Damping and spin pumping in ferromagnetic nanostructures

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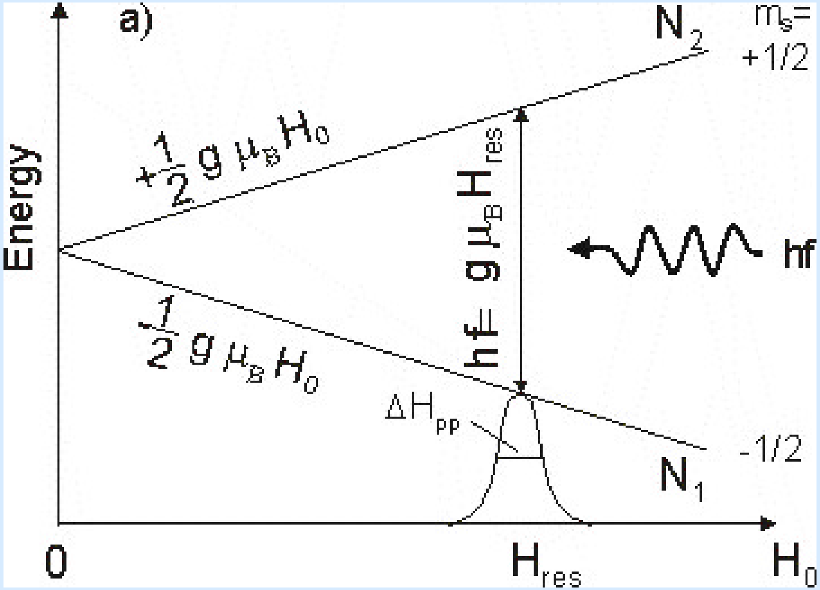
1. **UHV – EPR/FMR in magnetic monolayers**
   Landau-Lifshitz equation of motion
2. **ESR from 1 – 200 GHz; Gilbert-damping ??**
3. **“Spin pump” effects, spintronics**

Þ **http://www.physik.fu-berlin.de/~ag-baberschke**

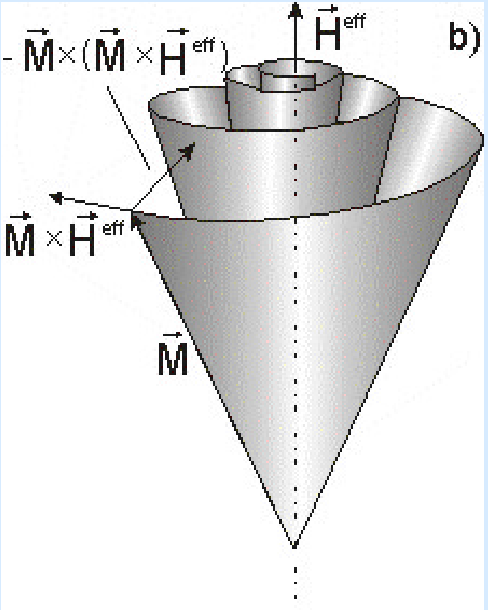
Linewidth in magnetic resonance

ESR



T_1 = long. relaxation, spin-phonon
T_2 = transv. Relaxation, spin-spin

FMR

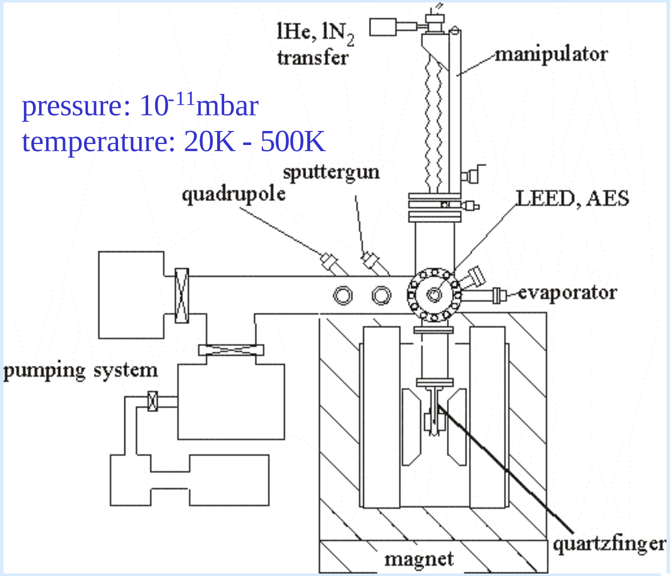


Landau-Lifshitz-Gilbert equation

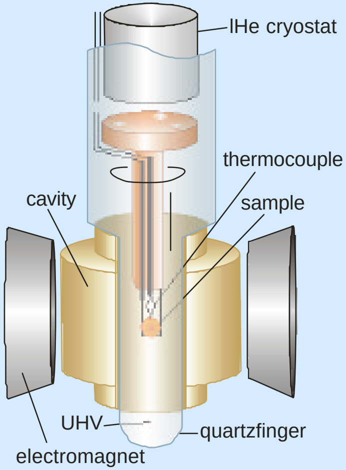
$$\frac{1}{g}\frac{\partial M}{\partial t} = -M\times H_{eff}(J_{inter},K) + \frac{G}{g^2 M_S^2}\left(M\times\frac{\partial M}{\partial t}\right)$$

