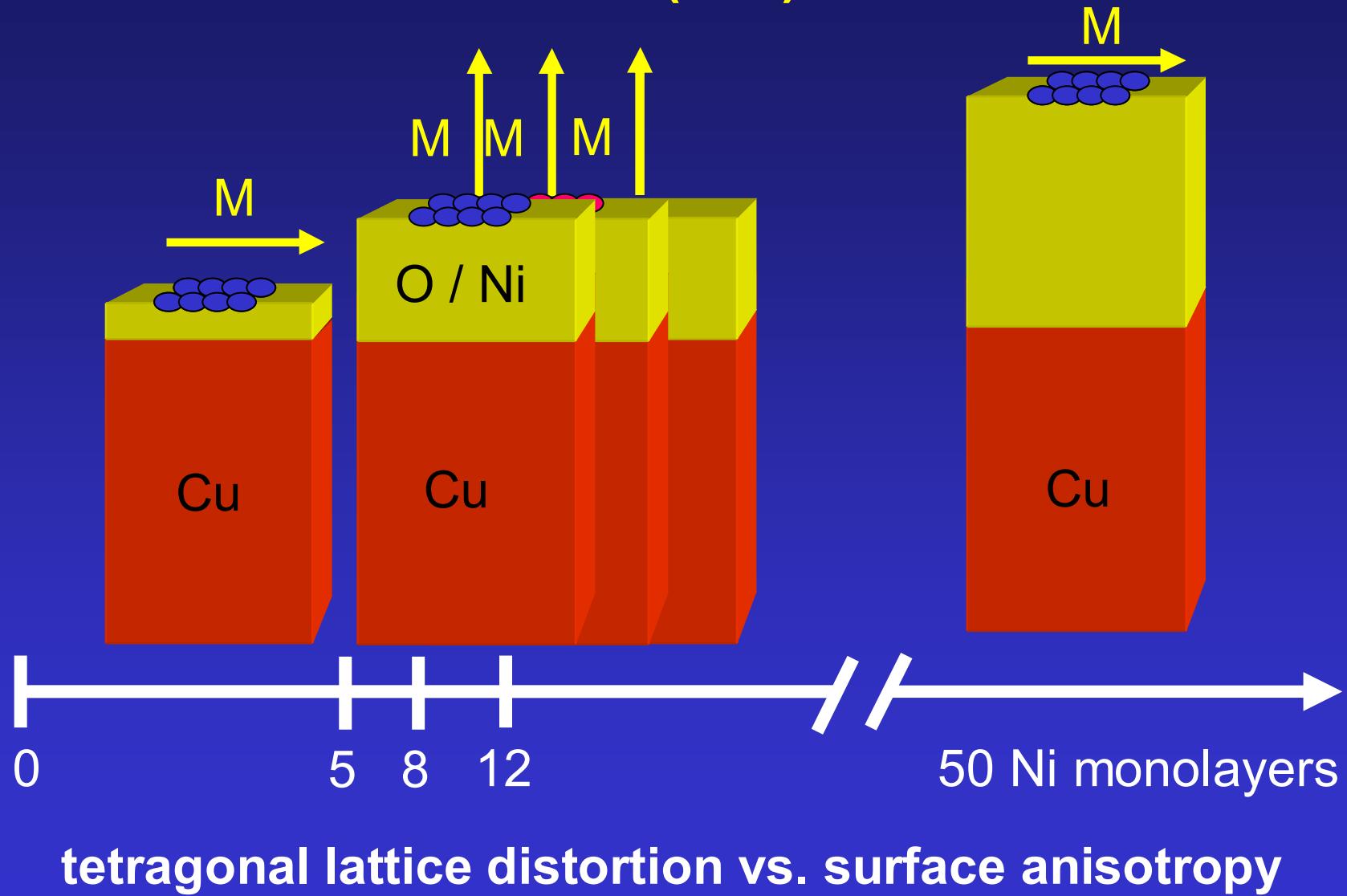
Spin-orbit coupling is modified,  
and modified magneto-crystalline  
anisotropy results



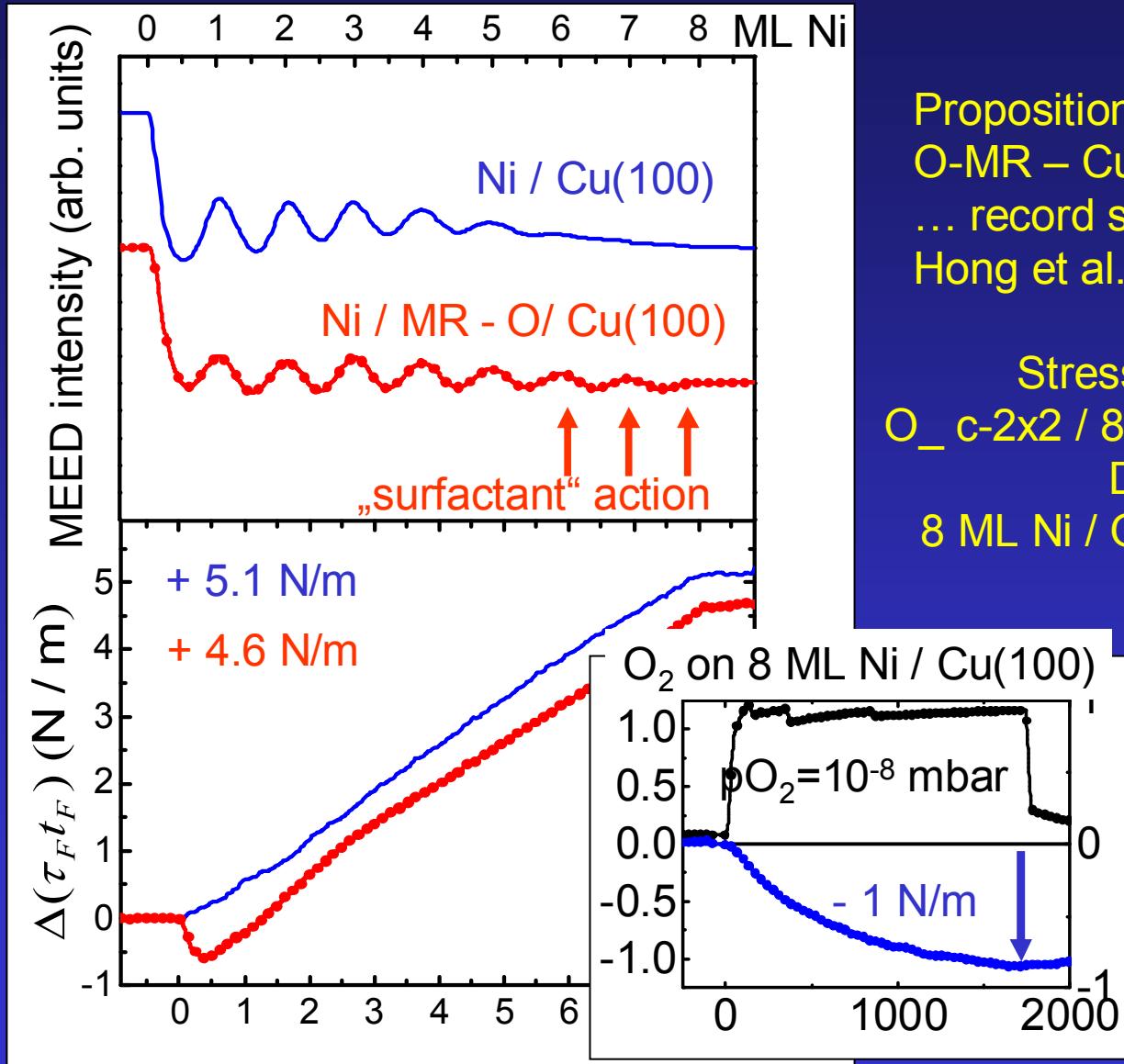
From: Wu, Chen, Shick, Freeman, Jmmm 177-181 (1997) 1216.

# Inverse spin-reorientation transition (SRT)

Ni / Cu(001)



# O-mediated surfactant growth of Ni / Cu(100)



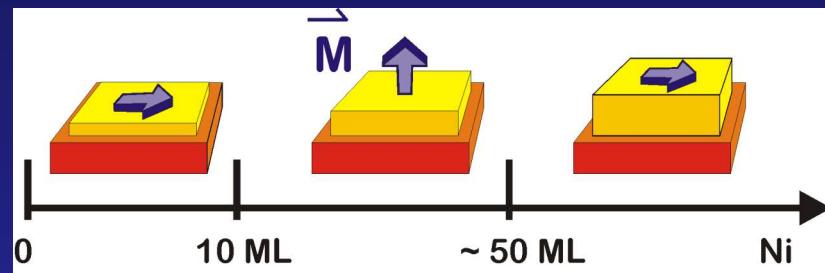
Proposition:  
O-MR – Cu(100) for Ni growth  
... record shift of SRT ...  
Hong et al. PRL 92 (2004) 147202

Stress shows HOWEVER:  
O<sub>c</sub>-c-2x2 / 8 ML Ni / Cu(100): + 4.1 N/m  
DIFFERS FROM  
8 ML Ni / O-MR\_Cu(100): + 4.6 N/m

