From spinwaves to Giant Magnetoresistance (GMR) and beyond

P.A. Grünberg, *Institut für Festkörperforschung*

Forschungszentrum Jülich, Germany

1. Introduction
2. Discovery of BLS from Damon Eshbach surface modes
3. Discovery of interlayer exchange coupling
4. Discovery of Enhanced Magnetoresistance(GMR)
5. Further development:TMR and CIMS
6. Applications

Forschungszentrum Jülich
in der Helmholtz-Gemeinschaft

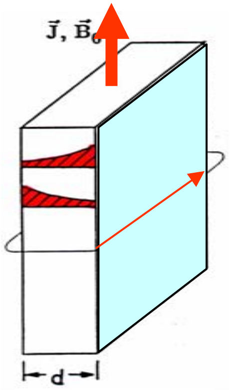
May I introduce myself

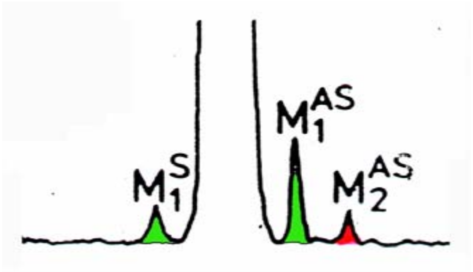
1969: PhD in Darmstadt (Germany) with
„Optical Spectroscopy and Crystal Field Analysis in some Rare Earth Garnets“
Mentor K.H.Hellwege, Supervisor: St.Hüfner

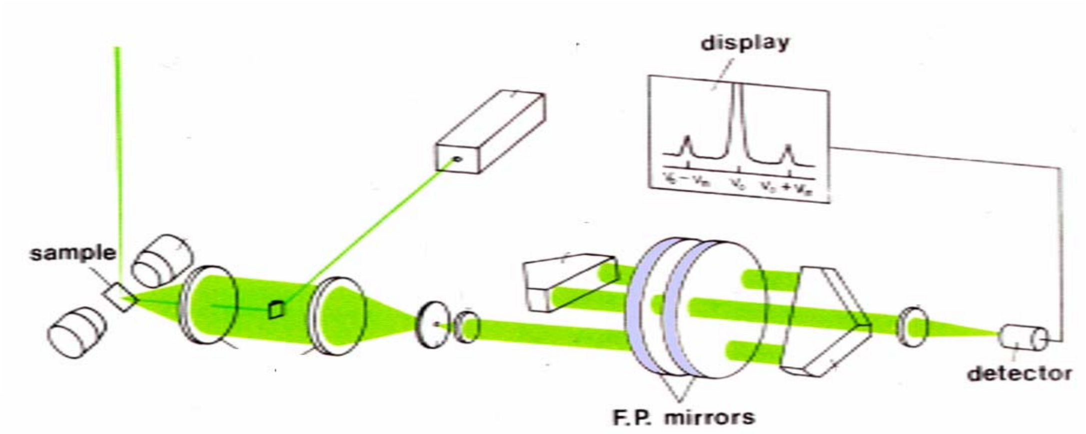
1969-1972 postdoctoral fellow at
Carleton University Ottawa Canada.
Raman Spectroscopy on electronic states and phonons
Supervisor: J. A.Koningstein

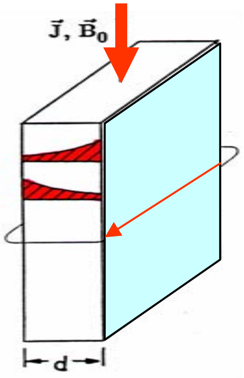
since 1972 Research Center Jülich,
Institute for Magnetism founded in 1971
Investigation of magnetic semiconductors EuO, EuS
Fabrication, magnetic and transport properties of layered magnetic structures
Mentor: W.Zinn

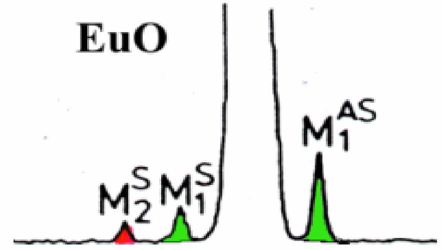
Bulk and Surface Spinwaves in EuO



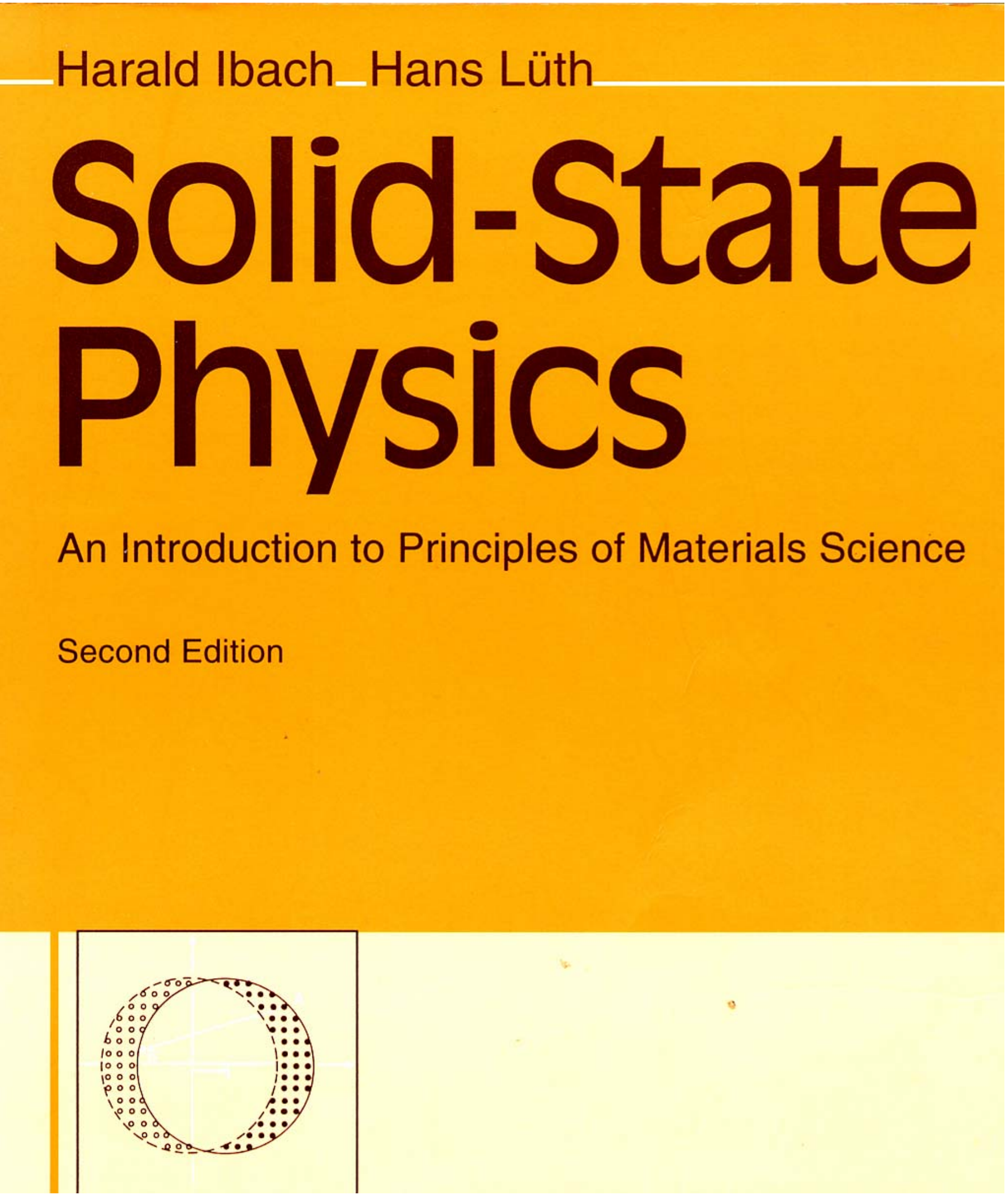








New instrumental development



Harald Ibach Hans Lüth

Solid-State Physics

An Introduction to Principles of Materials Science

Second Edition

Page 186

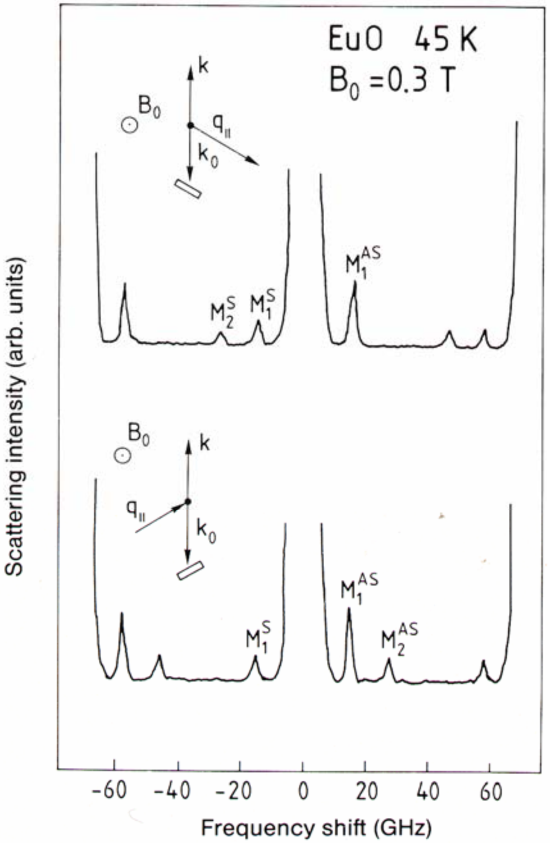
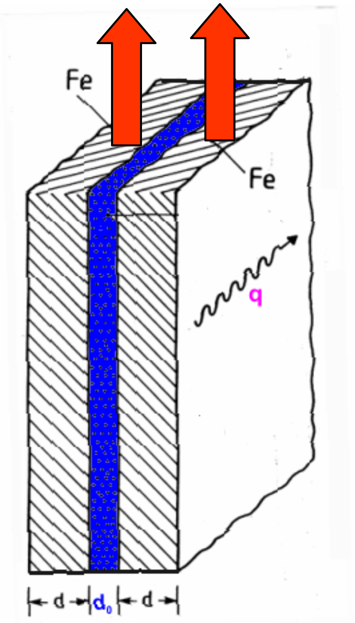