EPR / FMR in UHV

In situ UHV-FMR set up 1,4,9 GHz

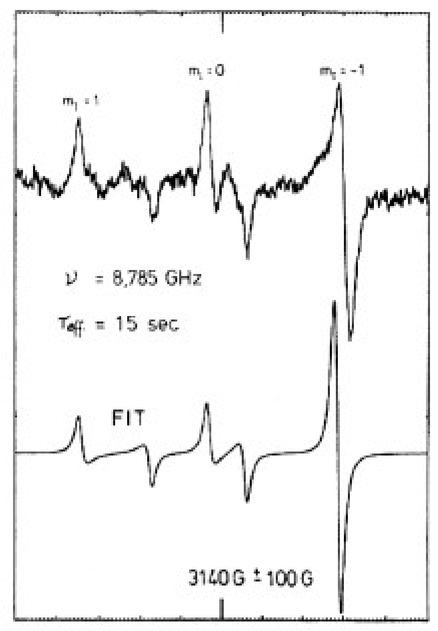


pressure: 10^{-11}mbar
temperature: 20K - 500K



ESR of
0.01L NO_2/10L Kr/Ag(110);
T=20K
1/100 ML ~ 10^{12} particles

M. Zomak et al.,
Surf. Sci. **178**, 618 (1986)



M. Farle, K.B. PRL **58**, 511 (1987)

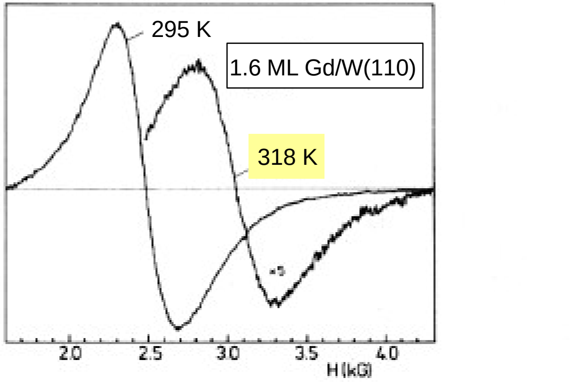


Fig. 4. ESR spectra for the new 1.6 ML sample (not cited in [2, 3]). Note the significant change in intensity and resonance field from 16 to 39 K above T_c

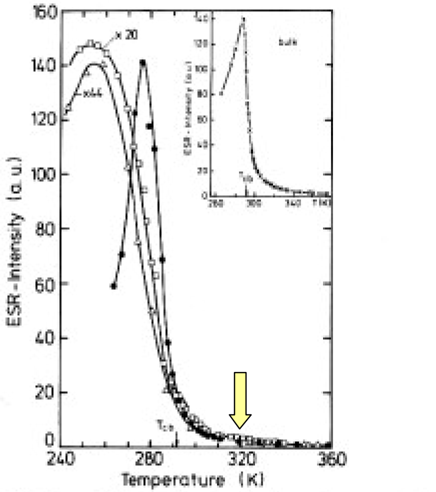
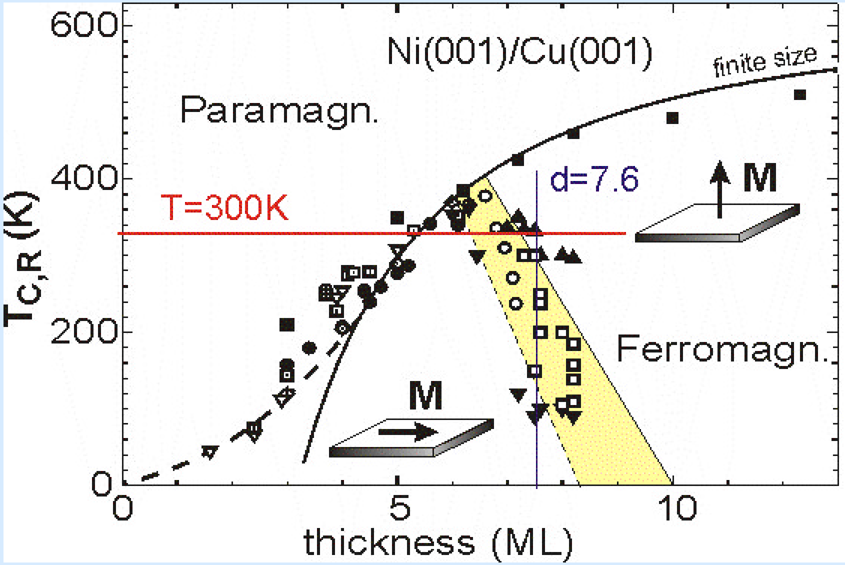
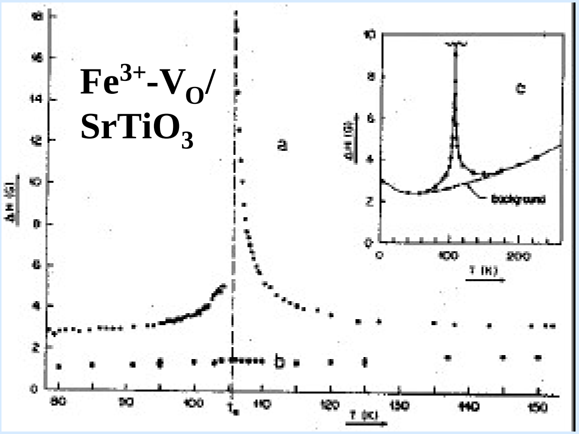