Surfactant does  
NOT only float on top  
  
SXRD:  
O-enriched zone

# H-induced reversible switching of the magnetic anisotropy

reverse SRT in Ni monolayers



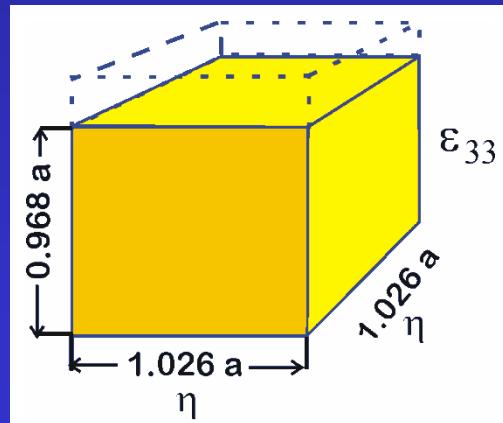
pseudomomorphic up to  $\sim 3$  nm (18 ML)

in-plane strain:  $\eta = +2.6\%$

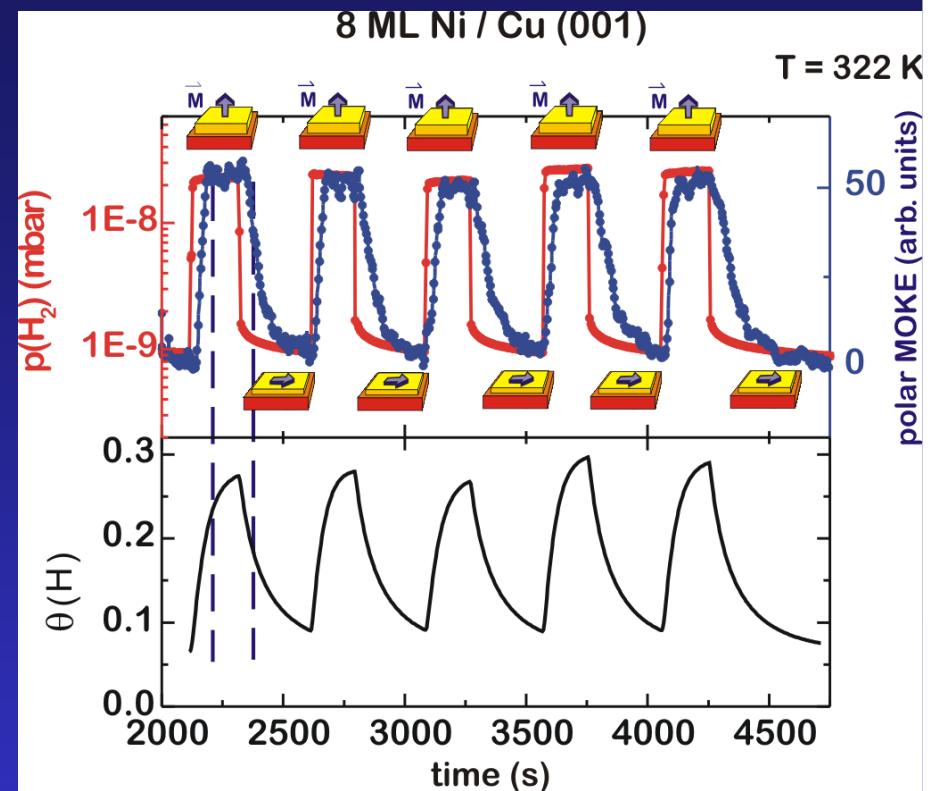
out-of-plane:  $e_{33} = -3.2\%$

Ni, fct:

(agrees with experiment)



$$B_1^{\text{eff}}(\eta - \varepsilon_{33}) = 16 \mu\text{eV/atom}$$



quantitative LEED I(E) analysis, 8 ML Ni / Cu(001)

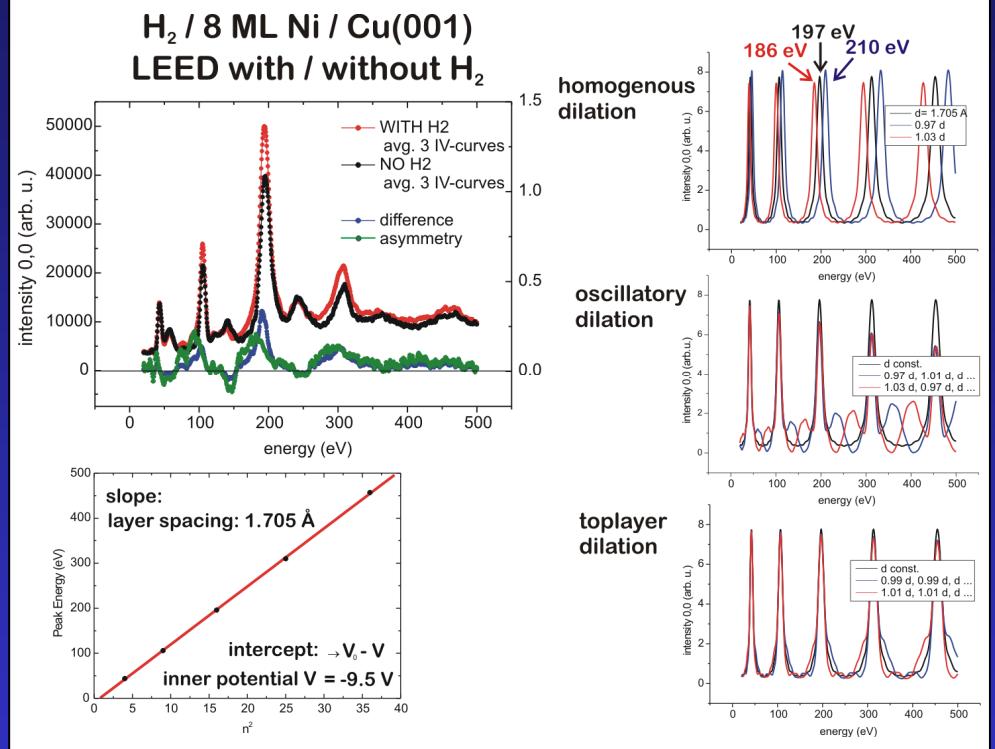
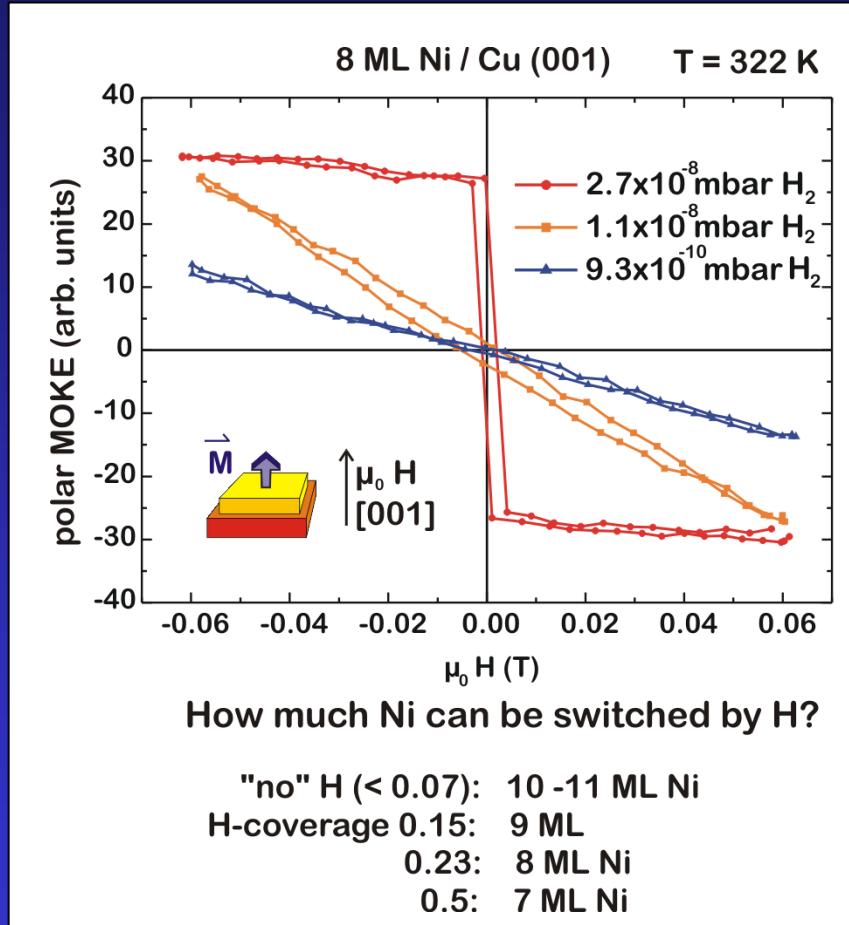
	$d_H$	$d_{12}$	$d_{23}$	$d_{34}$	$d_{45}$	$d_{56}$	$d_b$
8 ML Ni		1.675	1.720	1.705	1.715	1.720	1.710 +/- 0.005
H / 8 ML Ni	0.31	1.770	1.695	1.700	1.710	1.710	1.710