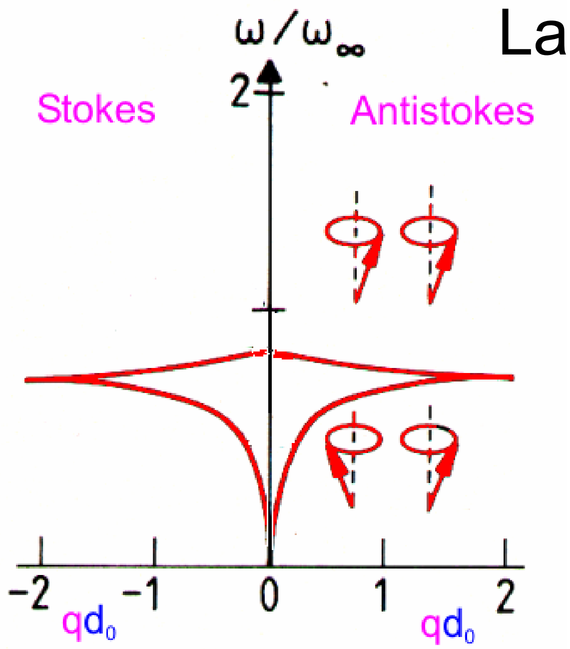
Fig. VI.3. Raman spectrum from EuO [VI.2]. According to the orientation of the sample one observes the Damon-Eshbach spin waves (labelled as M_2) as a Stokes line (*above*) or as an anti-Stokes line (*below*), while the volume spin waves appear with equal intensity in both geometries, although higher intensity is observed for the anti-Stokes line [VI.3]

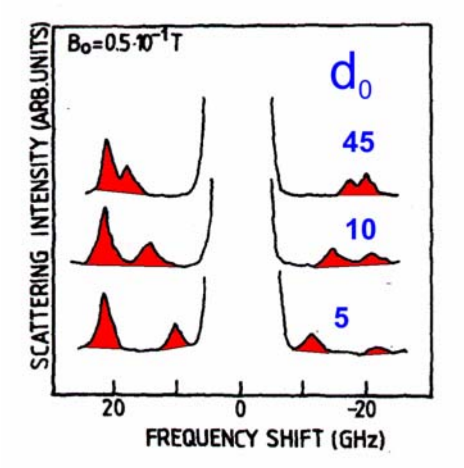
Coupled Damon-Eshbach-Spinwaves

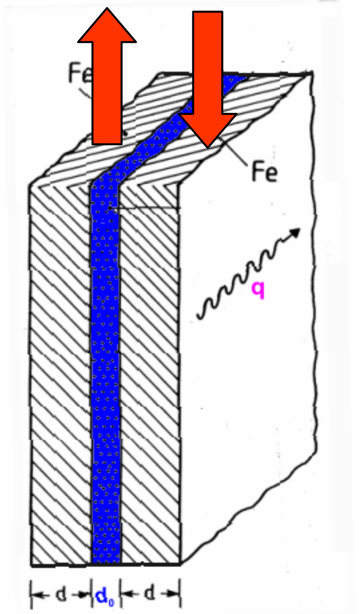
Landau Lifshitz equation

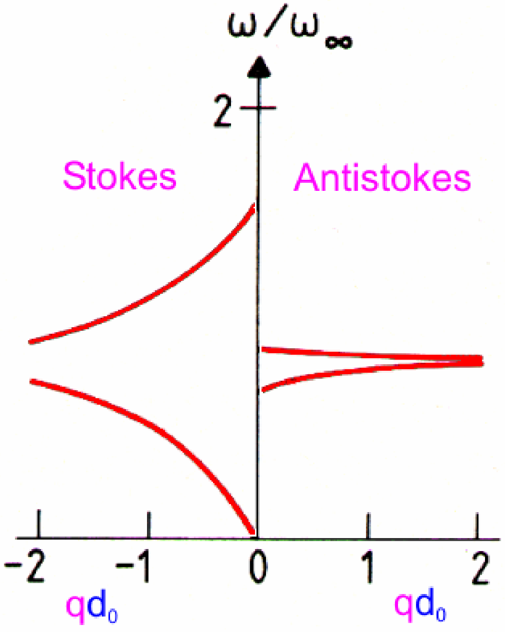
$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{\mathrm{eff}}$$







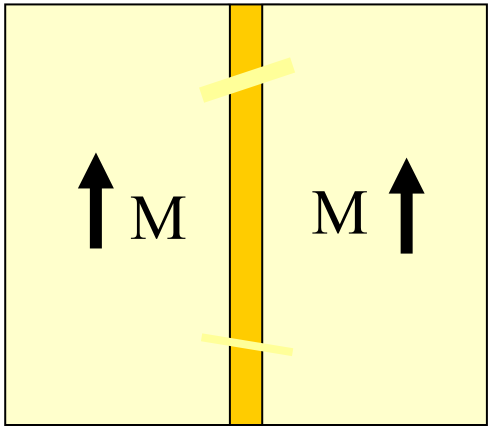




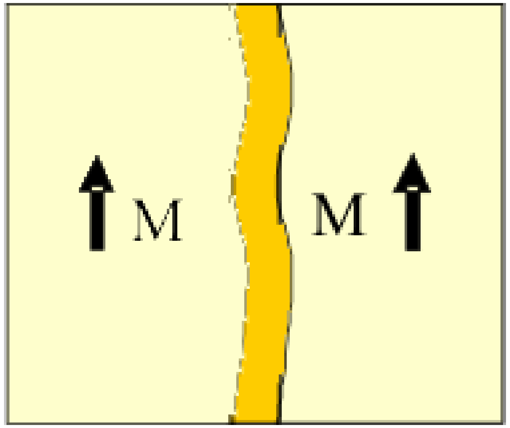
?

What was known in 1984 about interlayer coupling apart from the dynamic coupling?

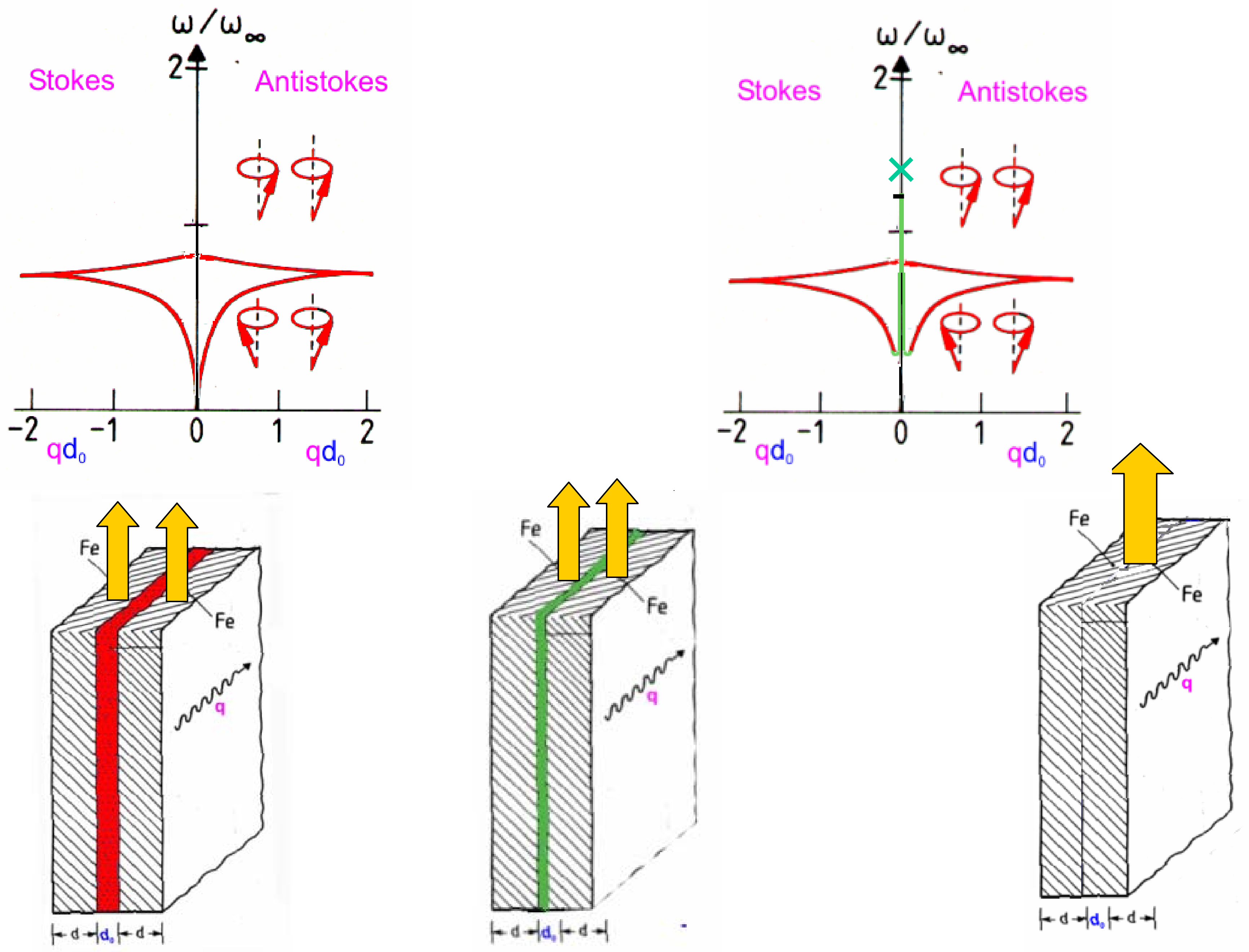
Pinhole coupling due to „magnetic bridges“



