Magnetic anisotropy and interlayer exchange coupling in ultrathin ferromagnets: experiment versus theory

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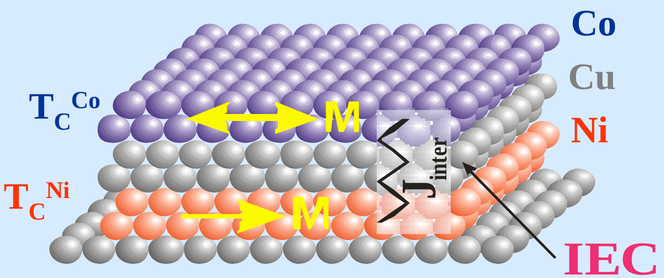
2. **Magnetic Anisotropy Energy**
3. **Interlayer Exchange Coupling and f (T)**
4. Summary



1. Prologue

Is this of interest
for the theory?

281. WE-Heraeus-Seminar

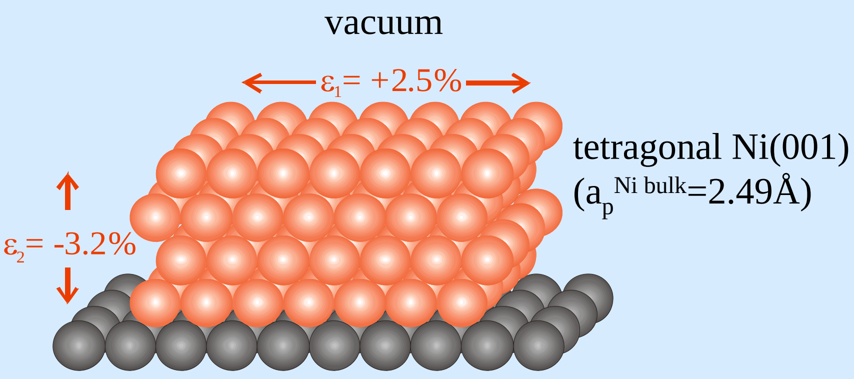
“Spin-Orbit Interaction
and Local Structure
in Magnetic Systems
with Reduced Dimensions“
June 2002 in Wandlitz


Peter Grünberg

2. **M**agnetic **A**nisotropy **E**nergy

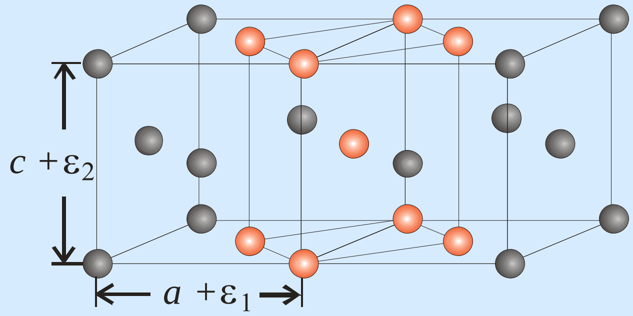
Growth of artificial nanostructures

bcc, fcc → tetragonal, trigonal



tetragonal Ni(001)
($a_p^{\text{Ni bulk}}$=2.49Å)

fcc Cu(001) substrate (a_p=2.55Å)

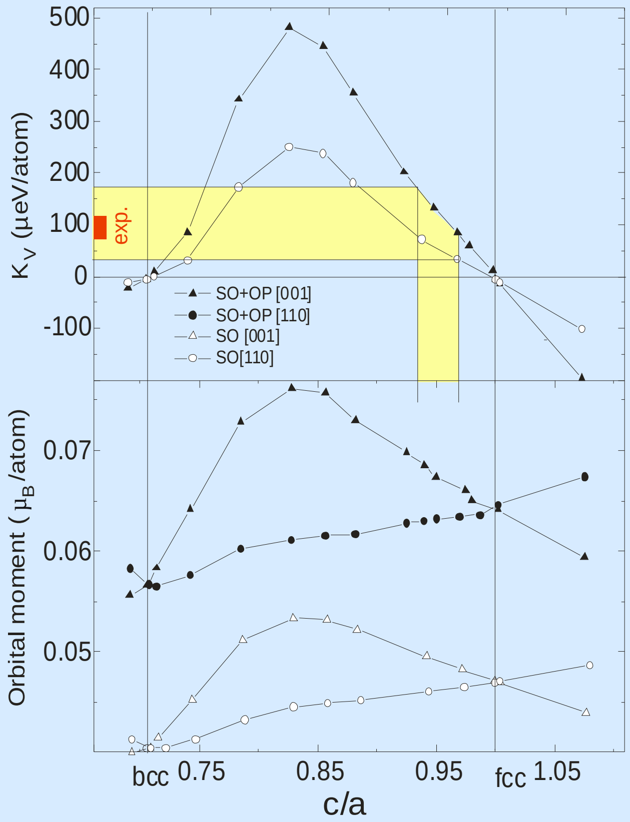


Bain path

c/a=1 fcc → fct → bcc c/a=1/√2

Infinite sized Ni x-tal
no surface effects

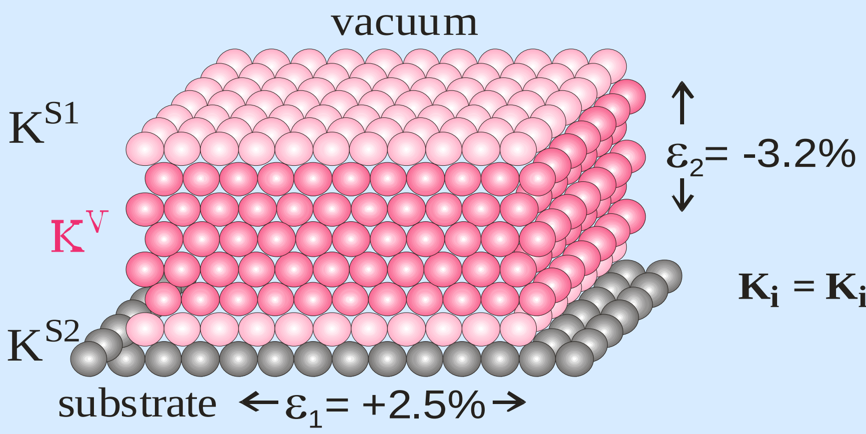
O. Hjortstam, K. B. et al. PRB **55**, 15026 ('97)



Structural changes by ≈ 0.05 Å increase **MAE**
by 2-3 orders of magnitude (~ 0.2 → 100μeV/atom)