bulk Ni: 1.759 Å

Phys. Rev. Lett. 93 (2004) 247203

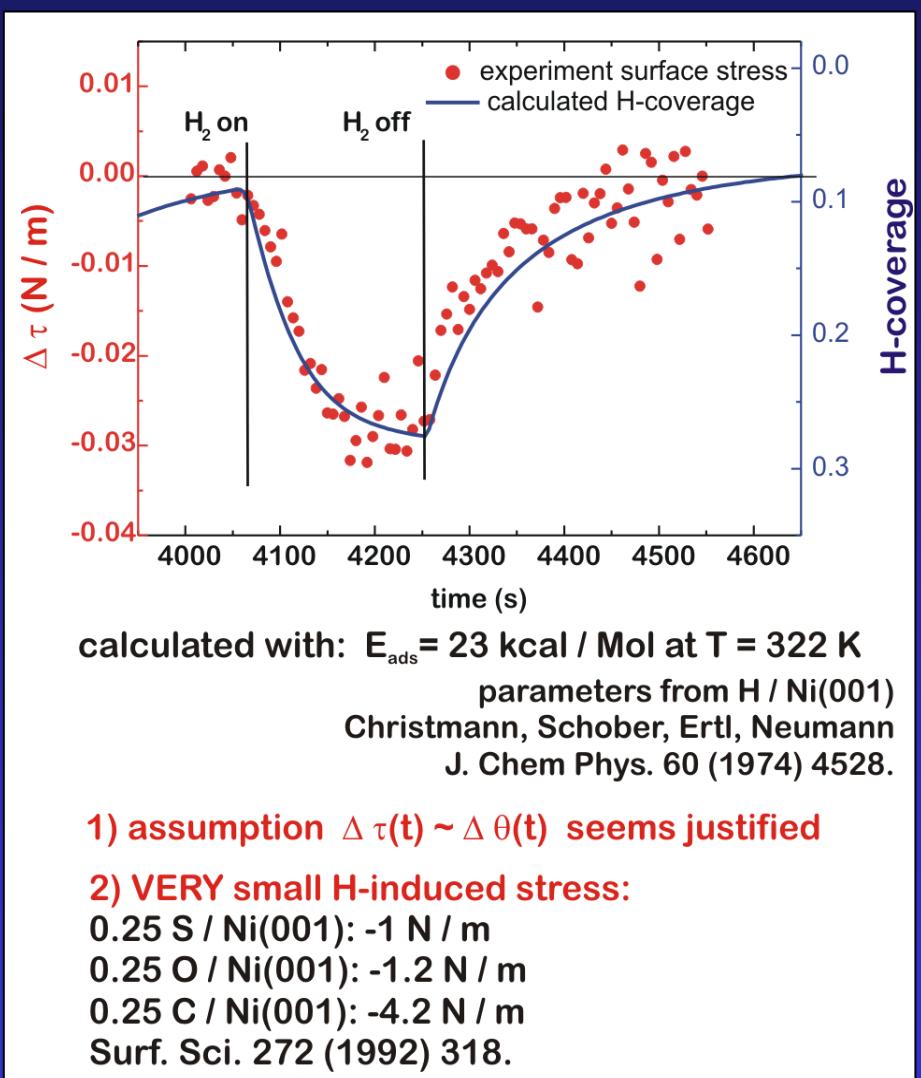
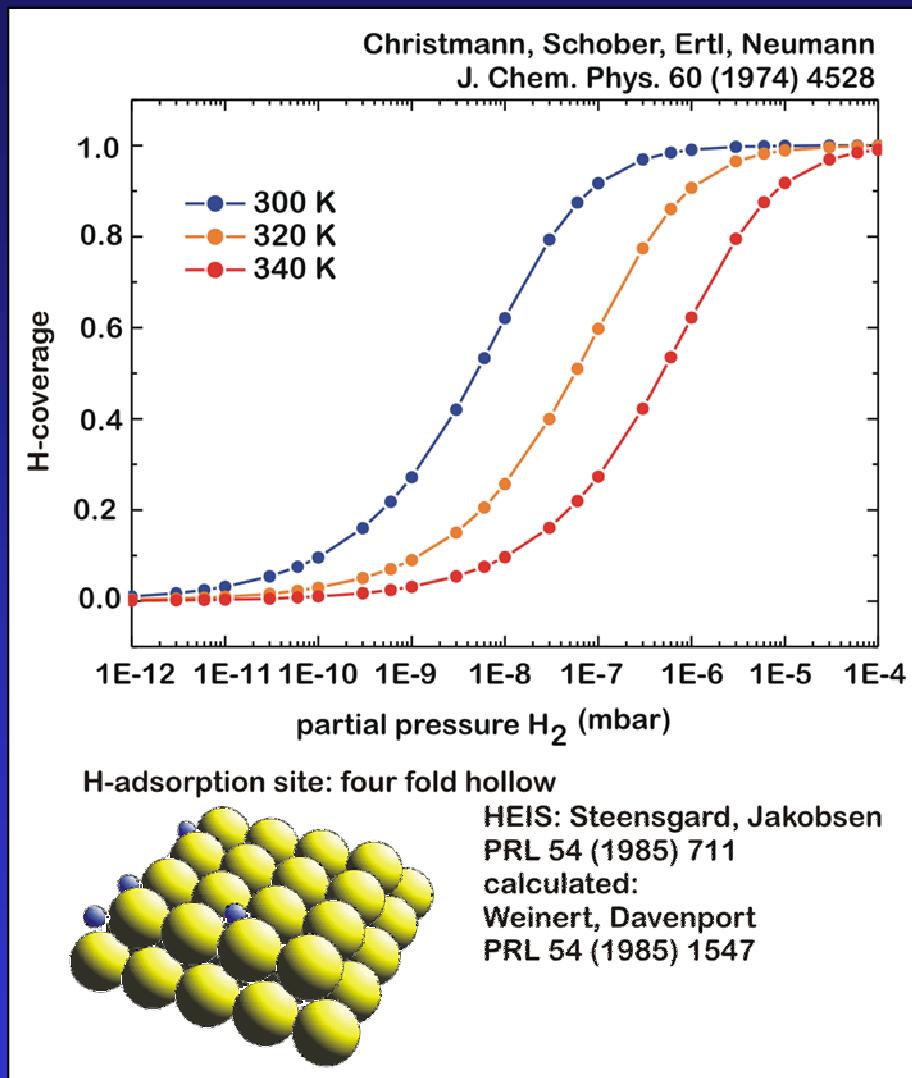
drastic outward relaxation upon H-coverage

# Adsorbate-induced SRT and structural change?

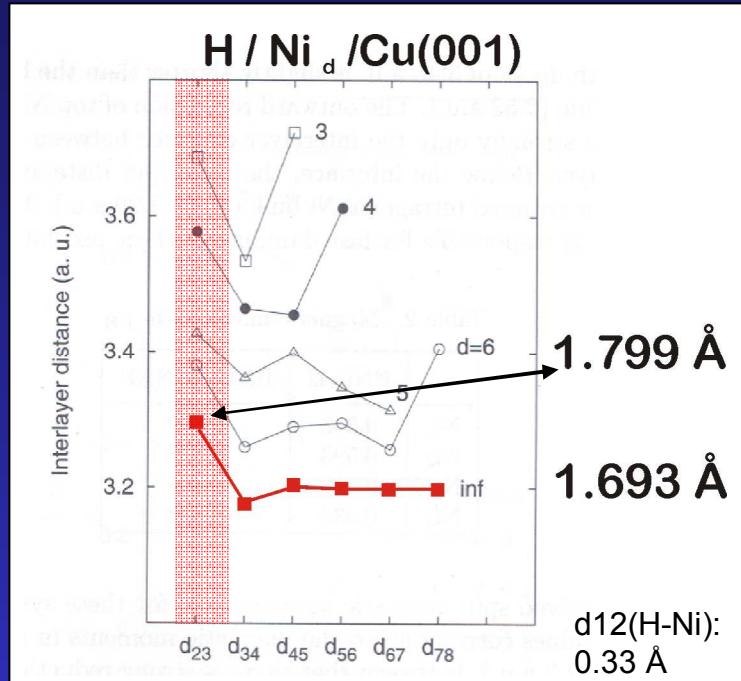


started collaboration with  
Lutz Hammer and Klaus Heinz, Erlangen

# Adsorbate coverage from stress measurements



# Theory: layer relaxation and layer-resolved magnetic anisotropy



calculated layer spacing:

Maca, Shick, Redinger,  
Podlucky, Weinberger  
Czech. J. Physics 53 (2003) 33

calculated layer-resolved anisotropy:

Uiberacker, Zabloudil, Weinberger,  
Szunyogh, Sommers

Phys. Rev. Lett. 82 (1999) 1289

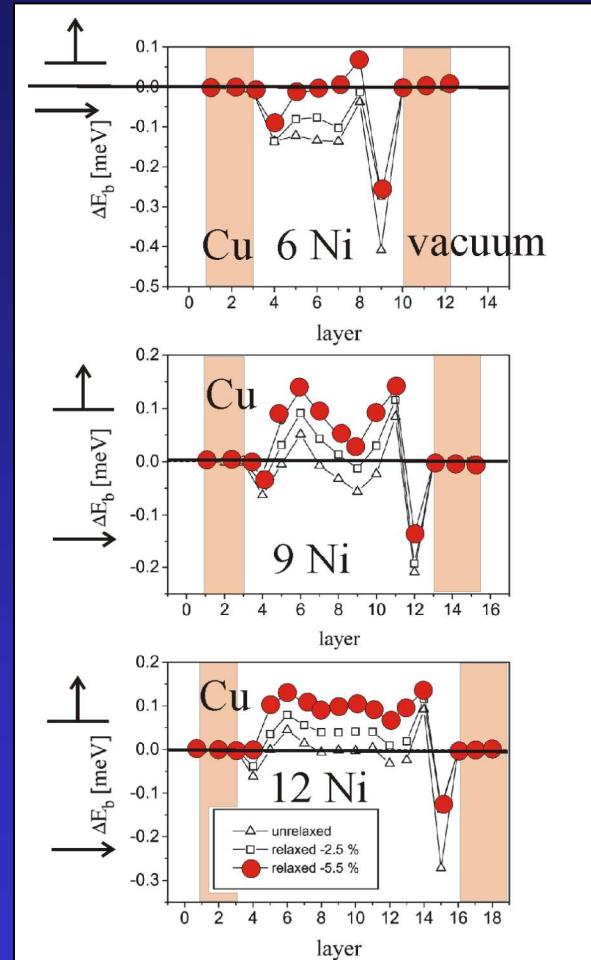
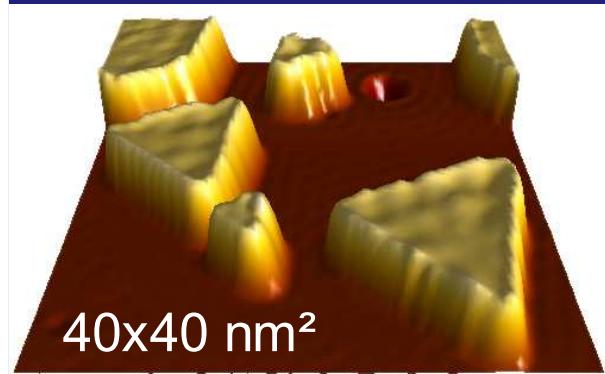