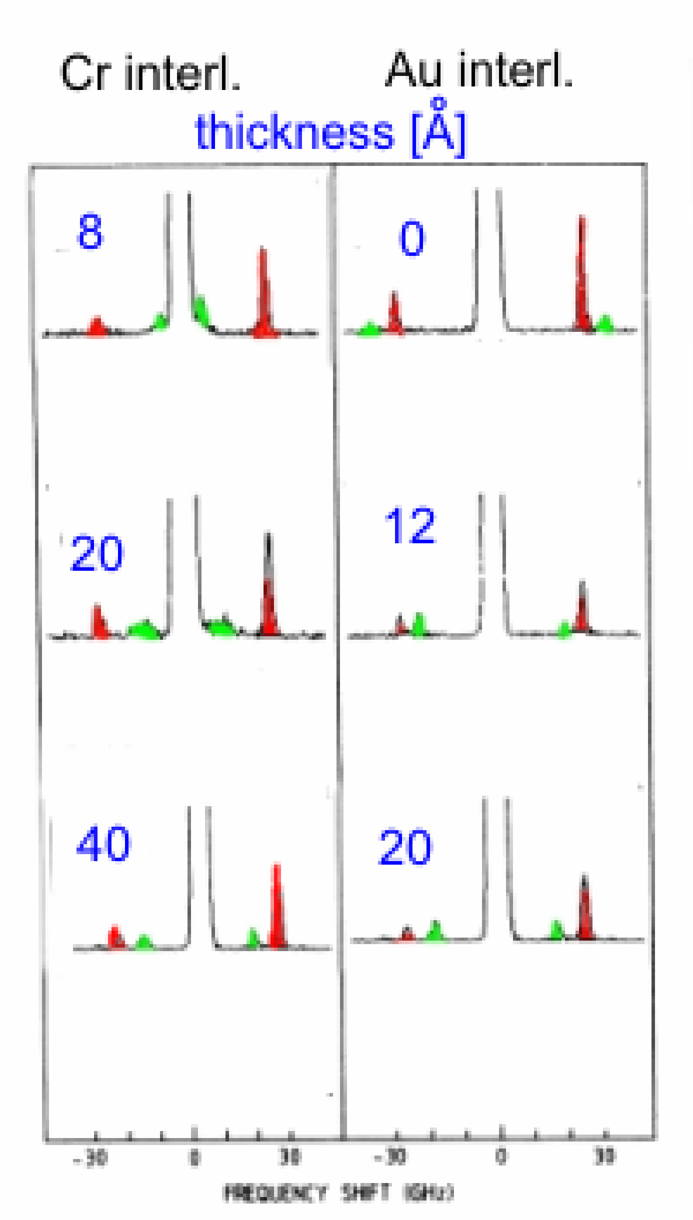
Orange peel or Neel type coupling caused by strayfields due to meandering interlayers