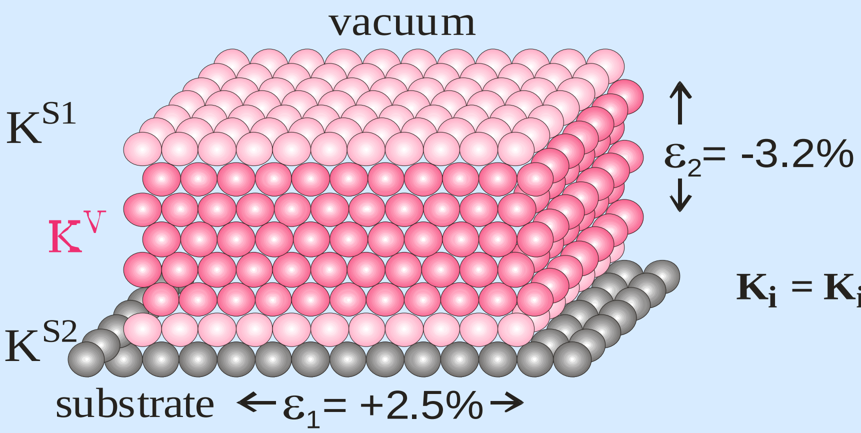
see also: R. Wu et al. JMMM 170, 103 ('97)

“volume”, “surface” and “interface” MAE



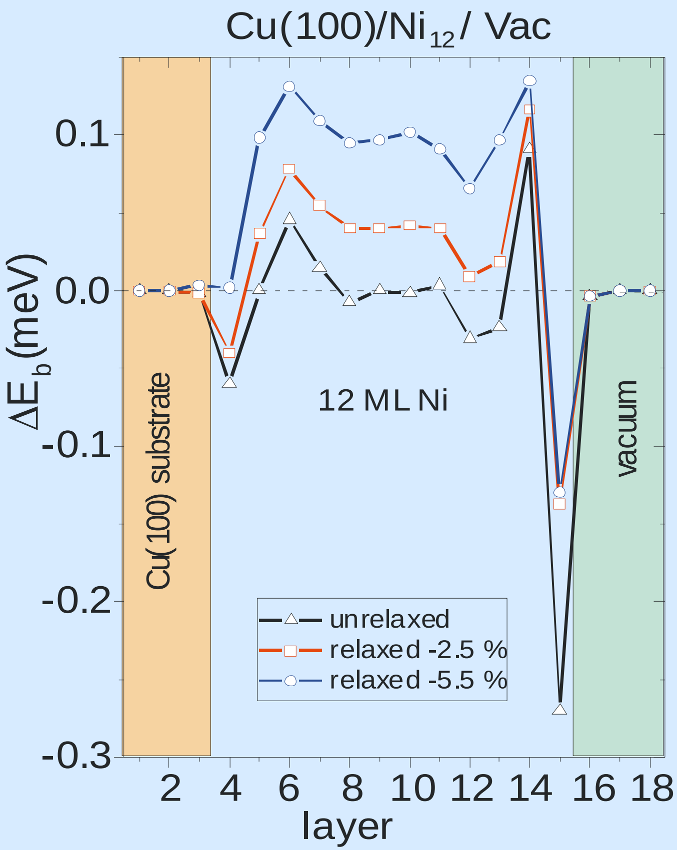
$$\mathbf{K_i = K_i^{V} + 2\frac{K_i^{S}}{d}}$$