FIG. 2. Layer resolved band energy differences  $\Delta E_b^n$  for six (top), nine (middle), and twelve (bottom) Ni layers on Cu(100). Triangles, squares, and circles refer in turn to a uniform relaxation by 0%, -2.5%, and -5.5%, i.e., to a  $c/a$  ratio of 1, 0.975, and 0.945.

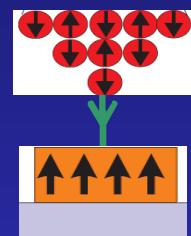
Interfaces are decisive

# Electron confinement, magnetic switching, and Spin-polarization: LT-spin STM studies

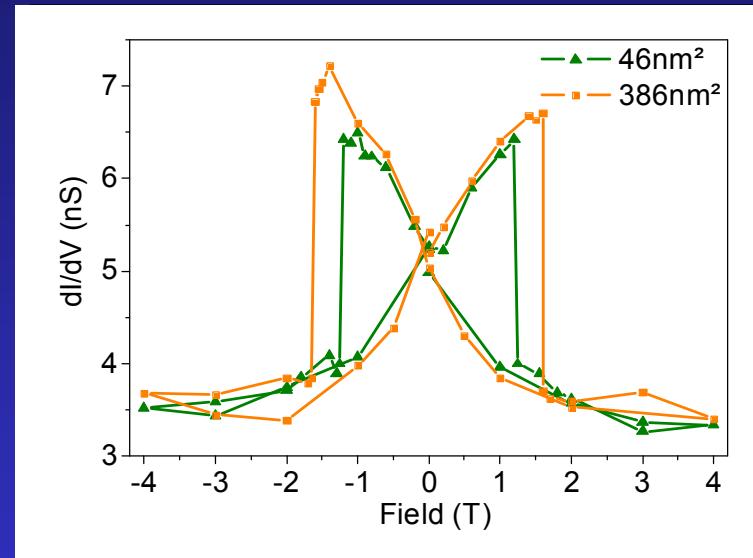
Co / Cu(111)



Cr / W tip

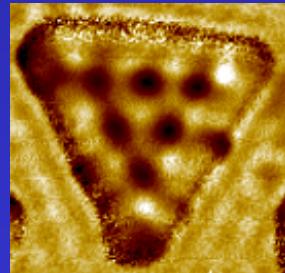


dI / dV hysteresis loop



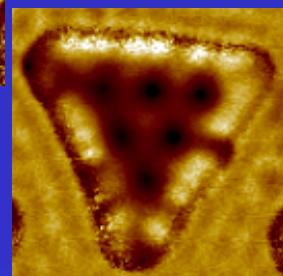
dI/dV maps

Antiparallel (AP)

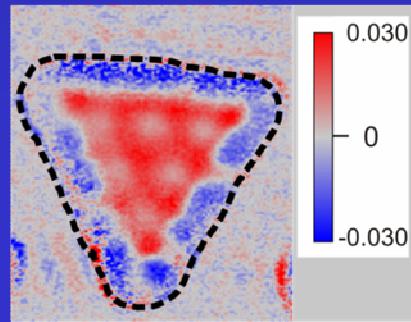


$V_s = +0.04$  V

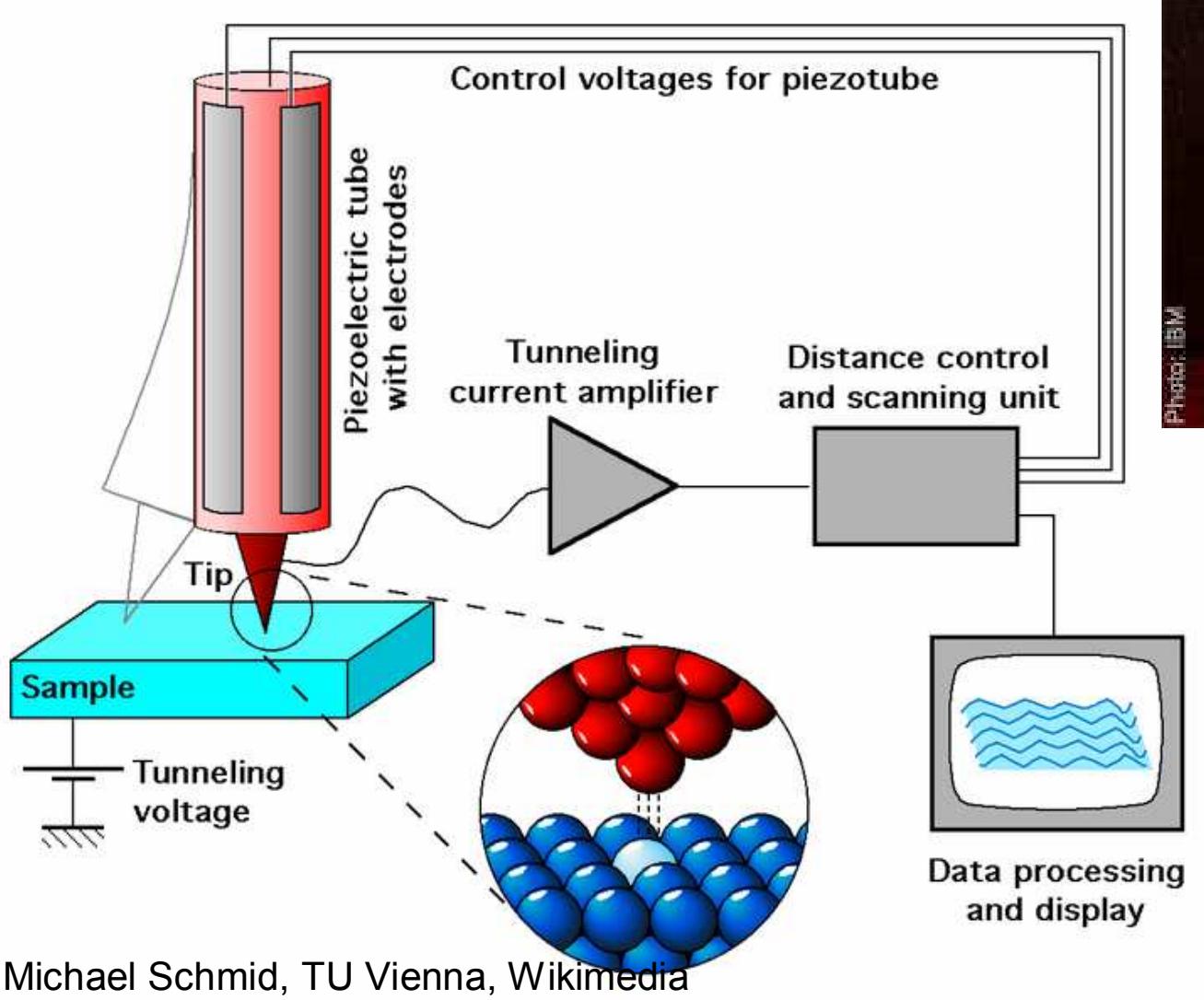
Parallel (P)