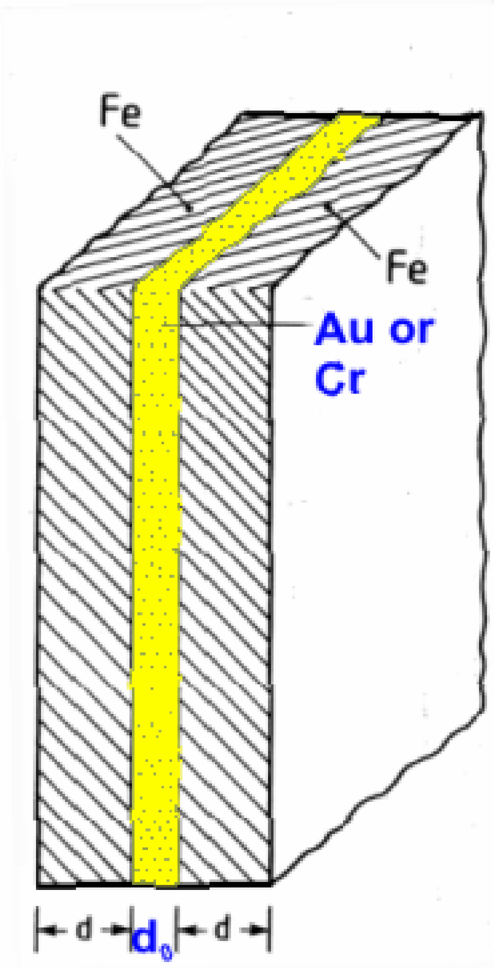


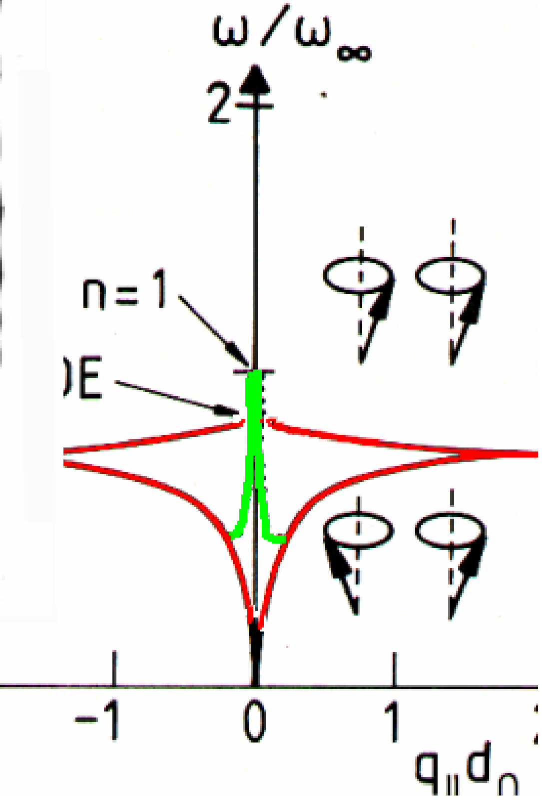
Coupled Damon-Eshbach-Spinwaves



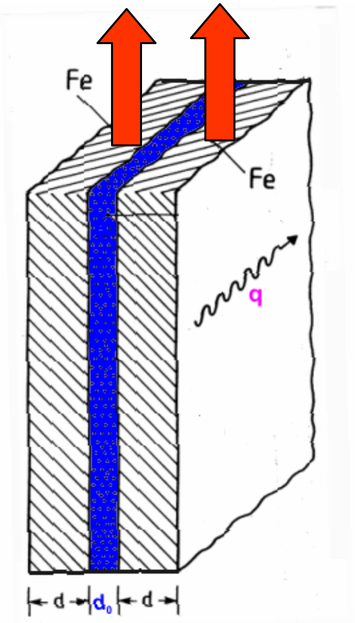
Effect of **exchange** coupling

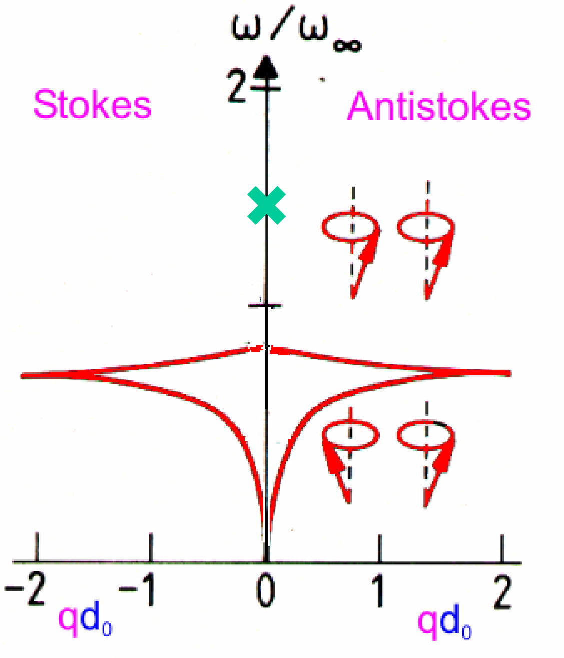


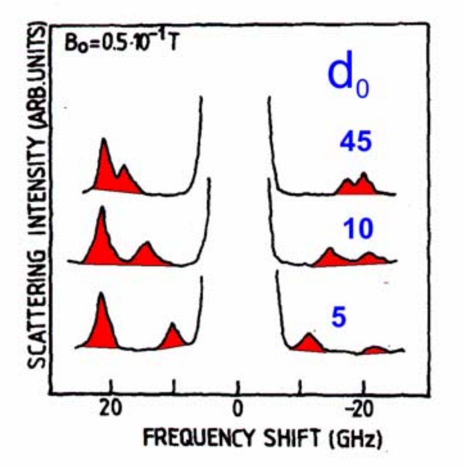


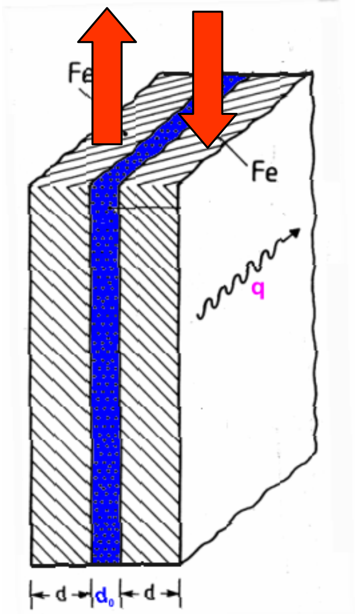


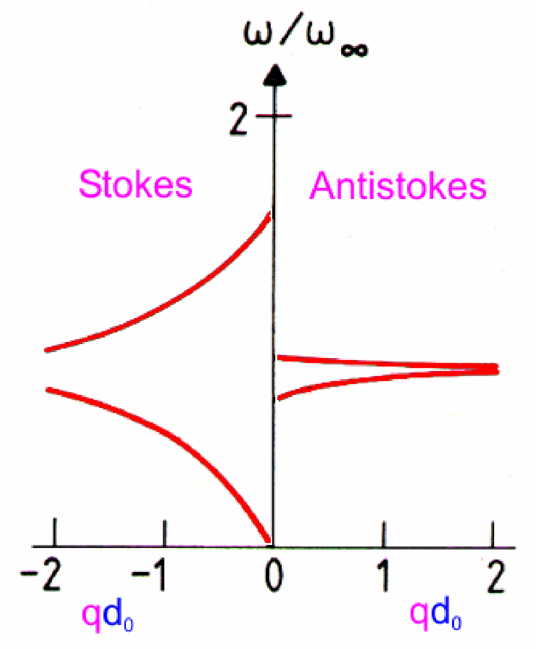
Coupled Damon-Eshbach-Spinwaves

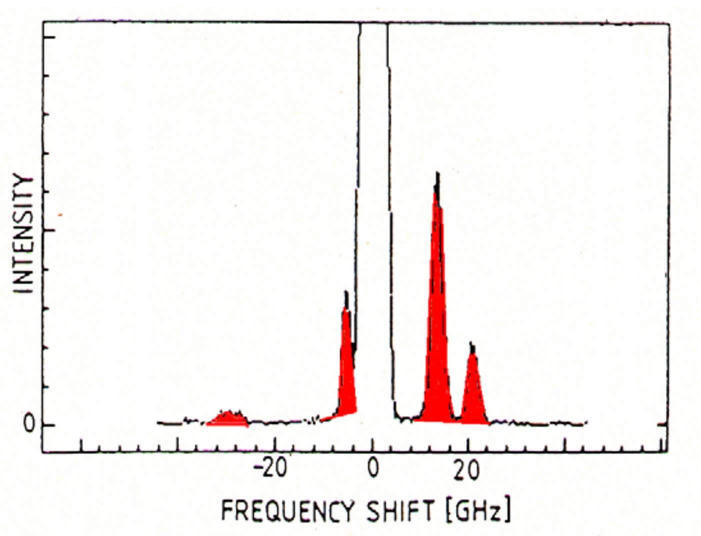






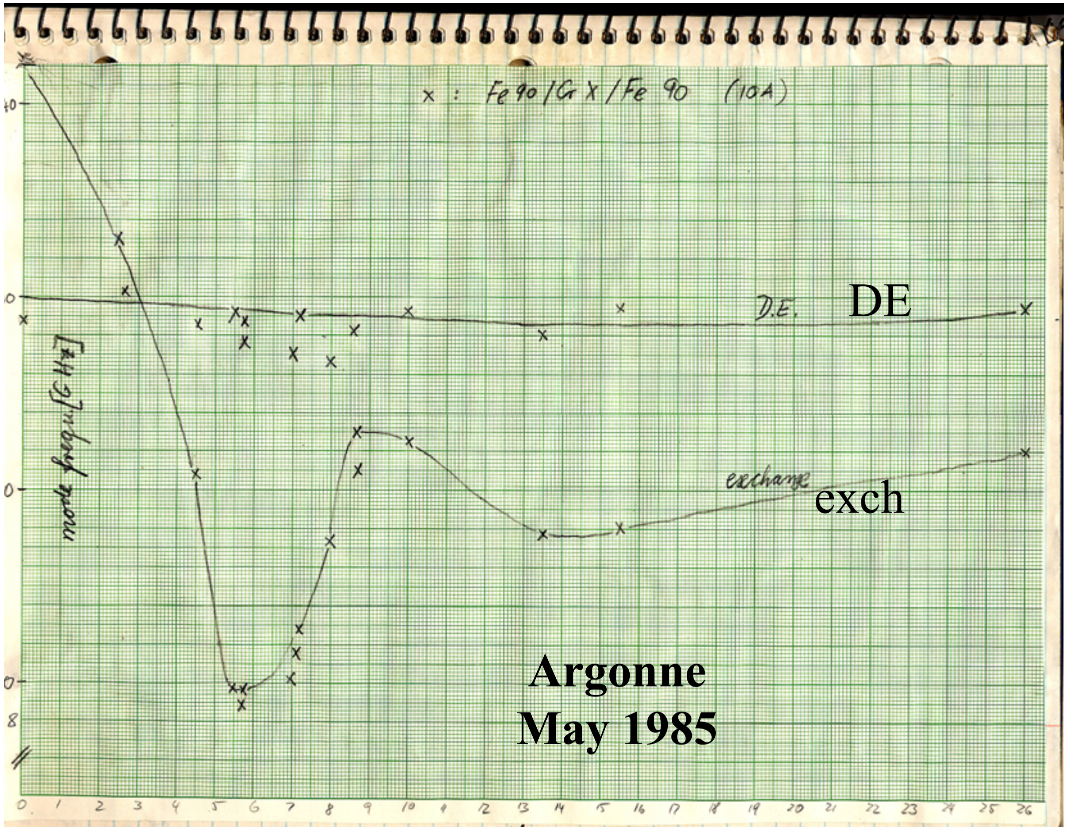




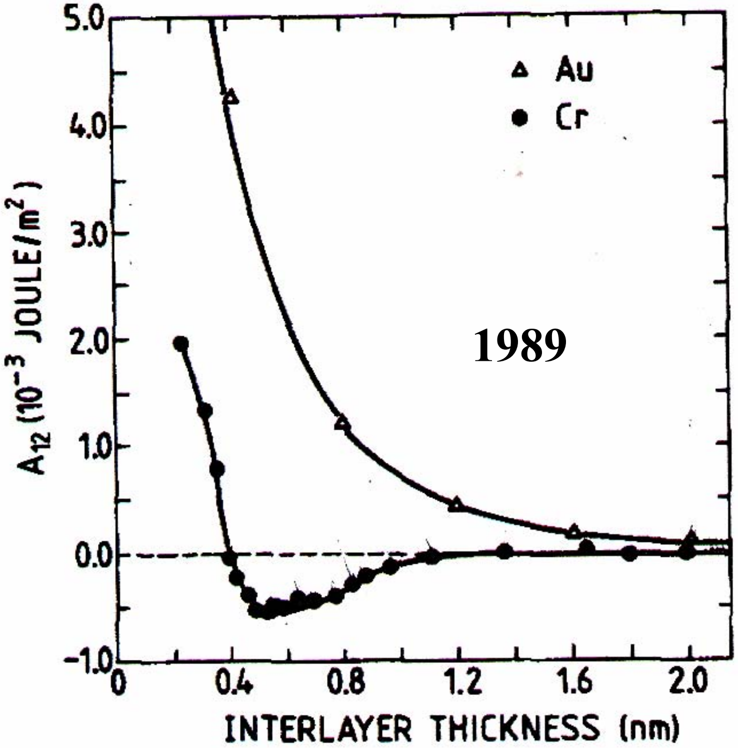


First measurement of interlayer exchange coupling as a function of the interlayer thickness

$$E_{exch} = -2A_{12}\frac{M_1 * M_2}{|M_1| * |M_2|}$$



Argonne
May 1985



1989

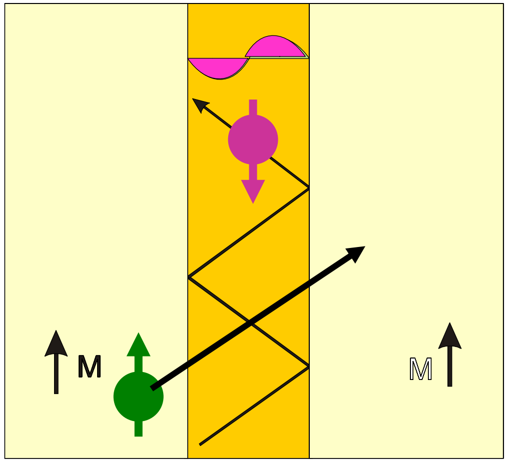
Work on interlayer exchange coupling published in 1986