“volume”, “surface” and “interface” **MAE**

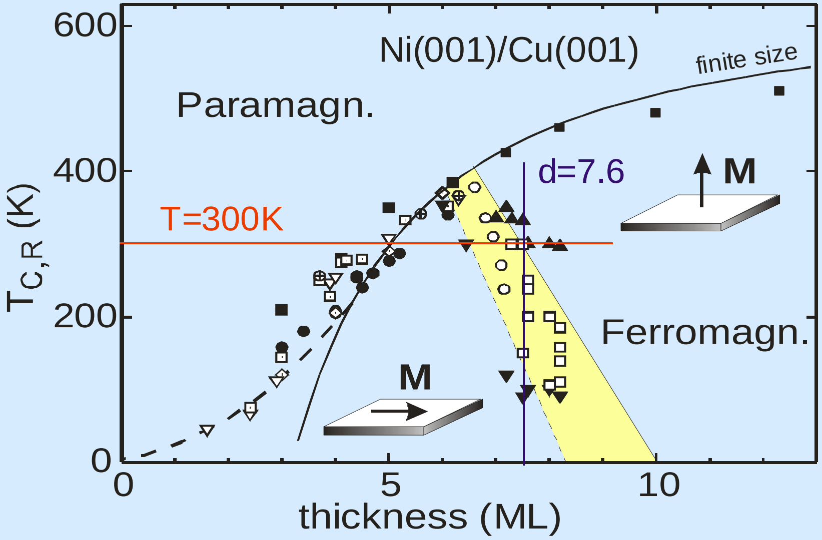


$$\mathbf{K_i = K_i^V + 2\frac{K_i^S}{d}}$$

C. Uiberacker et al.
Phys. Rev. Lett. **82**, 1289 (1999)

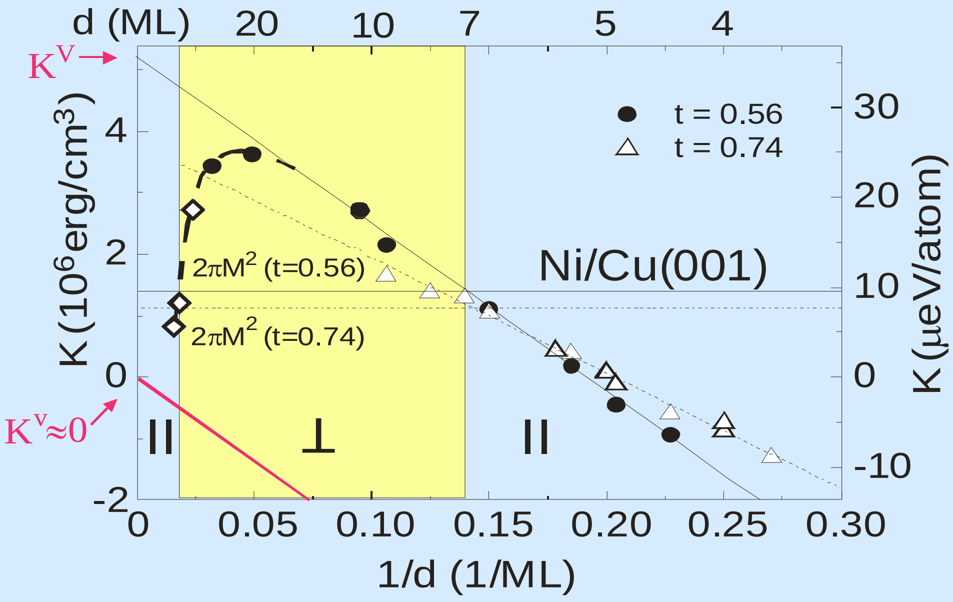


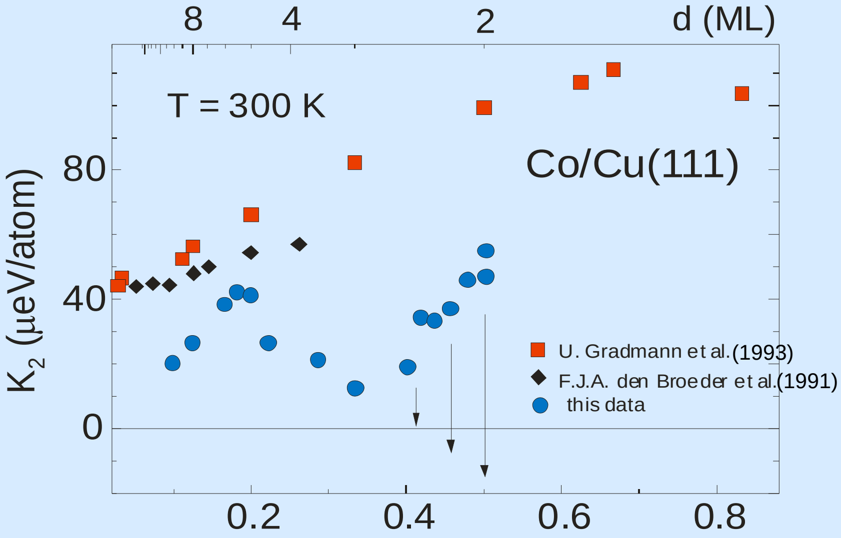
$t=T/T_C(d)$

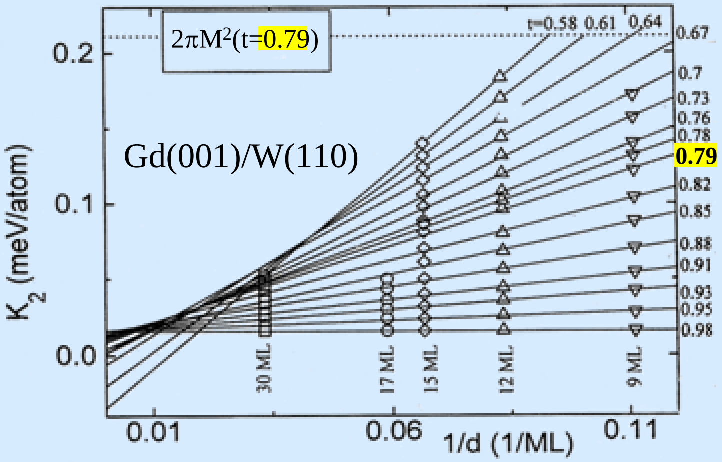


P. Poulopoulos and K. B.
J. Phys.: Condens. Matter **11**, 9495 (1999)

The surface and interface **MAE** are certainly large (L. Néel, 1954) but count only for one layer each. The inner part (volume) of a nanostructure will overcome this, because they count for in n-2 layers.

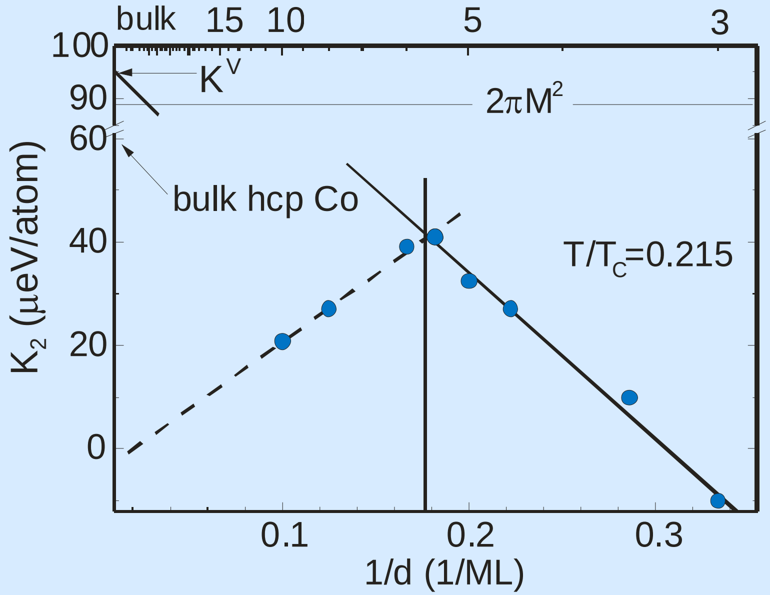






G. André et al., Surface Science **326**, 275 (1995)

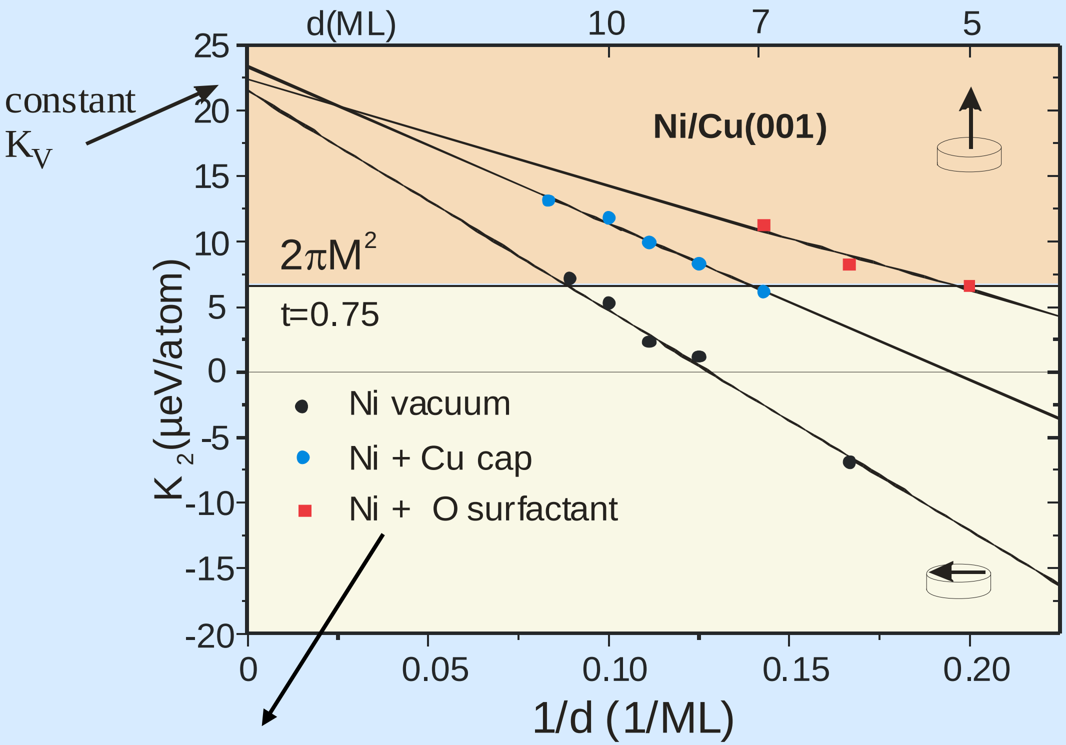
K. B. and M. Farle, J. Appl. Phys. **81**, 5038 (1997)



M. Farle et al., Surf. Sci. **439**, 146 (1999)

In a proper analysis, taking T/T$_C$(d) in consideration, we always find a linear $K=K_V+2K_S/d$ dependence.
A departure from this “Néel argument” indicates changes in the x-tal structure

Manipulation of surface MAE, K_S by adsorbed molecules, metal cap and surfactant growth