Fig. 5. Area of the ESR signal as a function of temperature for 80 Å (●), the new 1.6 ML (□), and the 0.8 ML (△). The insert shows the same data for a 18 μm thick Gd foil (bulk). Solid lines are guides to the eye. The 1.6 and 0.8 ML have a vertical gain factor of 20 and 44 with respect to 80 Å. The insert is not to scale

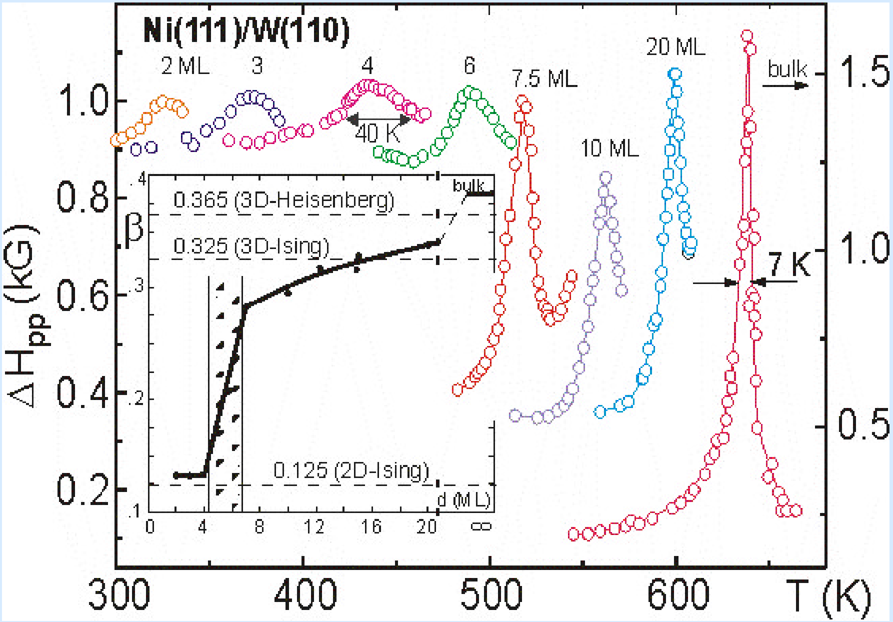
For thin films the Curie temperature can be manipulated



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



Th.v. Waldkirch, K.A. Müller, W. Berlinger, PRB (1973)

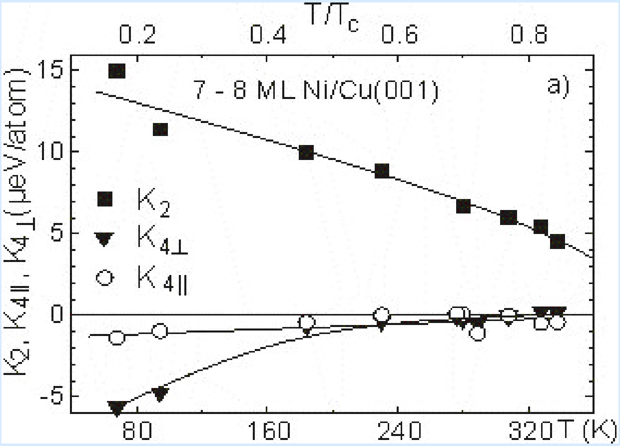


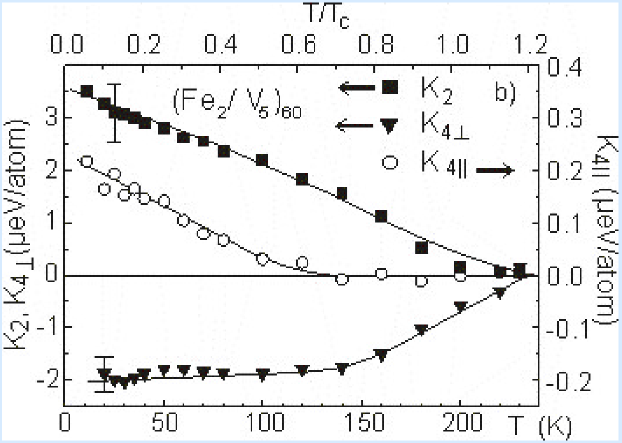
Yi Li, K. B., PRL **68**, 1208 (1992)