Oscillatory coupling in Gd/Y multilayers (Majkrzak et al)

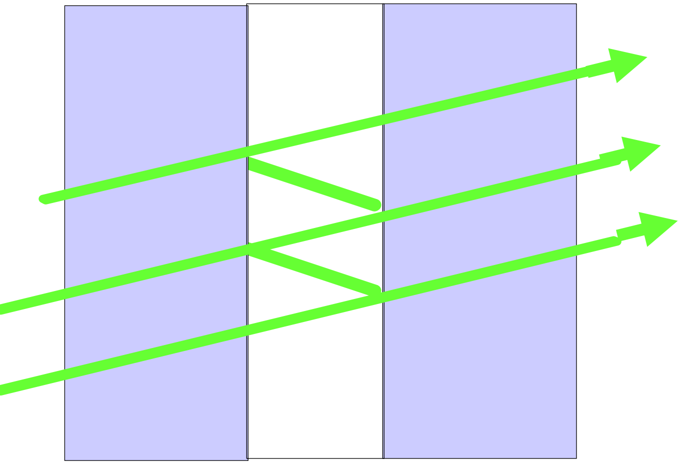
Helical structures in Dy/Y multilayers (Salamon et al.)

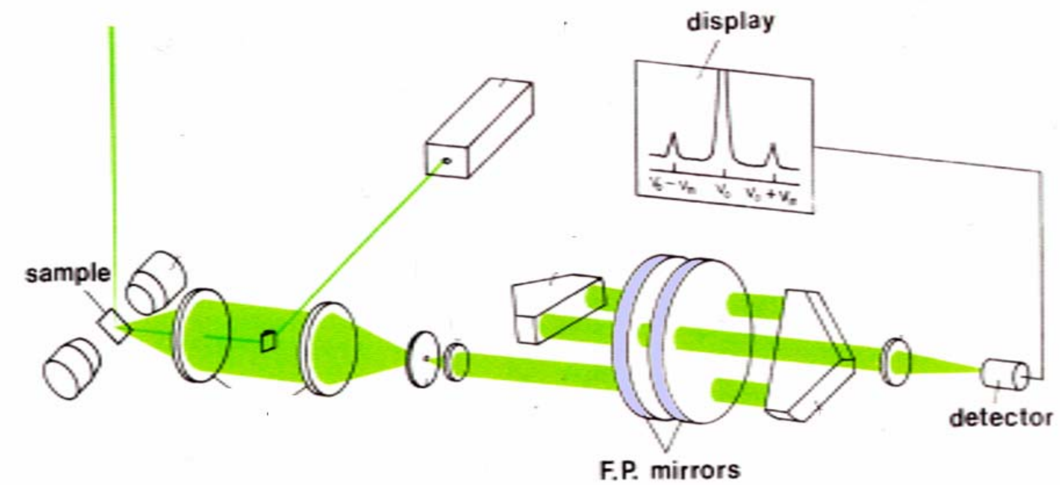
AF coupling in Fe/Cr/Fe layered structures (Grünberg et al)

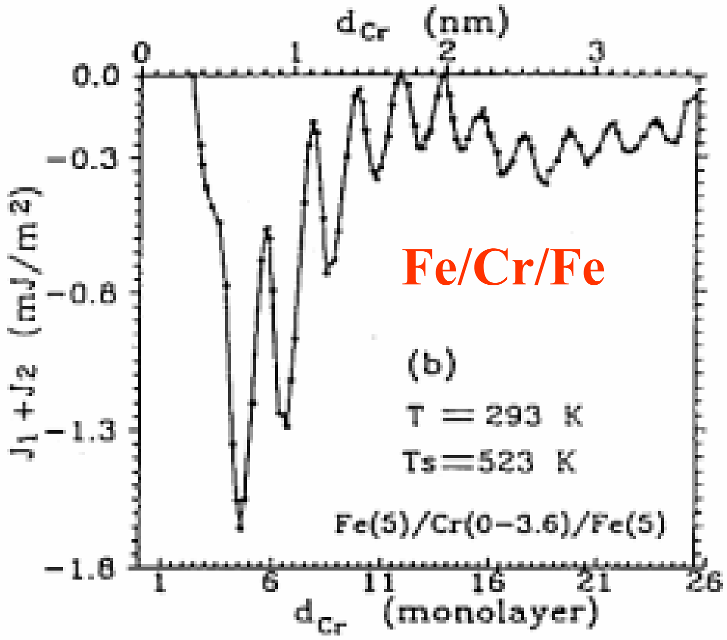
Fabry Perot model of interlayer exchange coupling