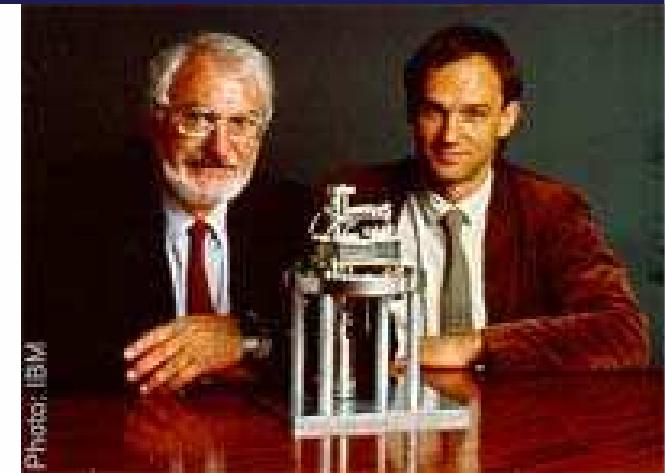
dI/dV asymmetry



# How does a STM work?

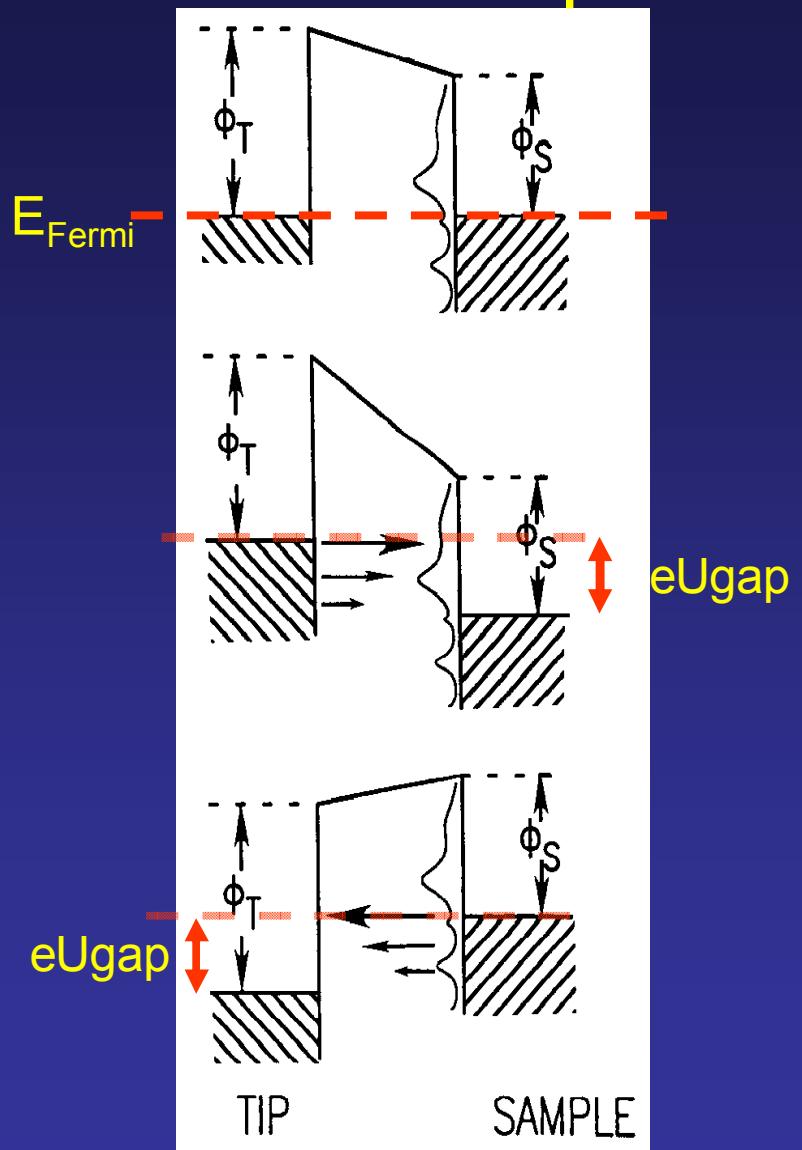


Michael Schmid, TU Vienna, Wikimedia



Heinrich Rohrer  
Gerd Binnig  
IBM Zürich,  
Nobelprize 1986  
(with Ernst Ruska)

# Tunneling through a vacuum barrier: occupied vs. unoccupied electron states



Zero voltage  $U_{\text{gap}}$   
No net tunneling current

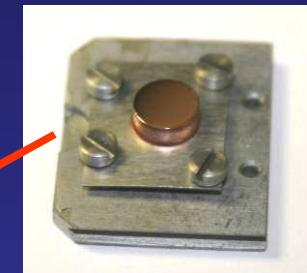
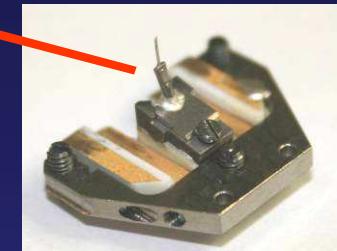
positive voltage  $U_{\text{gap}}$   
Tunneling from occupied tip states  
into empty sample states

negative voltage  $U_{\text{gap}}$   
Tunneling from occupied sample states  
into empty tip states

# Low Temperature STM with vertical field



Tip Carrier



Cu(111)

Low Temperature: 7 K  
High Magn. Field : 8 T

Scanning Tunneling Spectroscopy (STS)

$$\begin{aligned} U_{\text{mod}} &= 5-20 \text{ mV} \\ f_{\text{mod}} &= 4.8 \text{ kHz} \end{aligned}$$

Lock-in  
Amplifier

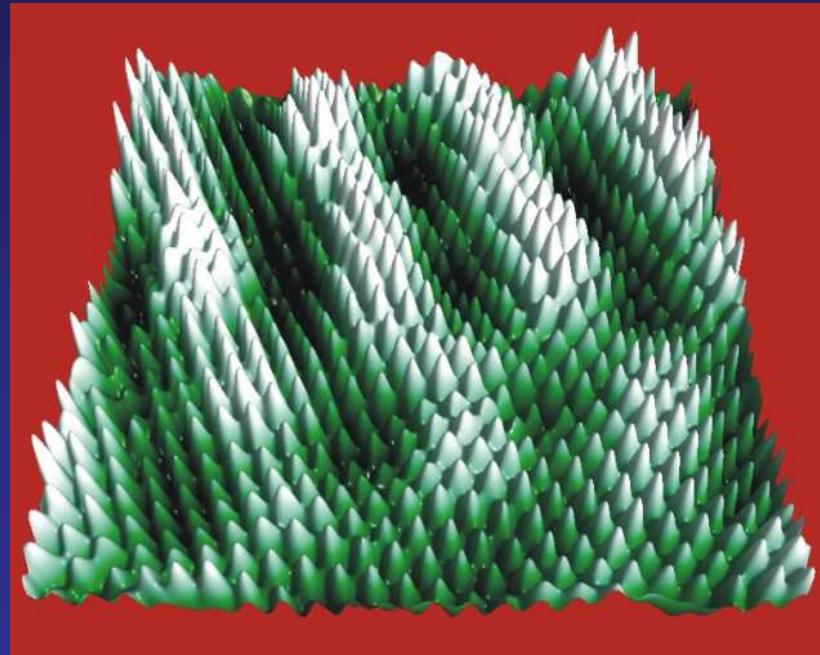
$$\frac{dI}{dV}(U_{\text{gap}}) \propto \text{LDOS}_{\text{sample}}$$

# High stability, low noise ...

factor 50 better than specs!

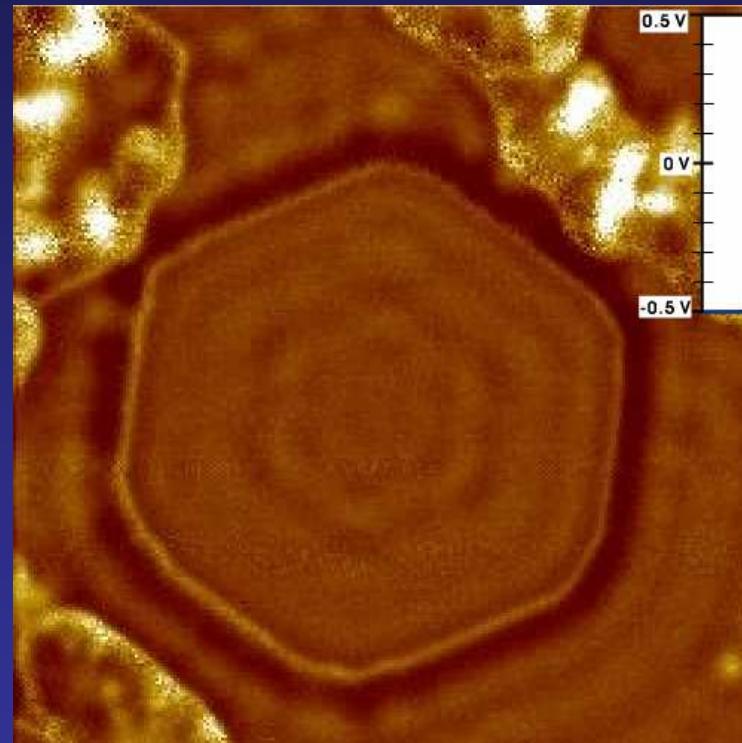
atomic resolution and  
standing wave modulation