J. Lindner et al. Surf. Sci. Lett. **523**, L65 (2003)

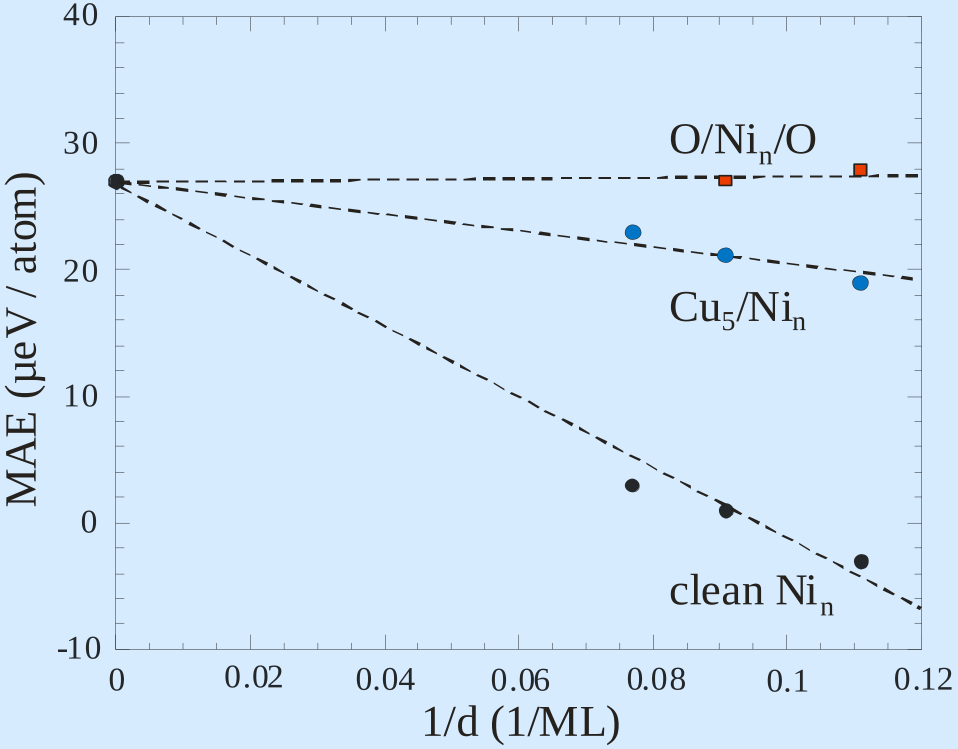
Interface	K_s (µeV/atom)	d_c (ML)
Ni/vacuum	-107	10.8
Ni/Cu	-59	7.6
Ni/CO (van Dijken et al.)	-81	7.3
Ni/H_2 (van Dijken et al.)	-70	6.8
Ni/O (surfactant)	-17	4.9

Changes of K_S shift
the spin reorientation transition d_C

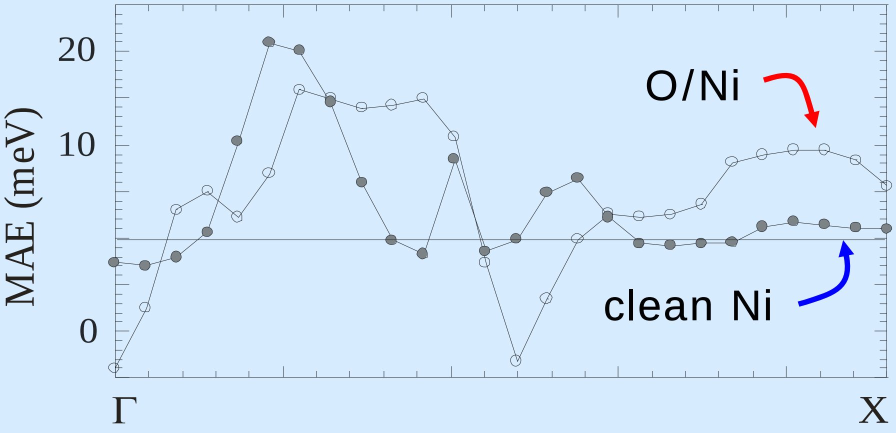
K. B. ***Handbook of Magnetism and Advanced Magnetic Materials,*** Vol. 3
Ed. Kronmüller and Parkin, 2007 John Wiley & Sons, Ltd.

Results of ab initio calculations

R. Q. Wu & coworkers



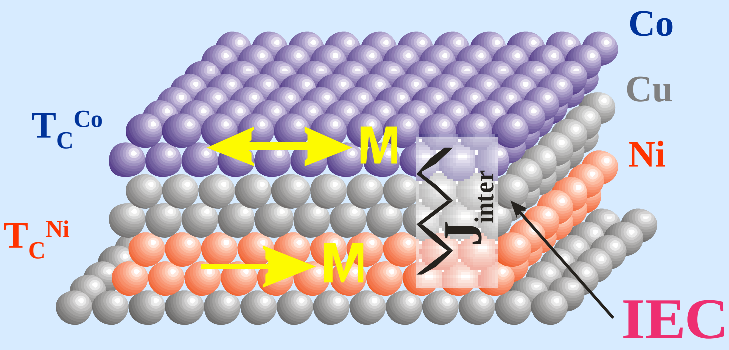
MAE along $\overline{\Gamma X}$ axis



O-induced surface state seen in the vicinity of $\overline{X}$-point is responsible for change in **MAE**

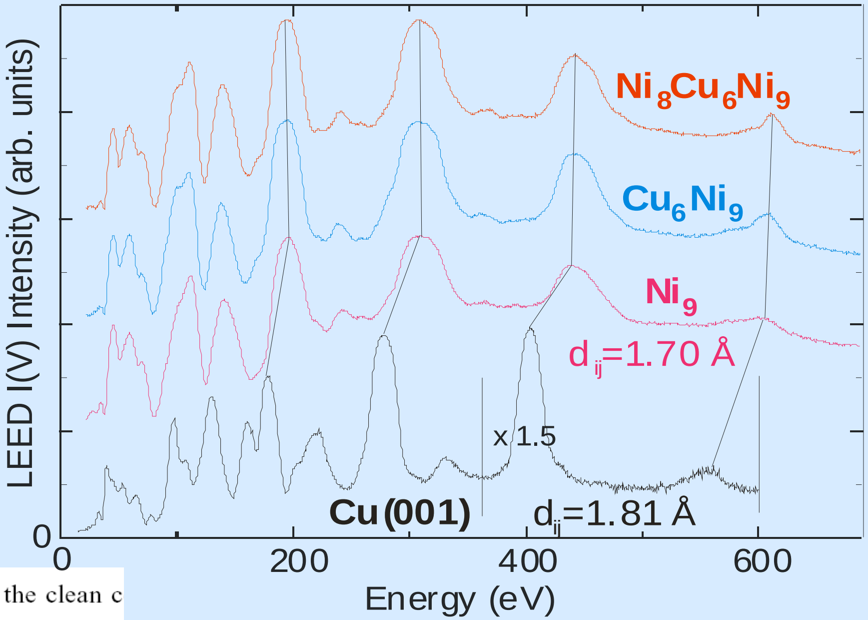
for details see Phys. Rev. Lett. **92**, 147202 (2004)