analogy: optical Fabry Perot interferometer

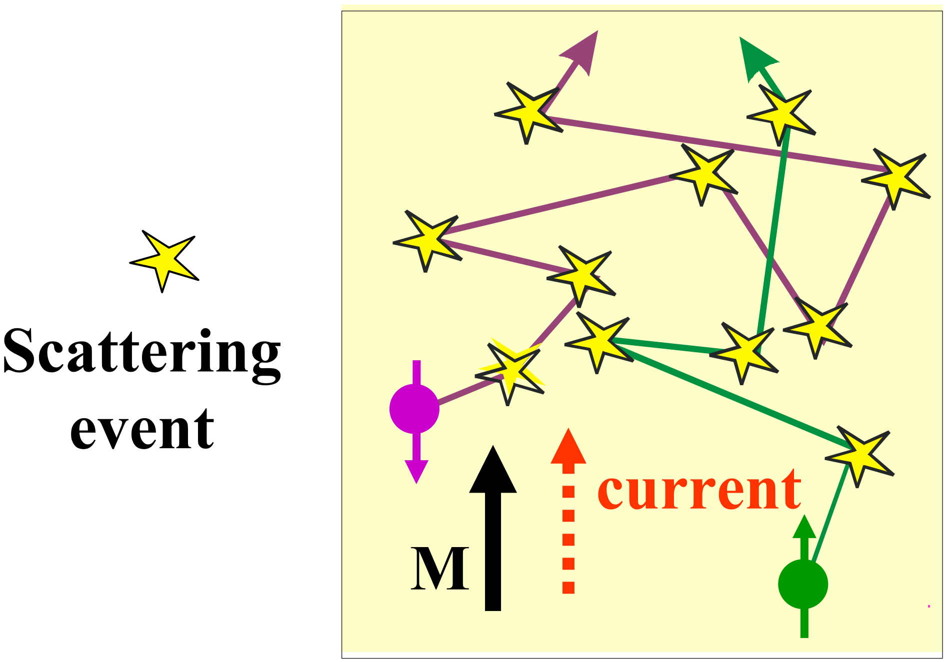




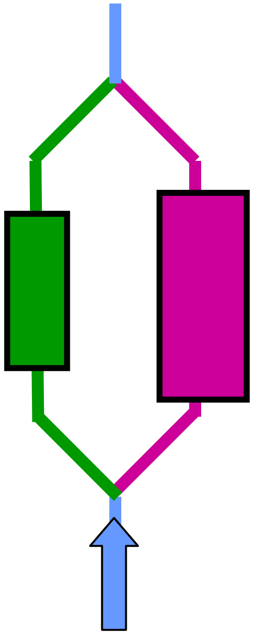


Short period oscillations after improvement of growth

Mott`s two current model

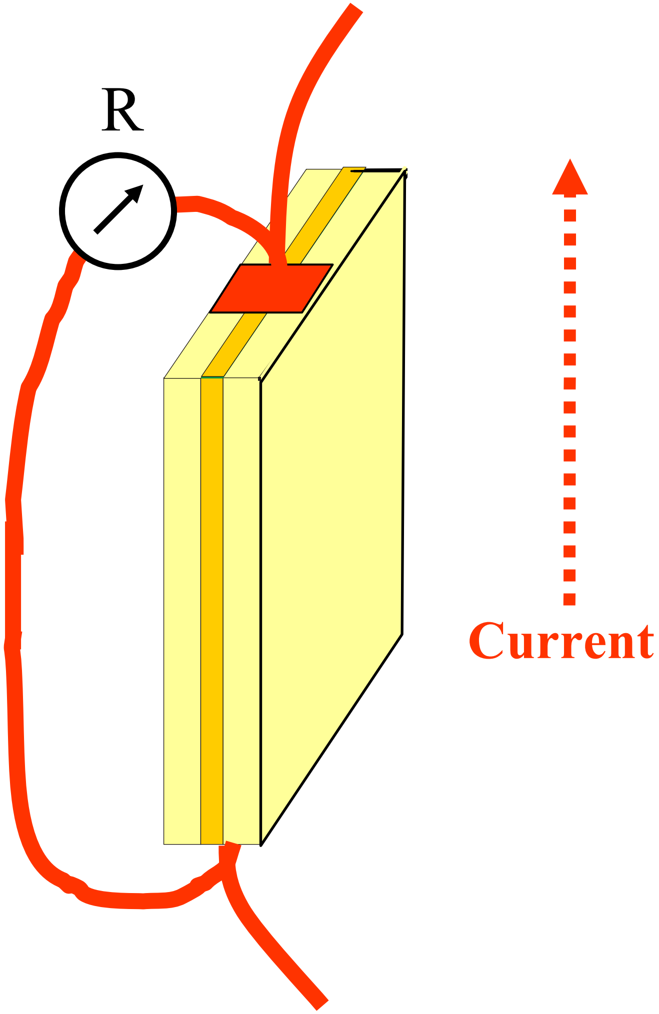


ferromagnetic alloy

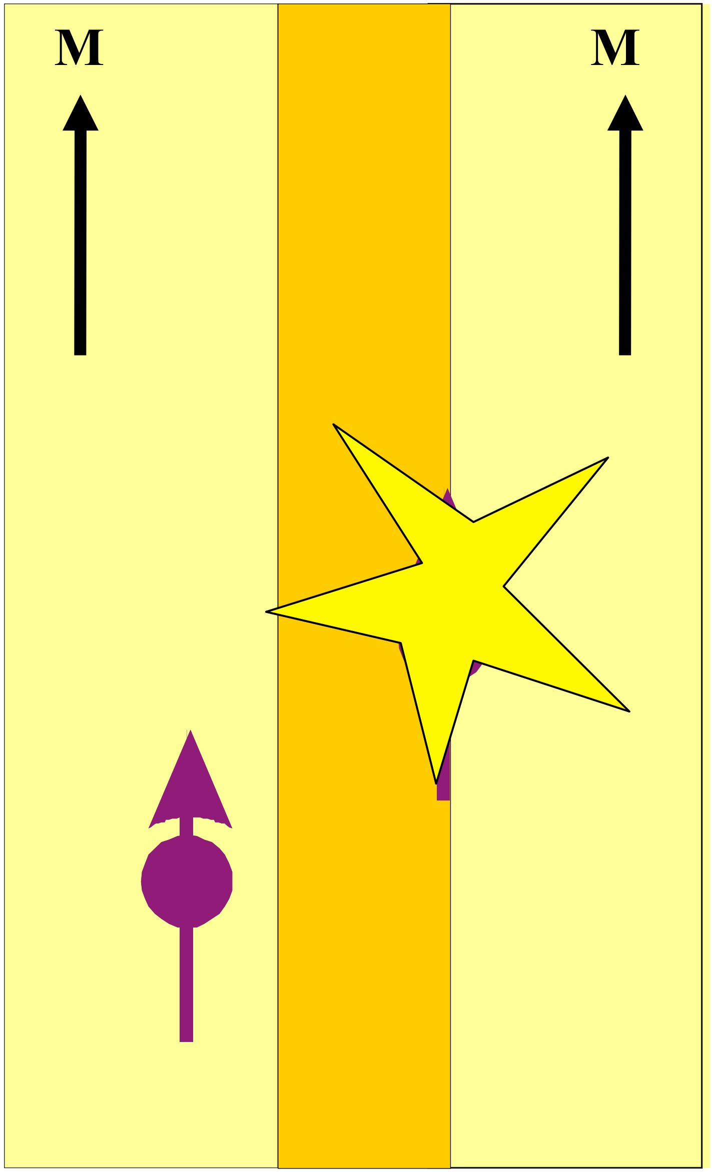


Equivalent circuit

What can we expect in magnetic multilayers?