dI / dU raw data, STS-movie  
250 x 250, acquisition time: 14 h



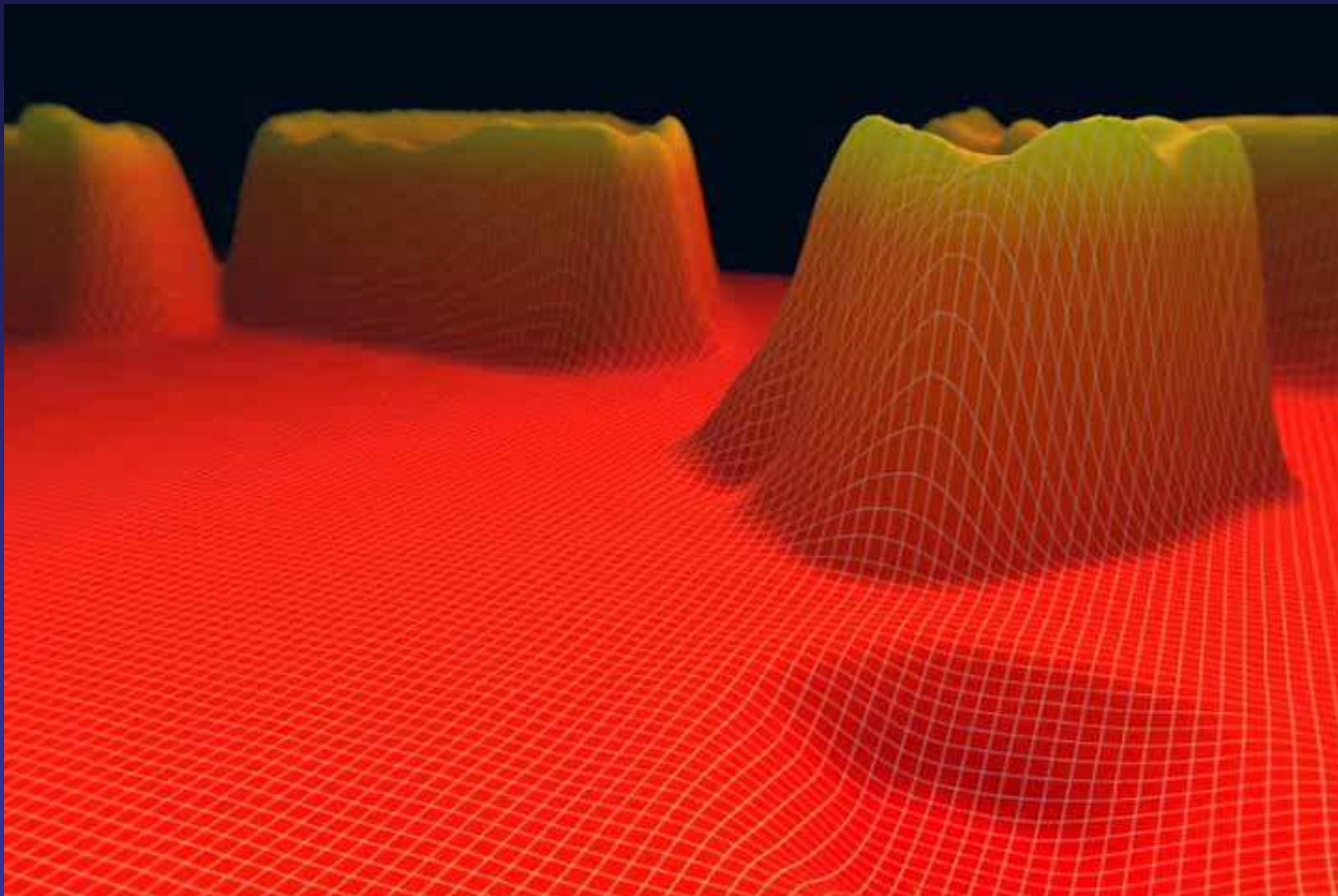
5 x 5 nm<sup>2</sup>  
Cu(111)  
7 K

low noise: < 200 fm\_pp  
low drift: < 1 nm / 24 h

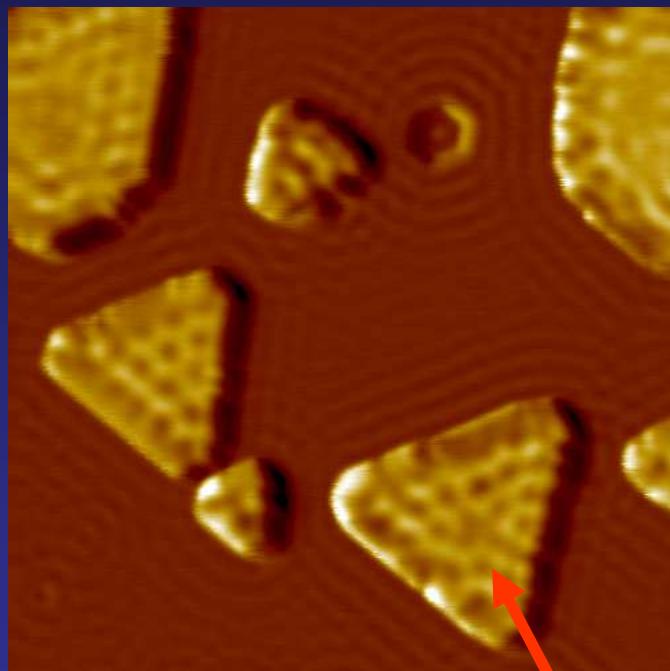


30 x 30 nm<sup>2</sup>  
Ugap: -0.5 V... + 0.5 V  
Cu(111)  
7 K

# Co islands on Cu(111)



# Co DL islands on Cu(111)



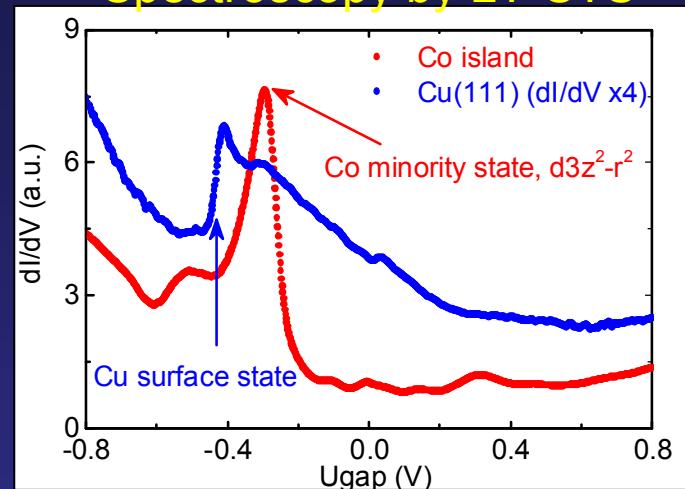
40 x 40 nm<sup>2</sup>, +0.225 V, 1 nA  
7 K, STS, dI/dV

LDOS modulation due to  
Co sp majority electrons

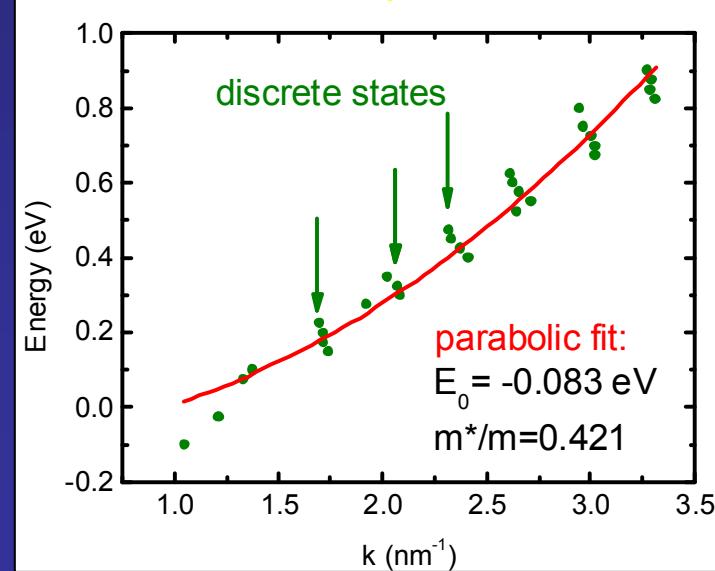
Theory:

Diekhöner, Schneider, Baranov, Stepanyuk, Bruno, Kern  
Phys. Rev. Lett. 90 (2003)236801

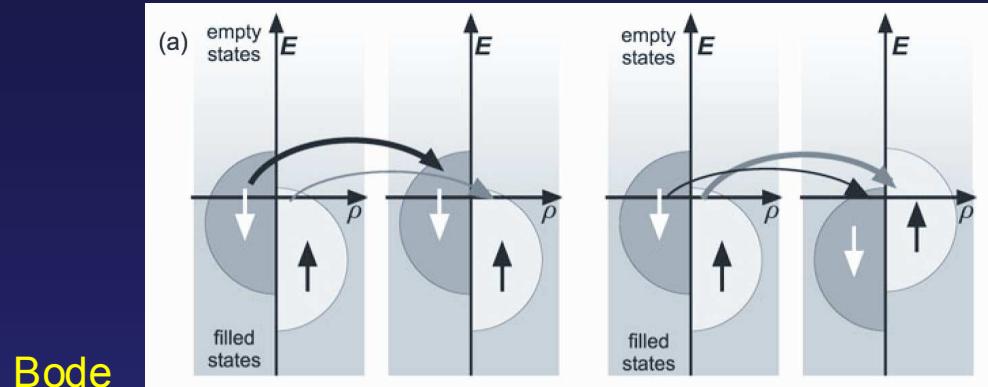
Theory: spin-polarized Co state  
Spectroscopy by LT-STS



Co island dispersion relation



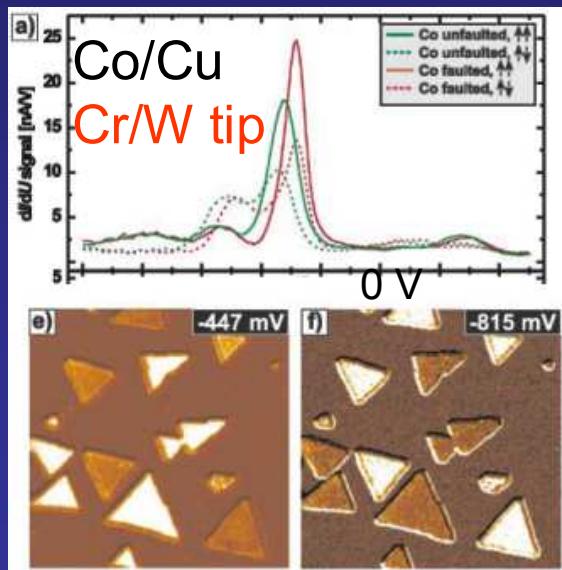
# ... towards Spin-STM...