3. Interlayer Exchange Coupling and f (T)



W. Platow et al. PRB **59,** 12641 (1999)

full trilayer grows in fct structure



R. Nünthel, PhD Thesis FUB 2003

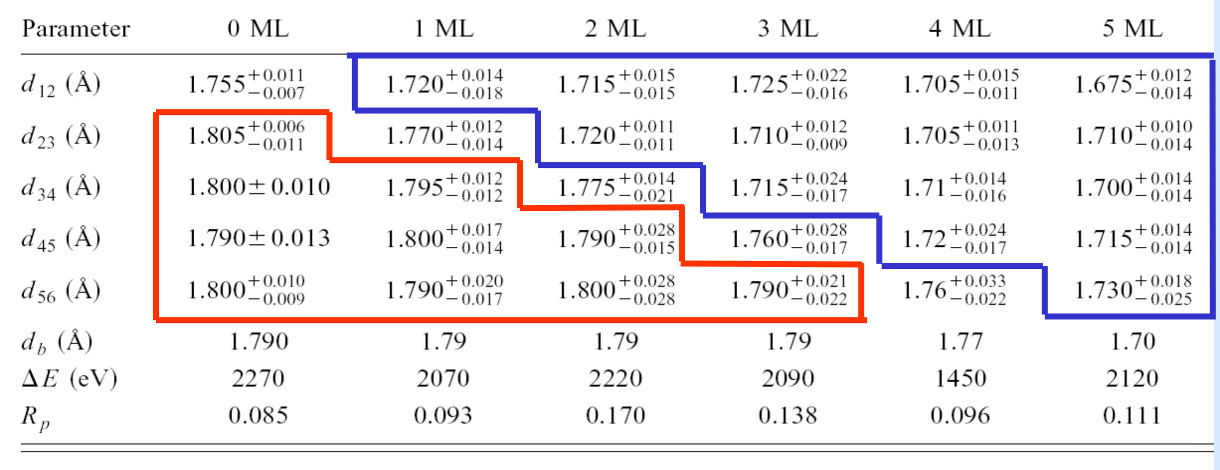
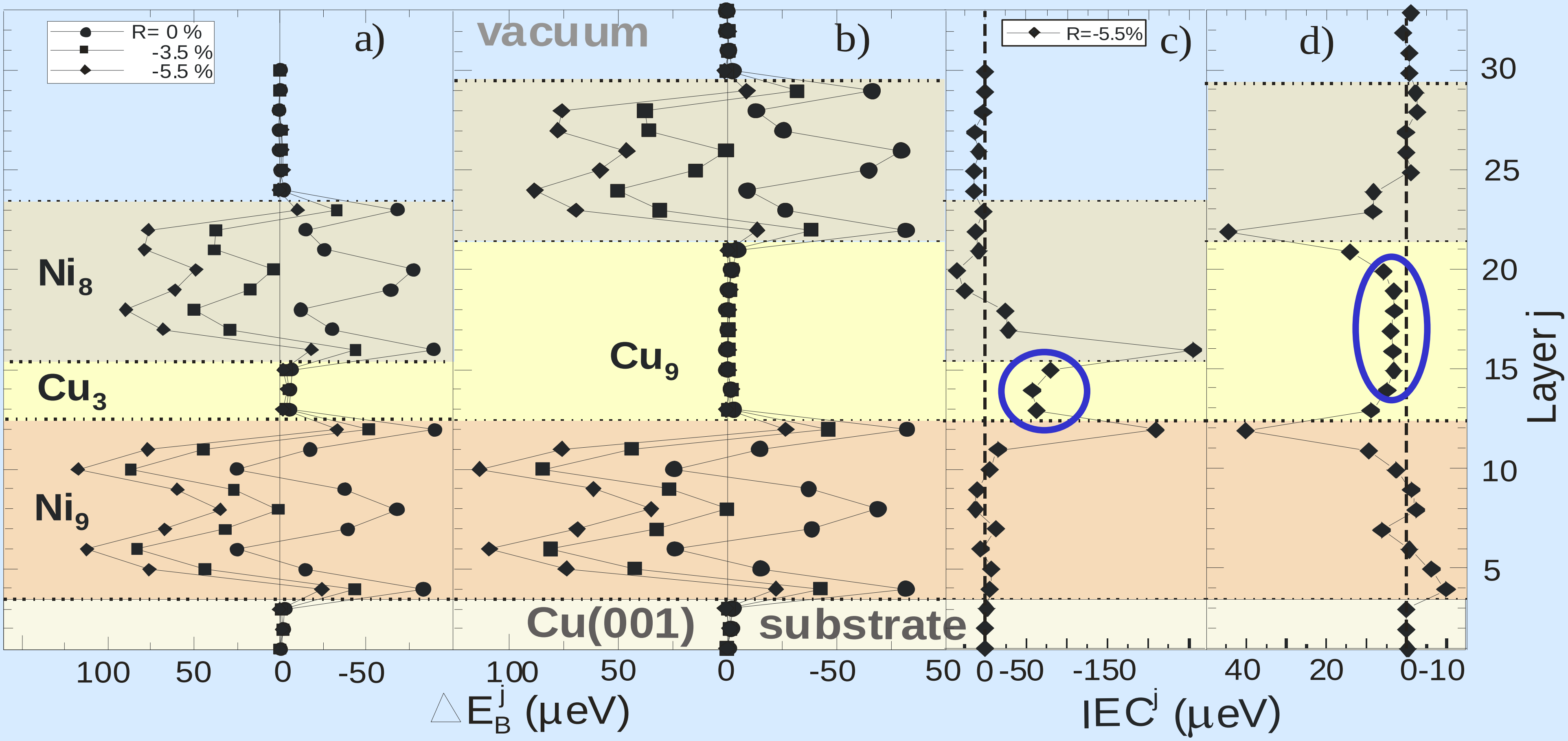


TABLE I. Best-fit structural data for the nickel films of different thickness and the clean c