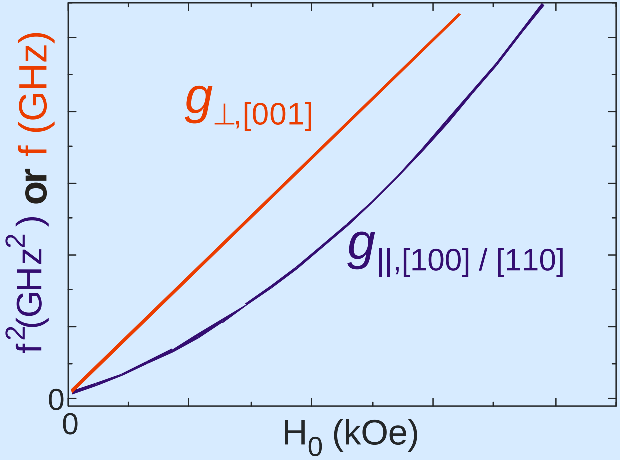
Determination of g-Tensor and Magn. Anisotropy Energy K

$$\frac{w^2}{g^2_{\|,[100]}} = H^2_{0,[100]} + H_{0,[100]}\left(4pM - 2\frac{K_2}{M} + \frac{4K_{4\|}}{M}\right) + 2\frac{K_{4\|}}{M}\left(4pM - 2\frac{K_2}{M} + \frac{2K_{4\|}}{M}\right)$$

$$\frac{w}{g_{\perp,[001]}} = H_{0,\perp} - 4pM + \frac{2\left(K_2 + K_{4\perp}\right)}{M}$$