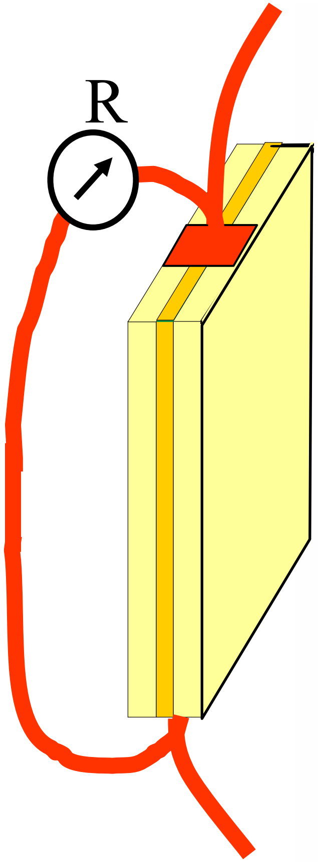


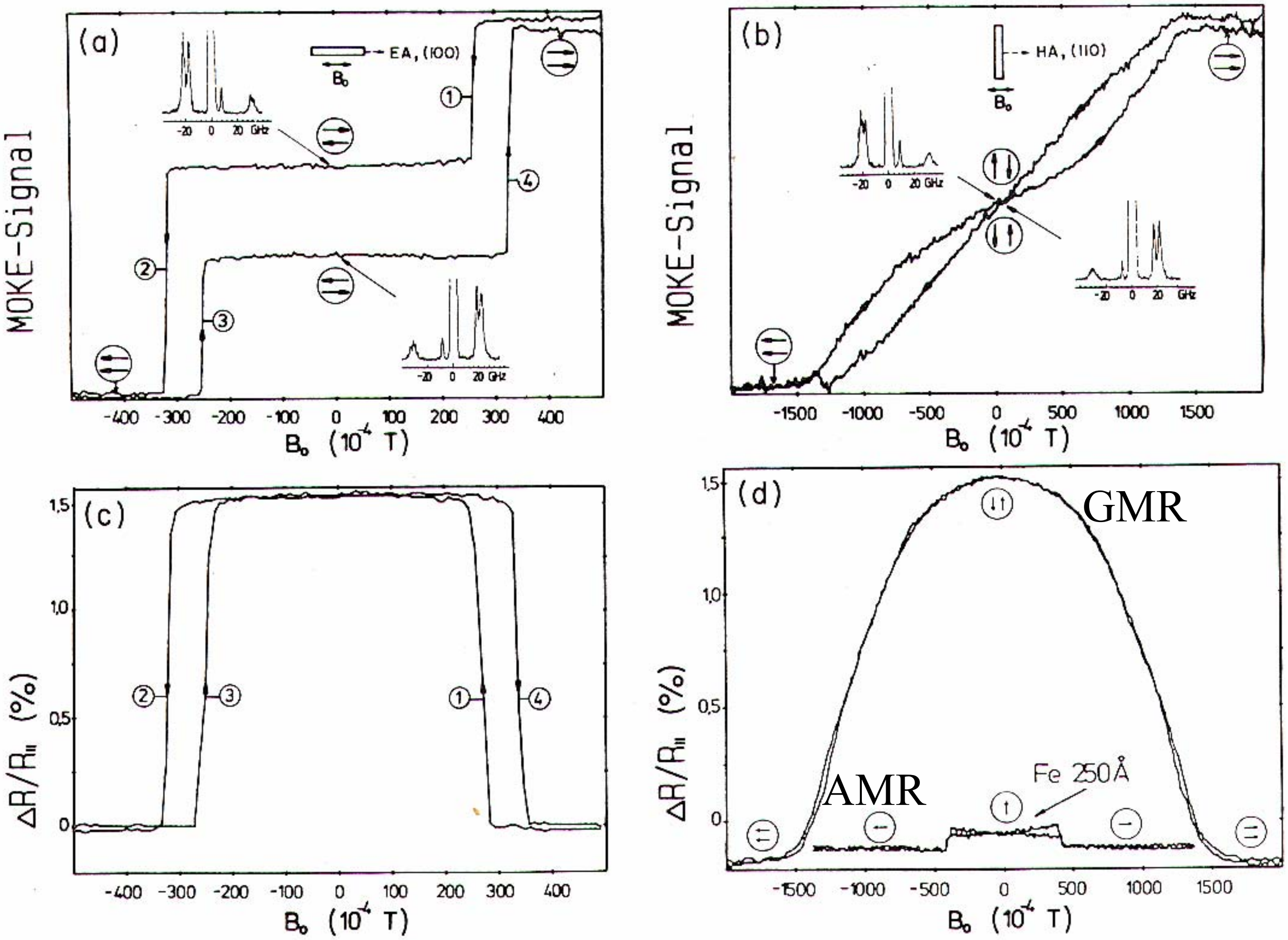
Coupled Fe/Cr/Fe structures



Phys. Rev. B 39, P. 4828, 1989

First measurement of GMR





Filing a patent: april 1988

Le Creusot, August 1988

First measurements of GMR in Fe/Cr/Fe

Orsay

Jülich

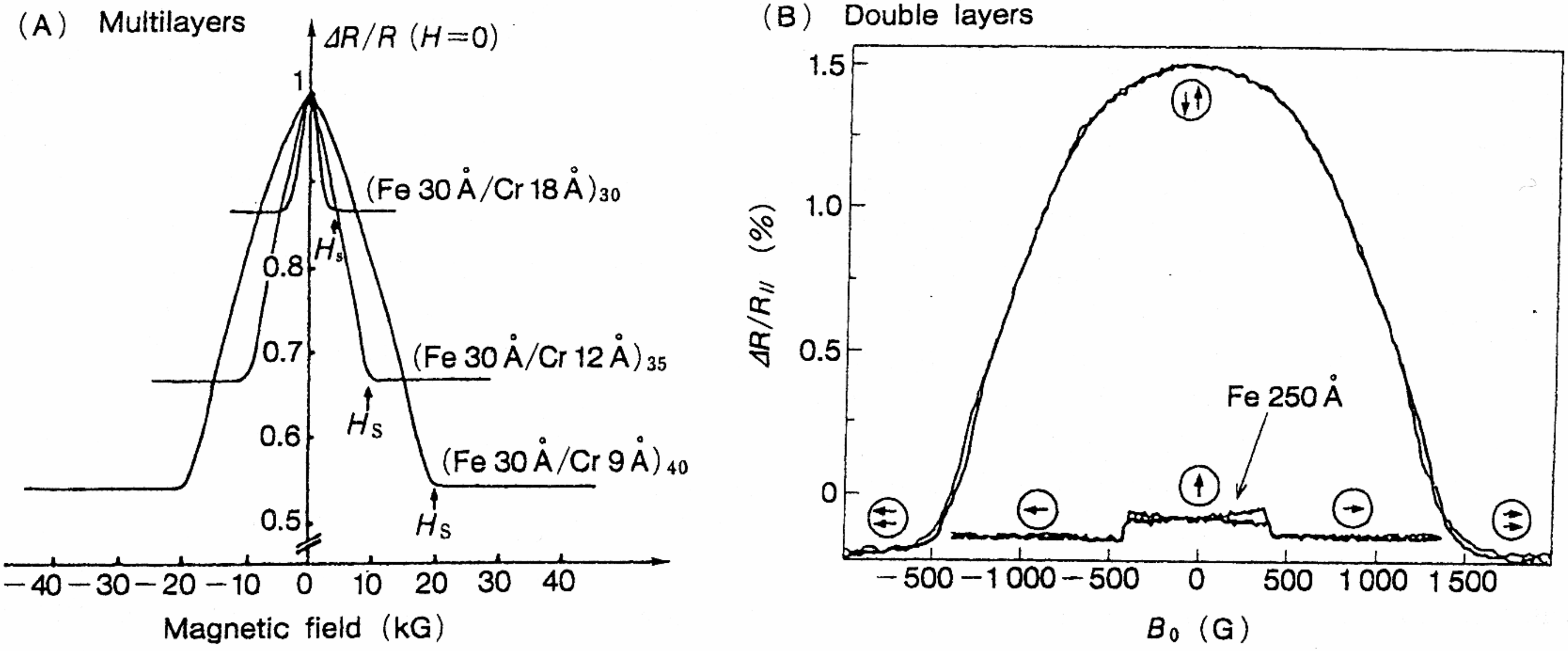
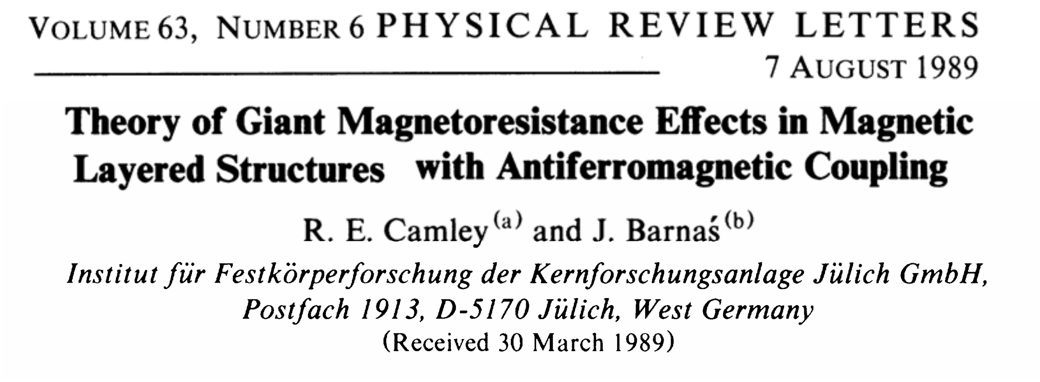


Fig. 5. GMR effect in a multilayer (A) and a double layer (B) of Fe interspaced by Cr. (B) The AMR effect in a single film of Fe with thickness 250 Å is also shown for comparison.

First theories of GMR

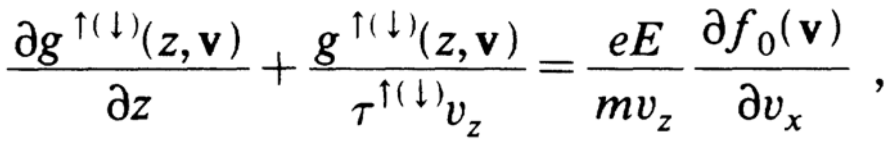


VOLUME 63, NUMBER 6 PHYSICAL REVIEW LETTERS
7 AUGUST 1989

Theory of Giant Magnetoresistance Effects in Magnetic Layered Structures with Antiferromagnetic Coupling

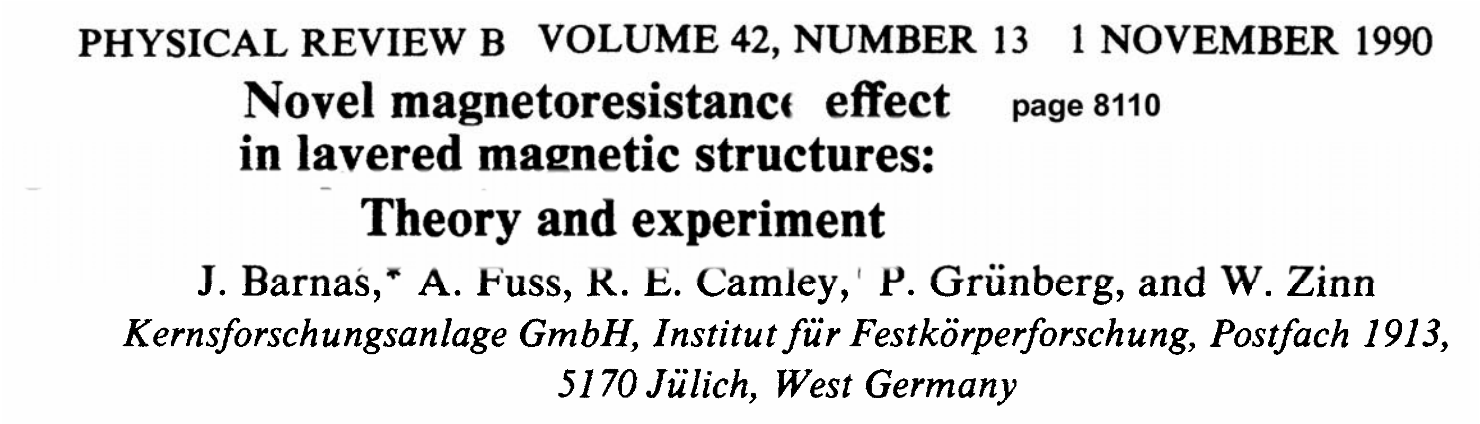
R. E. Camley[(a)] and J. Barnaś[(b)]
Institut für Festkörperforschung der Kernforschungsanlage Jülich GmbH,
Postfach 1913, D-5170 Jülich, West Germany

(Received 30 March 1989)



$$\frac{\partial g^{\uparrow(\downarrow)}(z,\mathbf{v})}{\partial z}+\frac{g^{\uparrow(\downarrow)}(z,\mathbf{v})}{\tau^{\uparrow(\downarrow)}v_z}=\frac{eE}{mv_z}\frac{\partial f_0(\mathbf{v})}{\partial v_x}\ ,$$