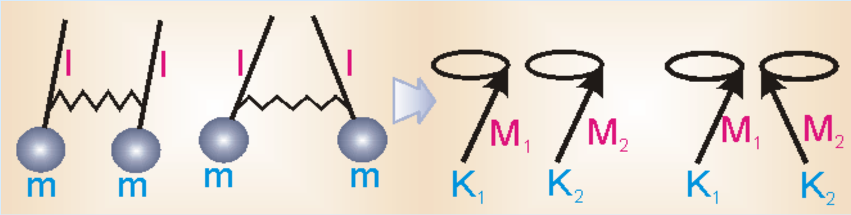
Parameter	0 ML	1 ML	2 ML	3 ML	4 ML	5 ML
d_{12} (Å)	$1.755^{+0.011}_{-0.007}$	$1.720^{+0.014}_{-0.018}$	$1.715^{+0.015}_{-0.015}$	$1.725^{+0.022}_{-0.016}$	$1.705^{+0.015}_{-0.011}$	$1.675^{+0.012}_{-0.014}$
d_{23} (Å)	$1.805^{+0.006}_{-0.011}$	$1.770^{+0.012}_{-0.014}$	$1.720^{+0.011}_{-0.011}$	$1.710^{+0.012}_{-0.009}$	$1.705^{+0.011}_{-0.013}$	$1.710^{+0.010}_{-0.014}$
d_{34} (Å)	1.800 ± 0.010	$1.795^{+0.012}_{-0.012}$	$1.775^{+0.014}_{-0.021}$	$1.715^{+0.024}_{-0.017}$	$1.71^{+0.014}_{-0.016}$	$1.700^{+0.014}_{-0.014}$
d_{45} (Å)	1.790 ± 0.013	$1.800^{+0.017}_{-0.014}$	$1.790^{+0.028}_{-0.015}$	$1.760^{+0.028}_{-0.017}$	$1.72^{+0.024}_{-0.017}$	$1.715^{+0.014}_{-0.014}$
d_{56} (Å)	$1.800^{+0.010}_{-0.009}$	$1.790^{+0.020}_{-0.017}$	$1.800^{+0.028}_{-0.028}$	$1.790^{+0.021}_{-0.022}$	$1.76^{+0.033}_{-0.022}$	$1.730^{+0.018}_{-0.025}$
d_b (Å)	1.790	1.79	1.79	1.79	1.77	1.70
ΔE (eV)	2270	2070	2220	2090	1450	2120
R_p	0.085	0.093	0.170	0.138	0.096	0.111

SP-KKR calculation for ΔE_{band} and IEC for rigit fcc and relaxed fct structures

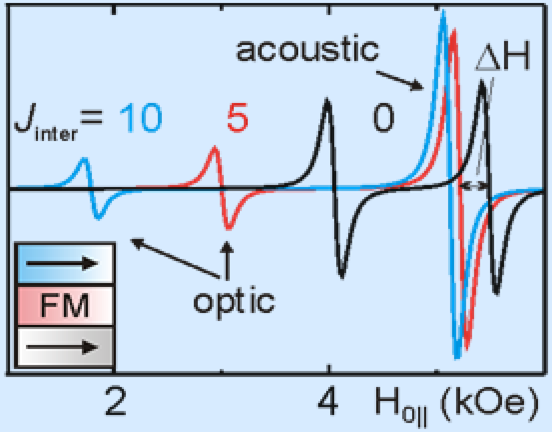
R. Hammerling, P. Weinberger et al., PRB **68**, 092406 (2003)



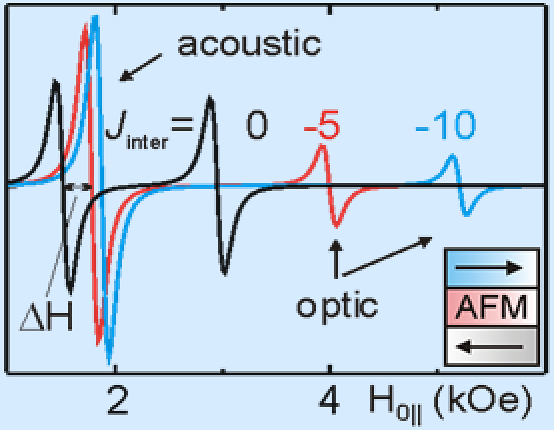
in-situ FMR in coupled films



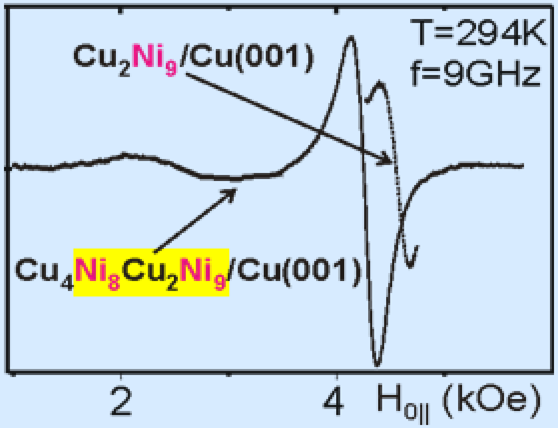
Advantage: FM and AFM
IEC => f(T) in μeV/ particle



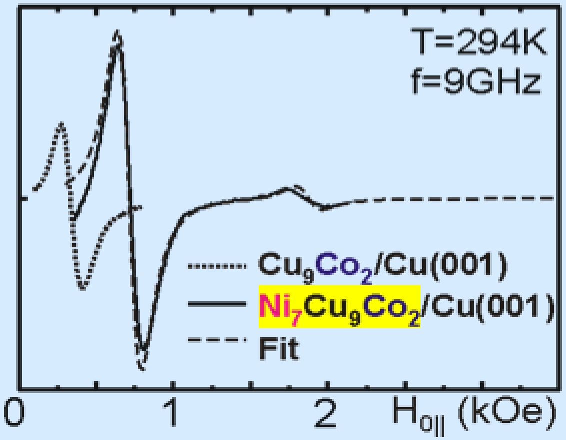
theory



FMR



in-situ
UHV-experiment



J. Lindner, K. B. Topical Rev., J. Phys. Condens. Matter **15**, R193-R232 (2003)

Interlayer exchange coupling and its T-dependence.

P. Bruno, PRB **52**, 411 (1995); V. Drchal et al. PRB **60** , 9588 (1999)

N.S. Almeida et al. PRL **75**, 733 (1995)

$$J_{inter} = J_{inter,0}\left[\frac{T/T_0}{\sinh(T/T_0)}\right] \quad T_0 = \hbar v_F / 2\pi k_B d$$

$$J_{inter} = J_{inter,0}\left[1-(T/T_C)^{3/2}\right]$$

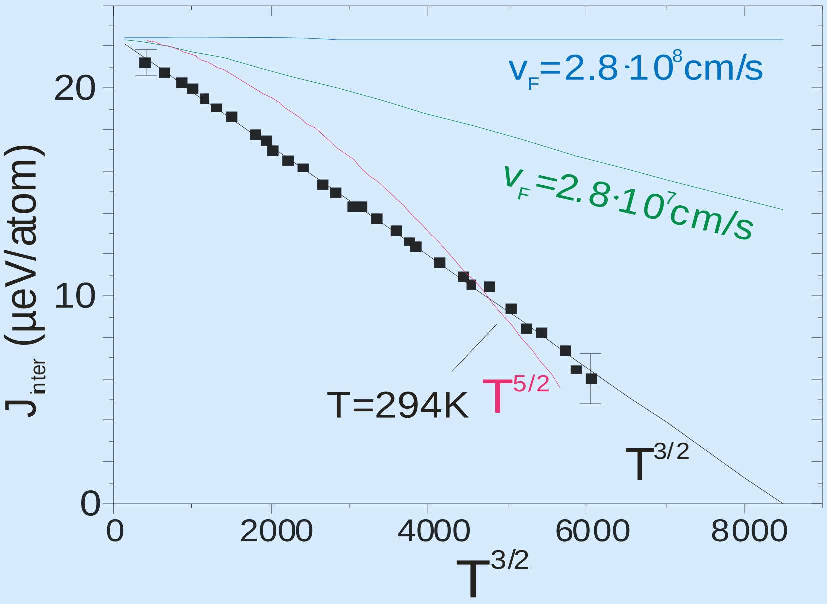
$Ni_7Cu_9Co_2$/Cu(001)