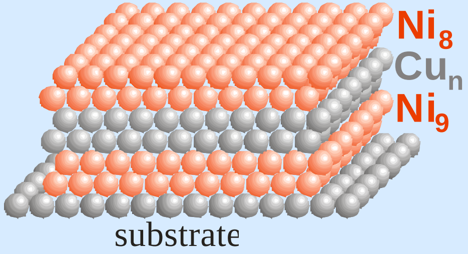


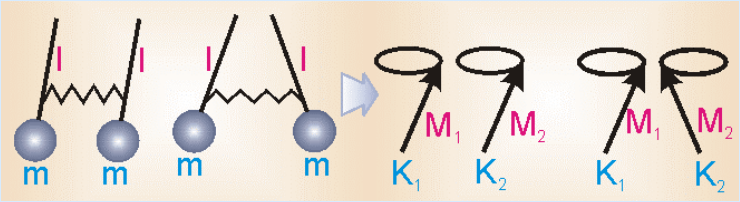


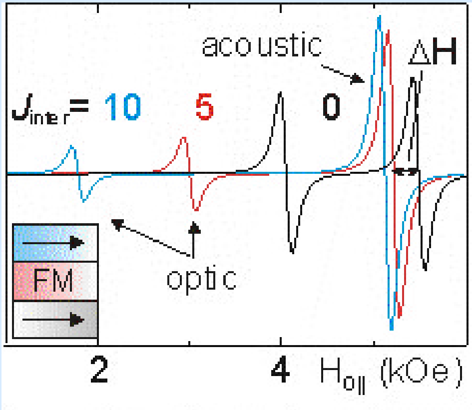
$$\frac{\mu_l}{\mu_s} = \frac{g-2}{2}$$

C. Kittel, *J.Phys. Radiat.* ***12****, 291 (1951)*

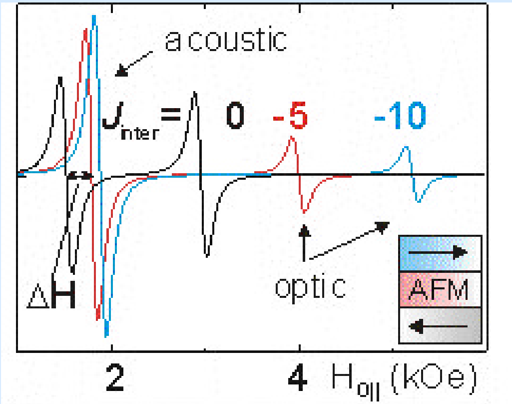
in-situ FMR in coupled films



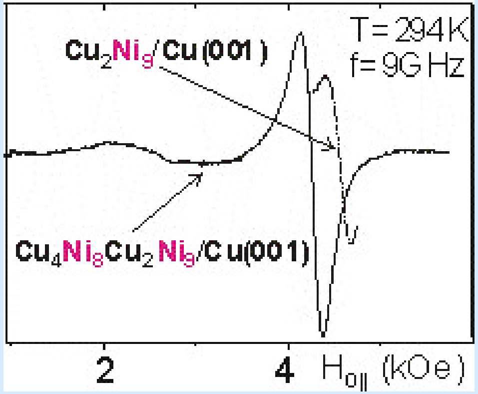




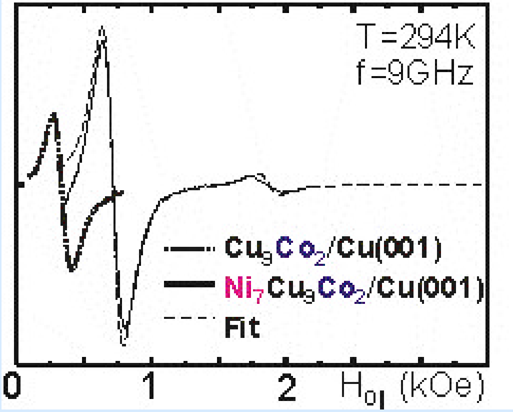
theory



FMR



in-situ
UHV-experiment



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

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   Landau-Lifshitz equation of motion
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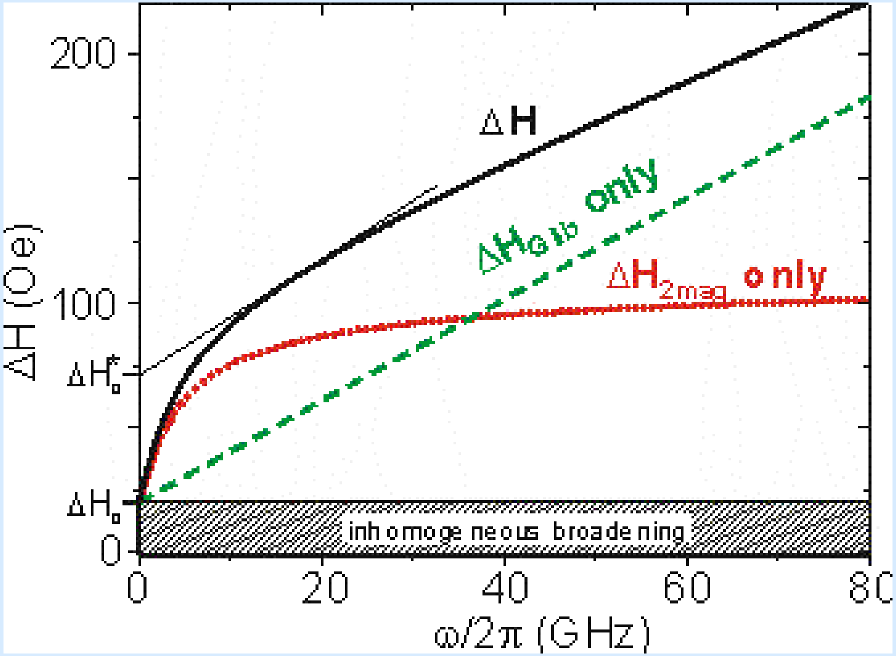
viscous damping, energy disipation



- **Gilbert damping contribution:**
  linear in frequency

$$\Delta H_{\text{Gilbert}}(w) = \frac{2}{\sqrt{3}}\frac{G}{g^2 M_S} w$$

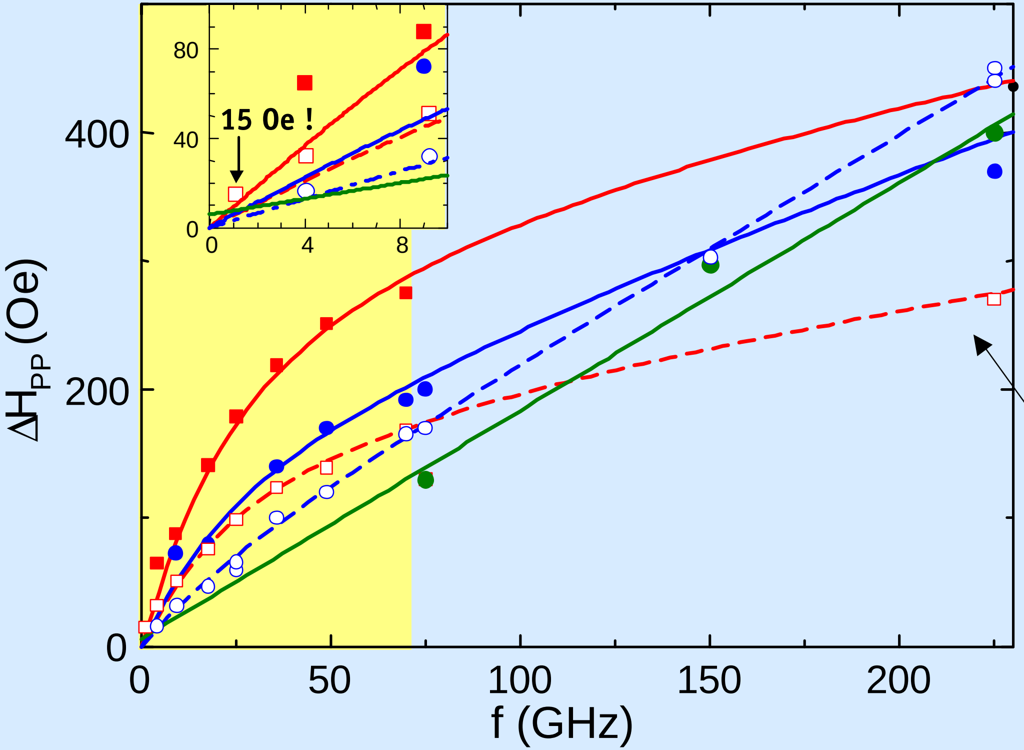
$$a = \frac{G}{g M_S}$$

- **Two-magnon scattering:**
  degenerate states created by dipole-dipole interaction due to surface defects
  non-linear frequency dependence

$$\Delta H_{2-\text{magnon}}(w) = \Gamma \arcsin \sqrt{\frac{\sqrt{w^2 + (w_0/2)^2} - w_0/2}{\sqrt{w^2 + (w_0/2)^2} + w_0/2}}$$