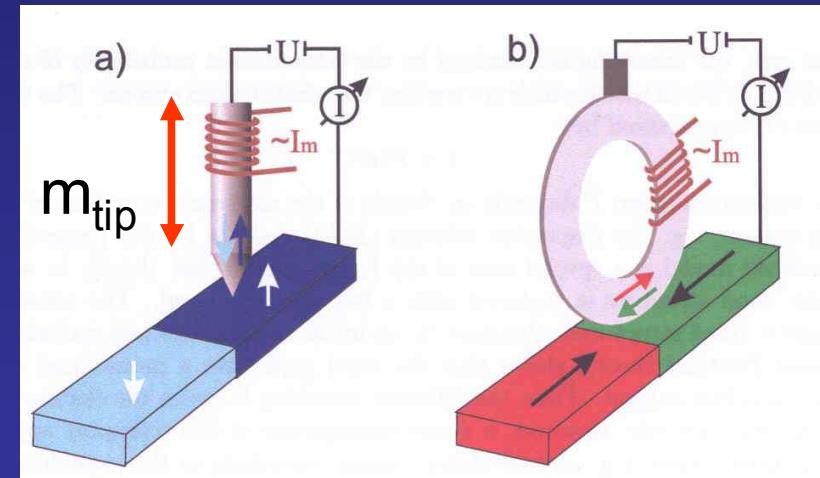
$I_t$  depends on the relative magnetization orientation tip vs. sample

$$dI / dm_{\text{tip}}$$

Wulfhekel, Kirschner, APL 75 (1999) 1944



Spin-STS:

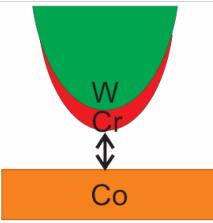


Pietzsch, Kubetzka, Bode, Wiesendanger  
PRL 92 (2004) 057202

Also: Co/Au/W tip: Prokop, Kukunin, Elmers, PRL 95 (2005) 187202

Cr/W: Rusponi, Weiss, Cren, Epple, Brune, APL 87 (2005) 162514

# Magnetic contrast in spin-STM



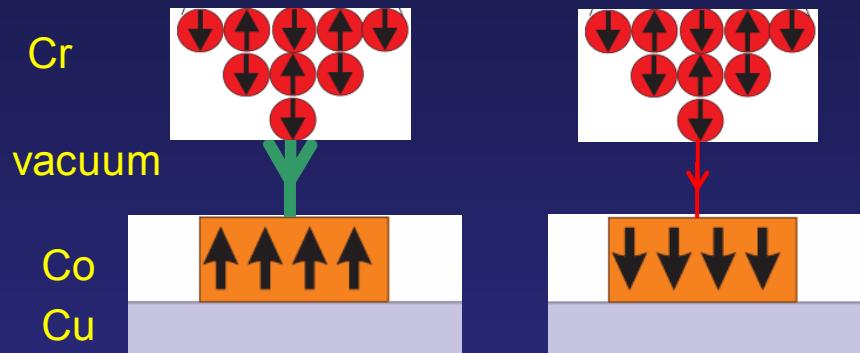
## Spin-STM:

Bode et al, PRL 81, 4256 (1998);  
Wulfhekel, Kirschner, APL 75, 1944 (1999)

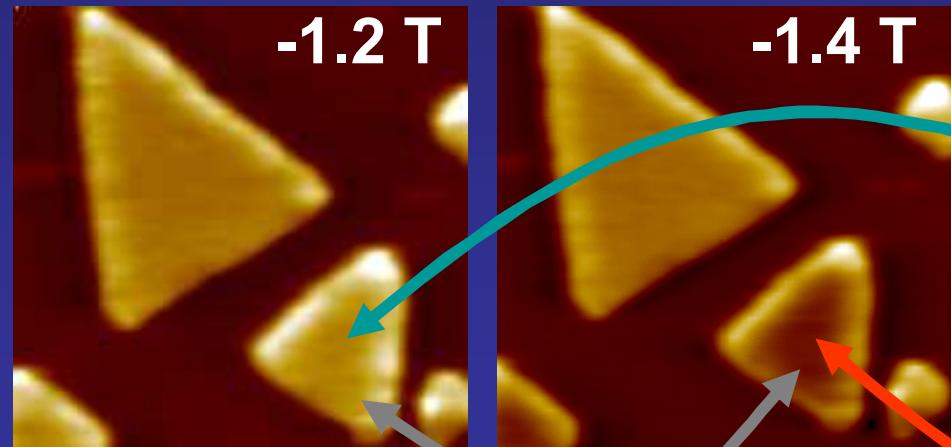
## Co / Cu(111):

Pietzsch, Kubetzka, Bode, Wiesendanger,  
PRL 92 (2004) 057202.

W tip with 40 ML Cr



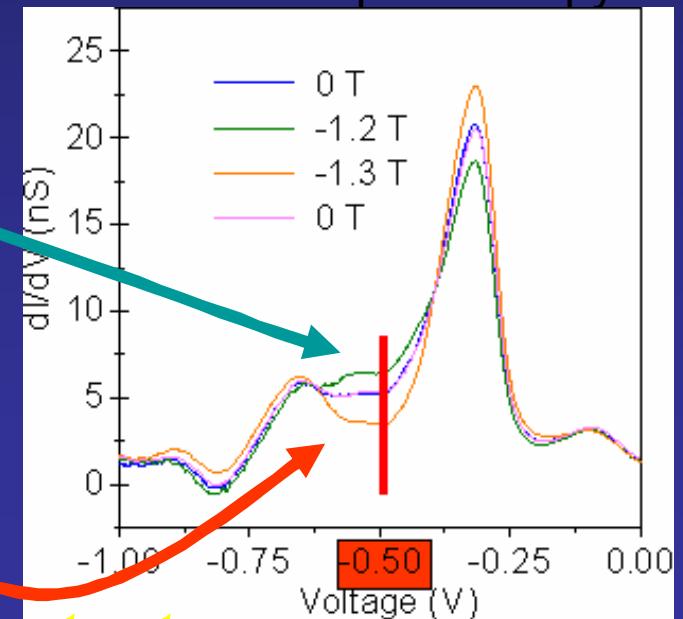
$dI/dV$  mapping



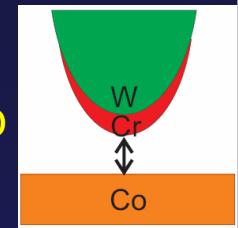
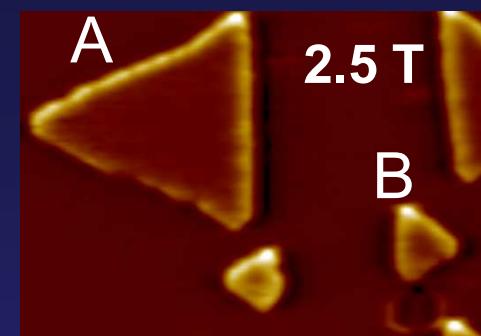
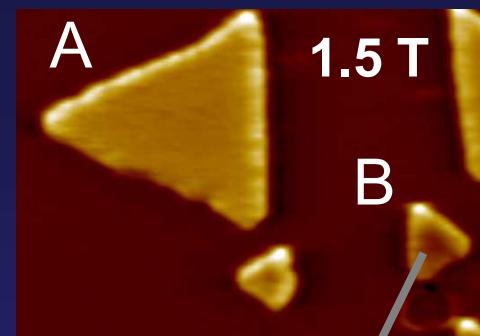
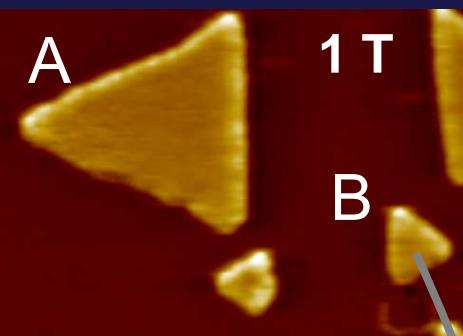
30 x 30 nm<sup>2</sup>  
-0.5 V, 1 nA