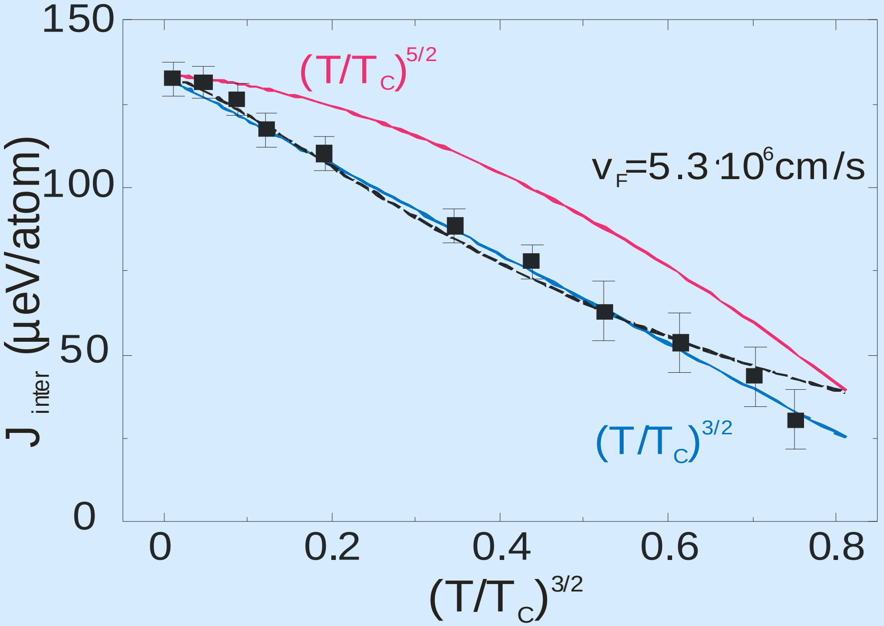
J. Lindner et al.
PRL **88**, 167206 (2002)