R. Arias et al., PRB ***60****, 7395 (1999)*

$\omega_0 = \gamma M_{eff}$



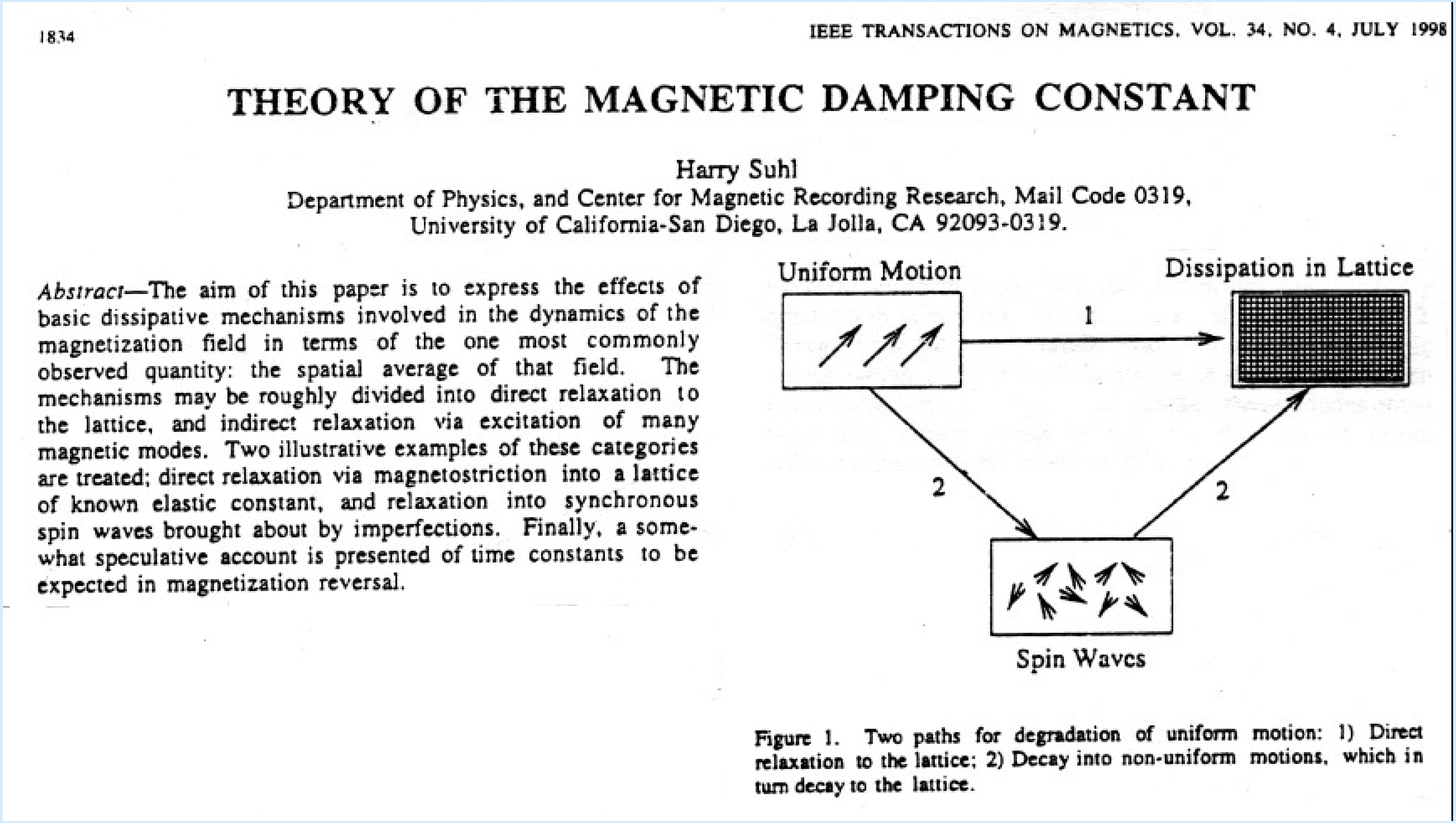
two-magnon scattering observed in Fe/V superlattices – interface defects

J. Lindner et al., PRB ***68****, 060102(R) (2003)*

HF FMR *A. Janossy et al.*
Budapest Univ. of Technology and Econ.

	Γ (kOe)	γ·Γ (10^8 s^{-1})	G (10^8 s^{-1})	α (10^{-3})	ΔH_0 (Oe)
■ Fe_4V_2 ; H||[100]	0.270	50.0	0.26	1.26	0
● Fe_4V_4 ; H||[100]	0.139	26.1	0.45	2.59	0
□ Fe_4V_2 ; H||[110]	0.150	27.9	0.22	1.06	0
○ Fe_4V_4 ; H||[110]	0.045	8.4	0.77	4.44	0
● Fe_4V_4 ; H||[001]	0	0	0.76	4.38	5.8

- **recent publications with similar results:**
  - Pd/Fe on GaAs(001) – network of misfit dislocations *G. Woltersdorf et al. PRB* ***69****, 184417 (2004)*
  - NiMnSb films on InGaAs/InP *B. Heinrich et al. JAP* ***95****, 7462 (2004)*



1834 IEEE TRANSACTIONS ON MAGNETICS, VOL. 34, NO. 4, JULY 1998

THEORY OF THE MAGNETIC DAMPING CONSTANT

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Abstract—The aim of this paper is to express the effects of basic dissipative mechanisms involved in the dynamics of the magnetization field in terms of the one most commonly observed quantity: the spatial average of that field. The mechanisms may be roughly divided into direct relaxation to the lattice, and indirect relaxation via excitation of many magnetic modes. Two illustrative examples of these categories are treated; direct relaxation via magnetostriction into a lattice of known elastic constant, and relaxation into synchronous spin waves brought about by imperfections. Finally, a somewhat speculative account is presented of time constants to be expected in magnetization reversal.