*field-induced change of contrast*

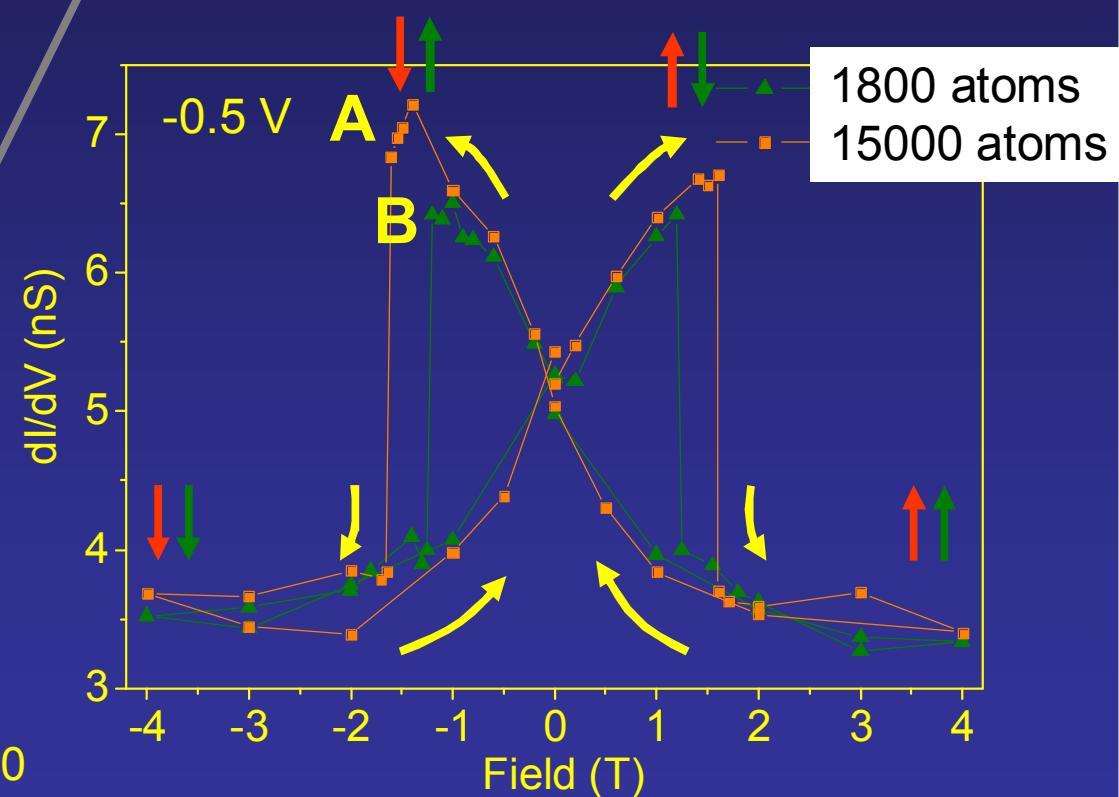
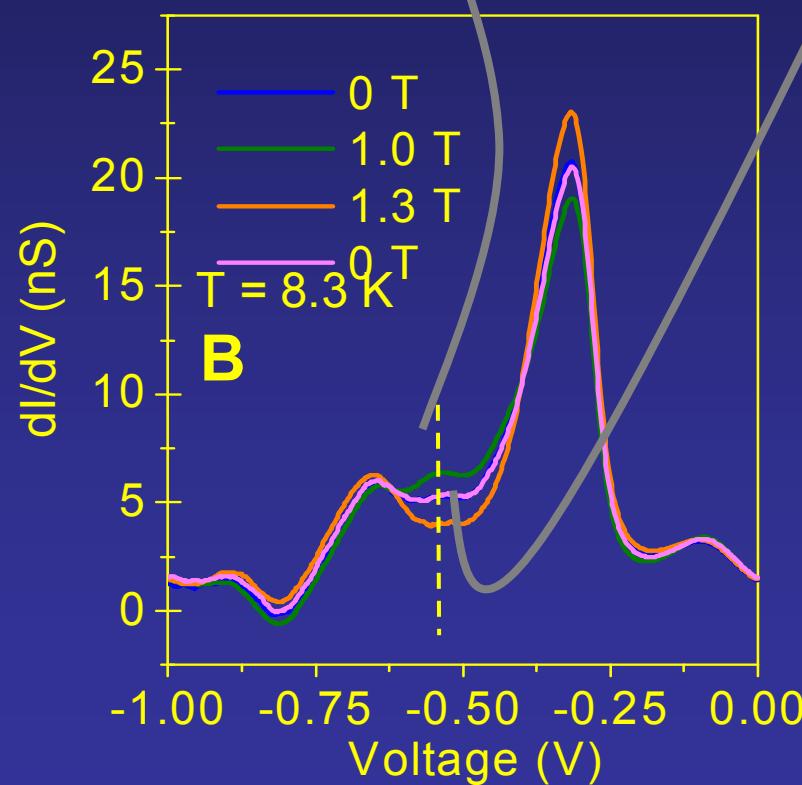
Point spectroscopy



# Field dependent spectroscopy



$dI/dV$ , 55x40 nm<sup>2</sup>, -0.5 V



$dI / dV$ : reorientation of **M** is accessible

# Magnetic switching field $H_{sw}$ of individual Co islands

influence of temperature and island size

T increases



size increases



*$H_{sw}$  decreases with  $T$  at fixed island size*

*$H_{sw}$  changes non-monotonic with island size at fixed  $T$*

# Size and T-dependence of the switching field $H_{SW}$

//

$H_{SW}(T,V)$ : all curves  
Néel-Brown model

//

1:  $H_{SW} = 0$  T; superparamagnetic regime

*thermally assisted switching*

2:  $H_{SW}$  increases with size: blocked magnetization

3:  $H_{SW}$  decreases with size: *additional* reversal mechanisms

# superparamagnetic – blocked magnetization state

## *Failure of the Néel-Brown model*

Simplistic, but *questionable* view:

nm small particle – single domain – magnetization reversal by coherent rotation  
? ?

stable = blocked magnetization implies a timescale, here  $\tau = 100$  s

$$\Delta E = KV$$

$$\tau^{-1} = f_0 \exp\left(-KV/k_B T\right), \quad f_0 = 10^9 \dots 10^{12} \text{ s}^{-1}$$

Dickson et al., JMMM125(1993)345

$$K = 233 \dots 297 \text{ kJ/m}^3, \quad V_{1200 \text{ atoms}} = 12 \text{ nm}^3, \quad T = 8.3 \text{ K}$$



*SURPRISE:* small  $K$  (hcp-Co: 513 kJ/m<sup>3</sup>)

*maximum switching field:*  $2K/M_S = 0.3 \dots 0.4 \text{ T}$

*CONFFLICT:* we observe 2 T



Theory:  $K(2 \text{ AL Co}) = 2.2 \text{ MJ/m}^3 (0.150 \text{ meV/atom})$  C. Etz, MPI Halle

# Limitations of the Néel-Brown model of thermally assisted switching

*Extension of the Stoner-Wohlfarth model to finite  $T$  is not valid here  
macrospin model does not work*

we have *no bulk sample*:

all interface atoms

coordination reduced and varies

possible complications:

reduced exchange constant,

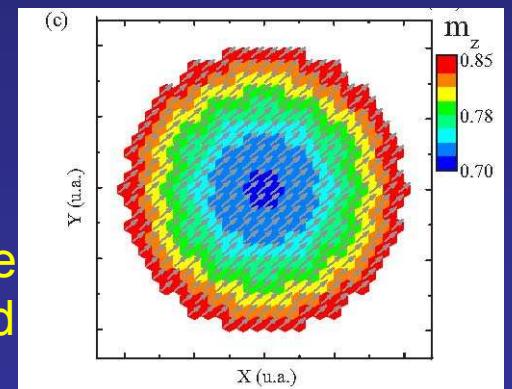
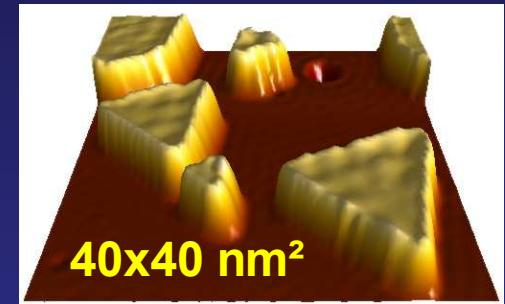
variation of  $K$ , inhomogeneous  $M$

*Limitations of the macrospin model:*

Rohart, Repain, Thiaville, Rousset, PRB76(2007) 104401

Wirth, Field, Awschalom, v. Molnár, PRB 57(1998)R14028

Non-collinear spin state  
Strong reduction of switching field



K at rim only  
5 nm diam.  
1 AL Co

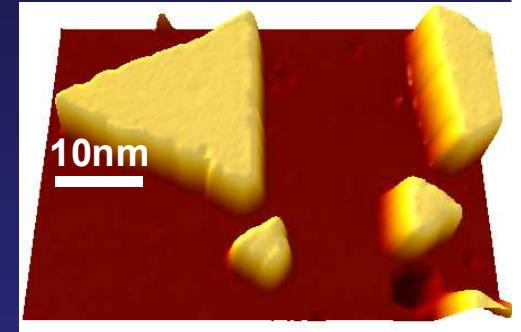
*more complicated than coherent rotation  
reversal modes need to be considered*

# Conclusion Spin-STM study of magnetic reversal

Magnetization reversal of nm small Co islands:

Coherent rotation of a macrospin  
is not supported by our experiments

Large switching fields:  
large anisotropy ( 0.150 meV / atom)



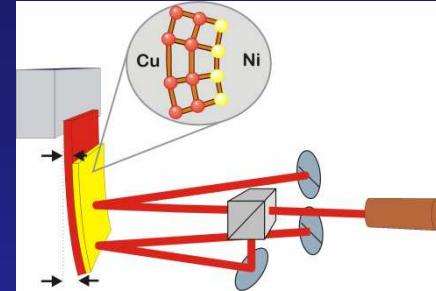
*Magnetization reversal by nucleation feasible:*

combination of reduced coordination and large K  
linear dimension more decisive than volume

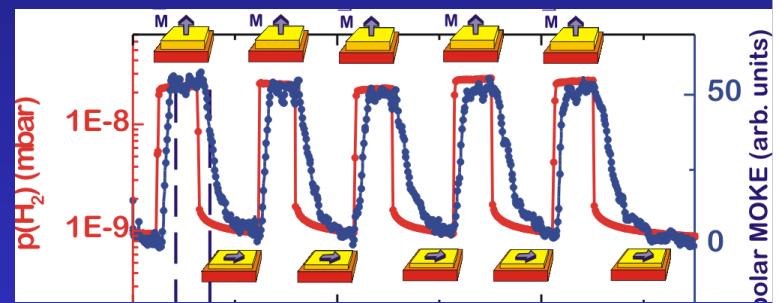
# Conclusion and outlook

stress measurements

surface stress, adsorption,  
reconstruction, growth mode,  
structural transitions



structural relaxation and SRT



complex magnetic switching and tip behavior

electron confinement and  
spatial modulation of spin-polarization