$(Fe_2V_5)_{50}$

T=55K - 332K

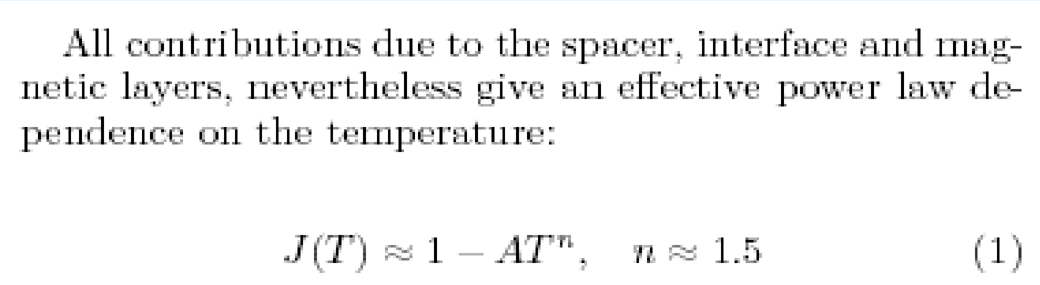
T=15K - 252K, T_C=305K





S. Schwieger, W. Nolting, PRB **69**, 224413 (2004)

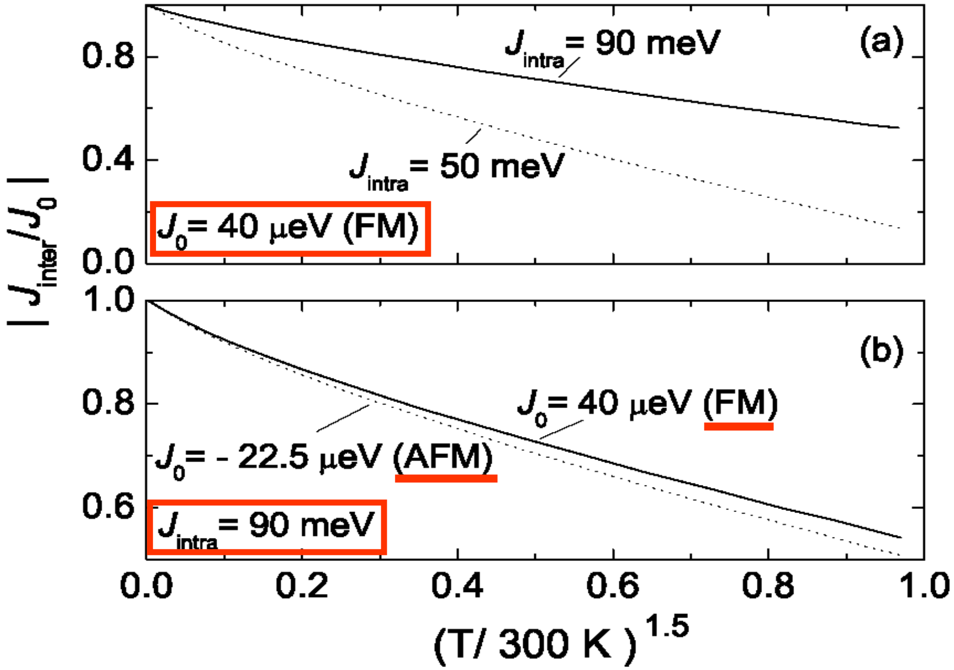
T dependence of IEC

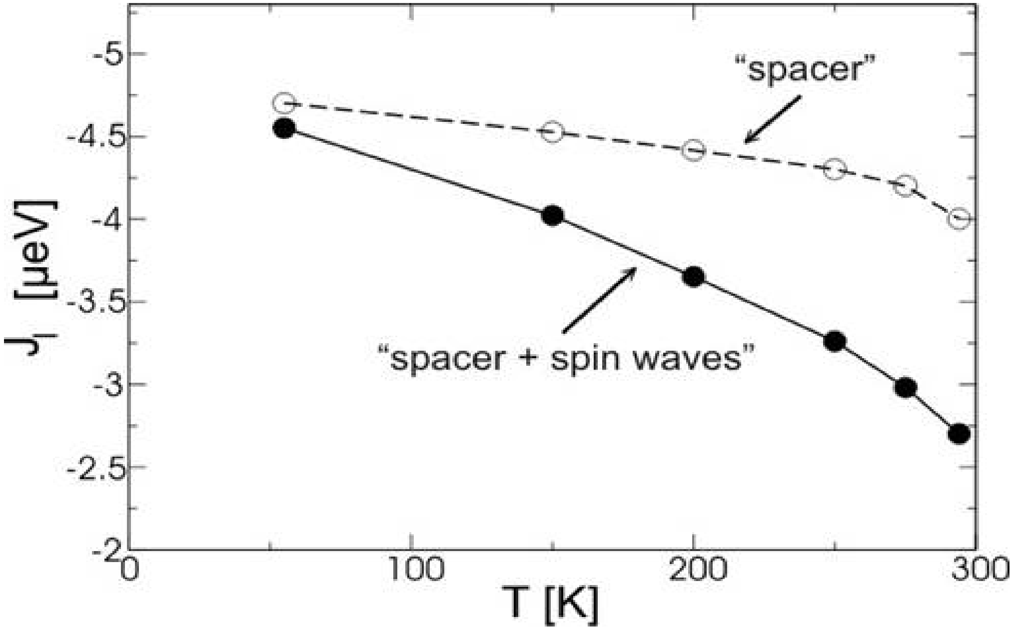


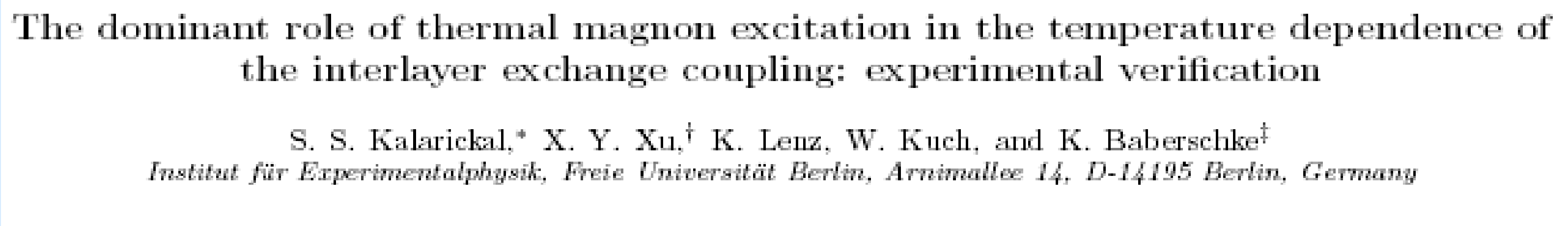
All contributions due to the spacer, interface and magnetic layers, nevertheless give an effective power law dependence on the temperature:

$$J(T) \approx 1 - AT^n, \quad n \approx 1.5 \qquad (1)$$

S. Schwieger et al., PRL **98**, 57205 (2007)







The dominant role of thermal magnon excitation in the temperature dependence of the interlayer exchange coupling: experimental verification

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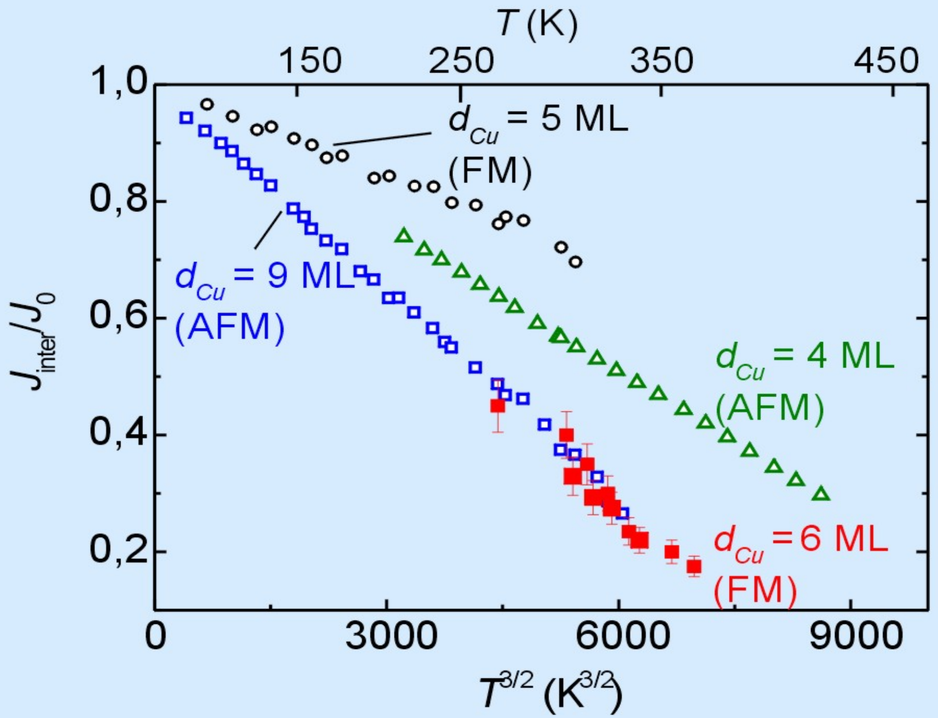
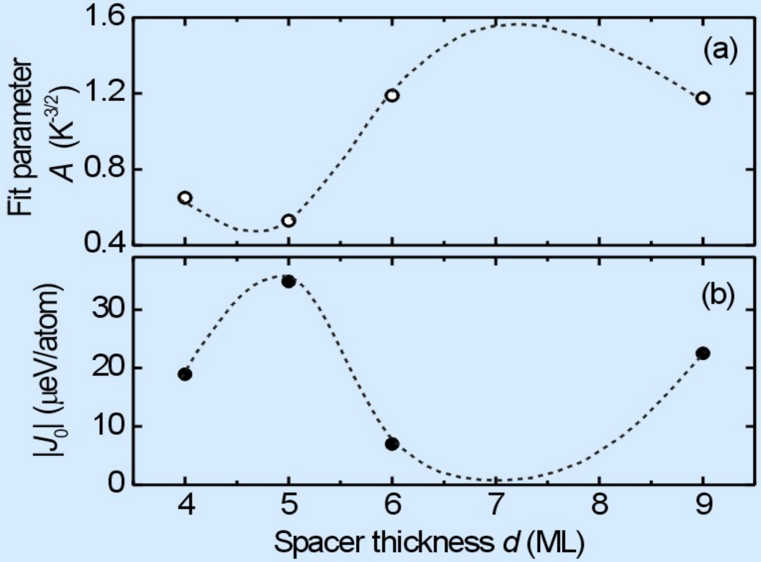
Institut für Experimentalphysik, Freie Universität Berlin, Arnimallee 14, D-14195 Berlin, Germany

PRB **75**, 224429 (2007)



$J(T) \approx 1 - A(d)T^n$, with n ≈1.5



A(d) ≠ const. (interface)

A(d) ≠ linear function (electronic bandstructure)

A(d) ≈ osc. function (spin wave excitation)

4. Summary: Very fruitful collaboration between theory and experiment.

Theory can disentangle various mechanisms (K^s, K^v, layer-by-layer, spin waves or band structure, etc.)

Experiment needs no muffin tin radius, is full-relativistic (anisotropy depends on orbital magnetism)

For details see: K. B. in Vol. 3 ***Handbook of Magnetism and Advanced Magnetic Materials,***
Ed. Kronmüller and Parkin, 2007 John Wiley & Sons, Ltd.

Theory: H. Ebert, LMU; J.J. Rehr, UW; O. Eriksson UU; P. Weinberger, TU Vienna;

R. Wu, D.L. Mills, UCI; P. Jensen + K.H. Bennemann, FUB; W. Nolting, HUB

www.physik.fu-berlin.de/~bab

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Support:
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