Figure 1. Two paths for degradation of uniform motion: 1) Direct relaxation to the lattice; 2) Decay into non-uniform motions, which in turn decay to the lattice.

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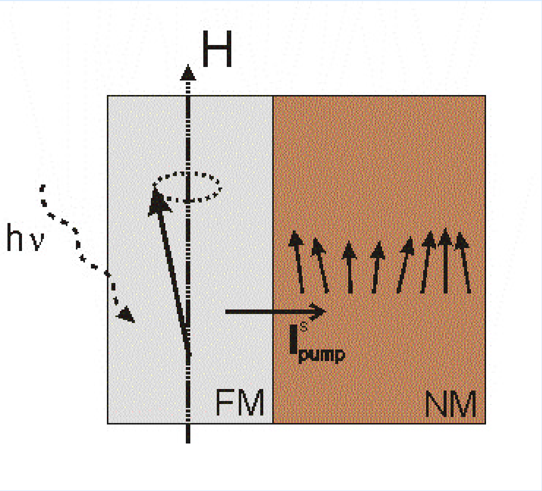


s-d-exchange between spin wave and s-electron

R.H. Silsbee, A. Janossy, P. Monod, PRB **19**, 4382 (1979)

Y. Tserkovnyak, A. Brataas, G.E.W. Bauer, PRB **66**, 224403 (2002)

Landau-Lifshitz equation + extension

precession Gilbert-damping spin-pump current

$$\frac{d\mathbf{M}}{dt} = -\gamma\,\mathbf{M}\times\mathbf{H}_{\mathrm{eff}} + \frac{G}{\gamma M_S^2}\,\mathbf{M}\times\frac{d\mathbf{M}}{dt} + \frac{\gamma}{M_S V}\,\mathbf{I}^{s}_{\mathbf{pump}}$$

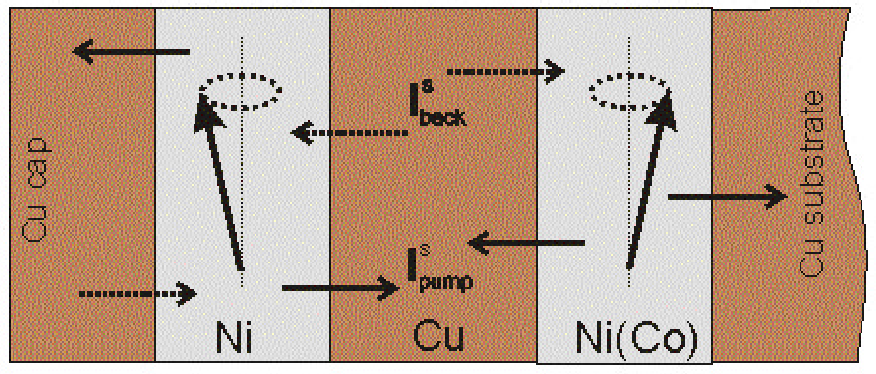
Precession drives spin current into NM

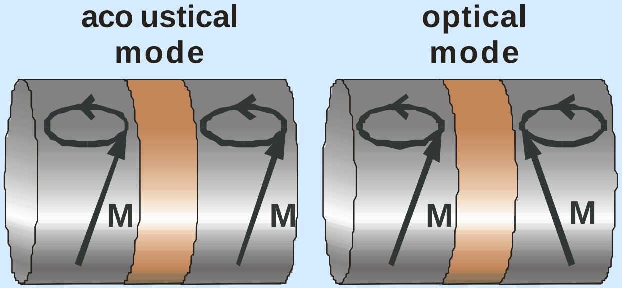
$$\mathbf{I}^{S}_{\mathbf{pump}} = \frac{\hbar}{4\pi}\left(A_r\,\mathbf{M}\times\frac{d\mathbf{M}}{dt} - A_i\,\frac{d\mathbf{M}}{dt}\right)$$

NM-substrate acts as spin-sink ⇒ $I^S_{\mathrm{back}} = 0$

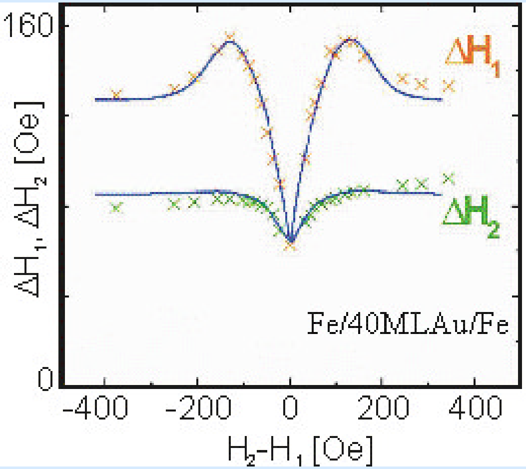
⇒ torque is carried away

⇒ Gilbert damping enhanced by spin-pump effect!





at „point of contact“ compensation of pumped currents decrease the linewidth



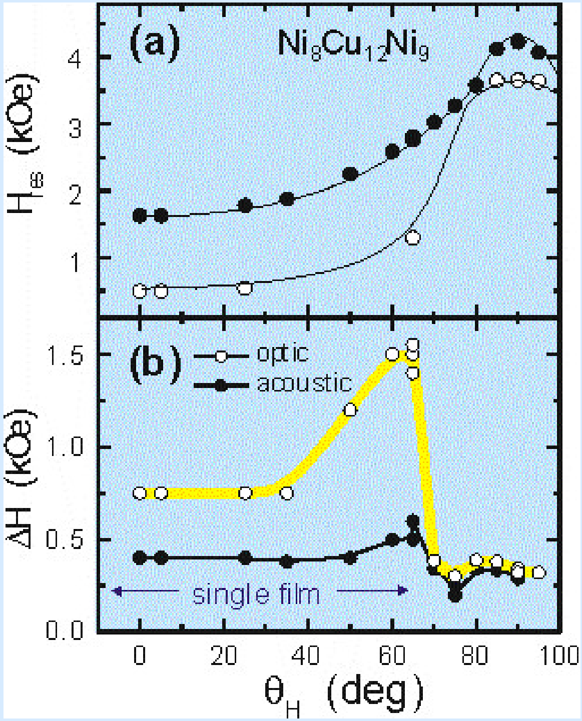
B. Heinrich et al., PRL **90**, 187601 (2003)

$d_{NM} \geq \lambda_{SF}$ ⇒ no spin-accumulation ⇒ $I^s_{back} = 0$

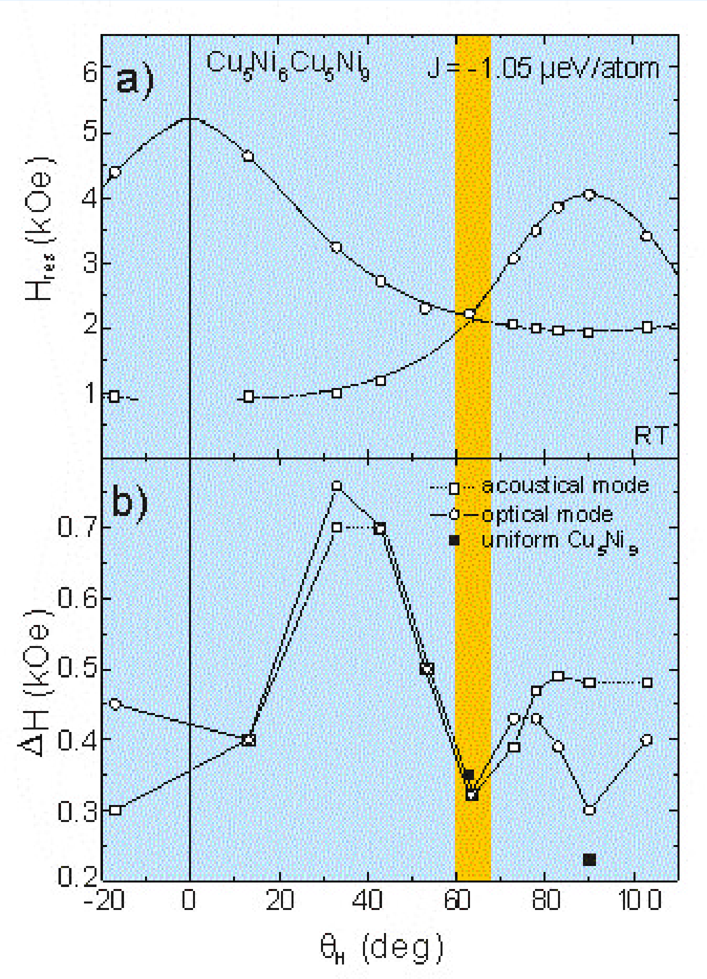
⇒ Gilbert-damping enhanced by spin-pump effect

compensation, if both films precess simultaneously ($H_{res1} = H_{res2}$)

⇒ only Gilbert contribution remains!

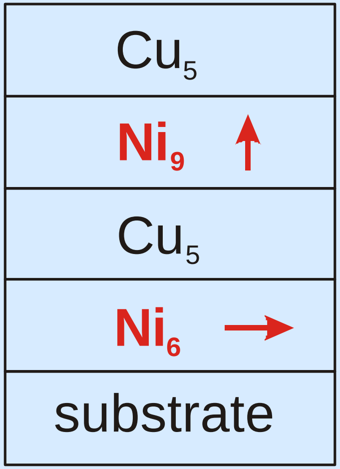


K. Lenz et al.,
Phys. Rev. B **69**, 144422 (2004)



K. Lenz et al. SCM 2004,
Physica Status Solidi (c) **1**, 3260 (2004)

Trilayers with non-collinear easy axes


Cu_5

Ni_9

Cu_5

Ni_6

substrate

strong decrease in ΔH when $H^{ac} = H^{op}$
$\Delta H^{op} = \Delta H^{ac} < \Delta H^{uni}$

Conclusion

- High sensitivity of ESR/FMR to investigate submonolayers
- *in-situ* UHV-ESR/FMR
- large frequency range of 1 to >200GHz is needed to study relaxation, dynamics