Boltzmann transport equation:
Camley-Barnas model



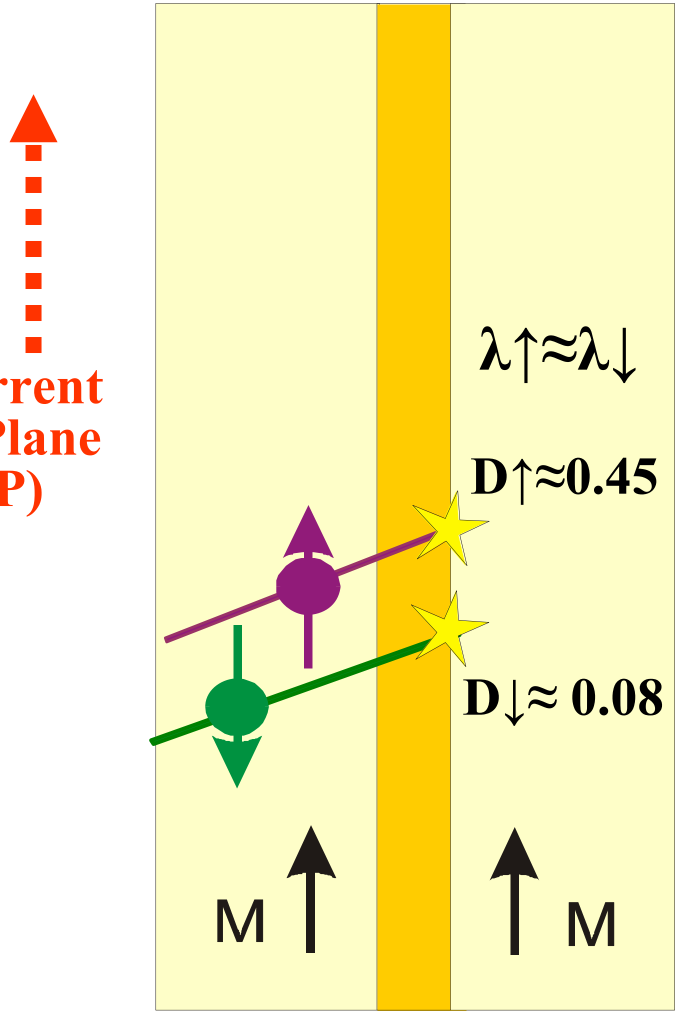
PHYSICAL REVIEW B VOLUME 42, NUMBER 13 1 NOVEMBER 1990

Novel magnetoresistance effect in layered magnetic structures: Theory and experiment

page 8110

J. Barnaś,* A. Fuss, R. E. Camley,[†] P. Grünberg, and W. Zinn
Kernsforschungsanlage GmbH, Institut für Festkörperforschung, Postfach 1913,
5170 Jülich, West Germany

Theory and Experiment



Current in Plane (CIP)

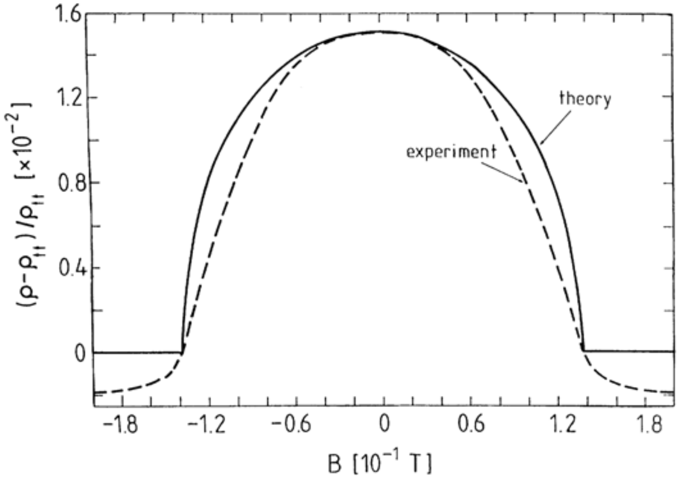
$\lambda\uparrow \approx \lambda\downarrow$

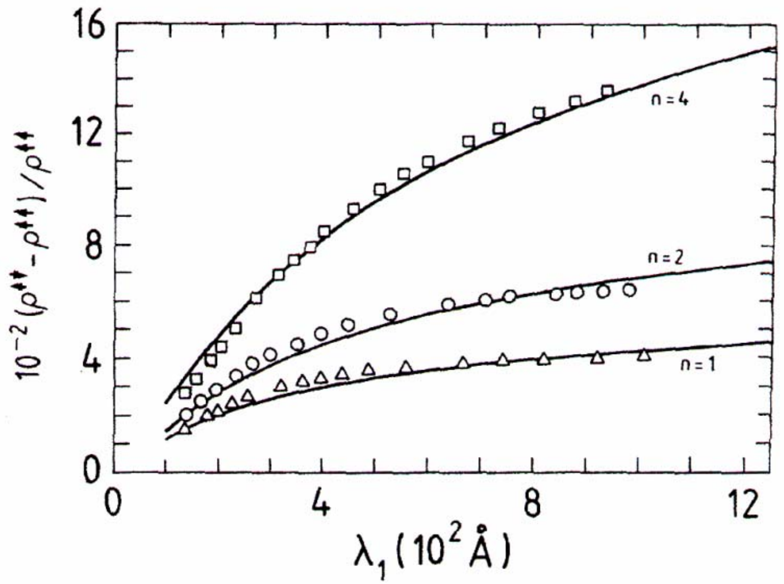
$D\uparrow \approx 0.45$

$D\downarrow \approx 0.08$

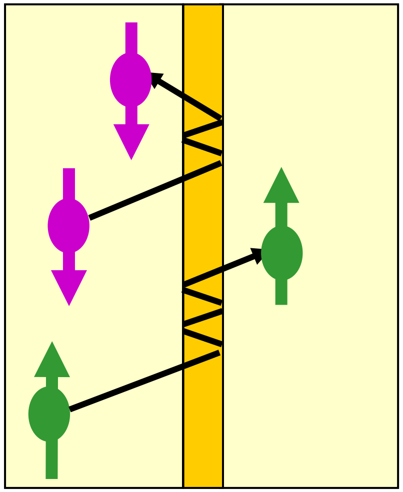
M

M

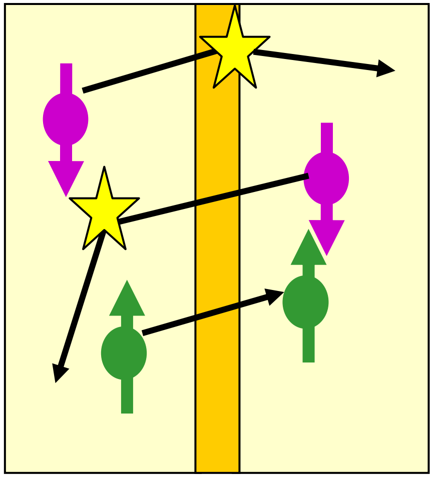




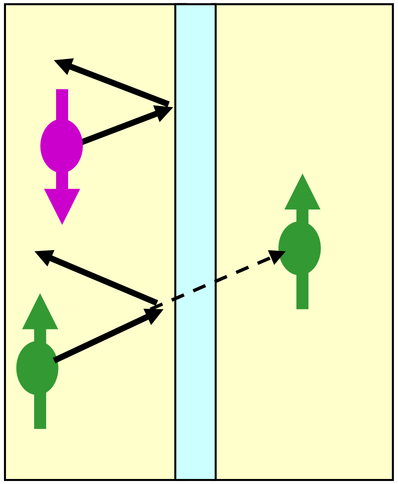
Spin dependent transfer phenomena in layered magnetic structures



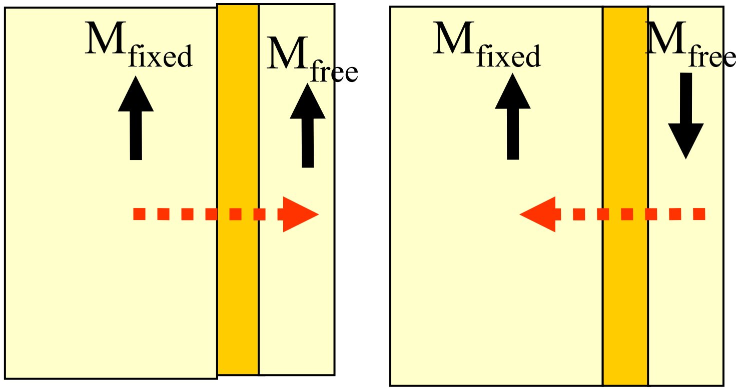
osc.
Interlayer
exchange
coupling



Giant
Magneto-resistance
(GMR)



Tunnelingmagnetoresistance
(TMR)



current induced magnetic
excitations and switching (CIMS)

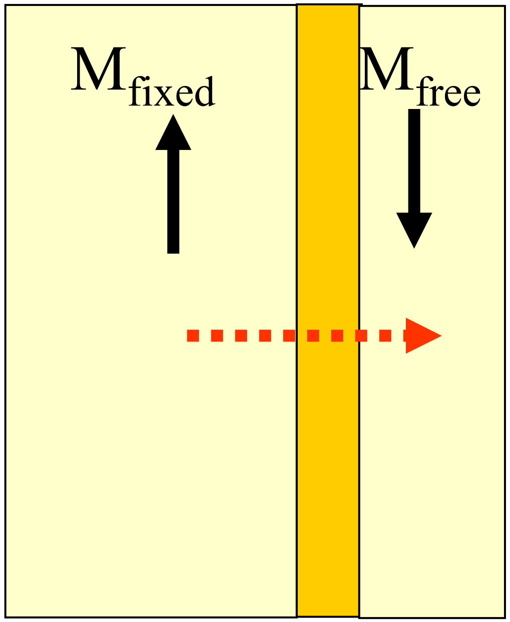
CIMS – advanced magnetic switching concept

due to spin polarized currents

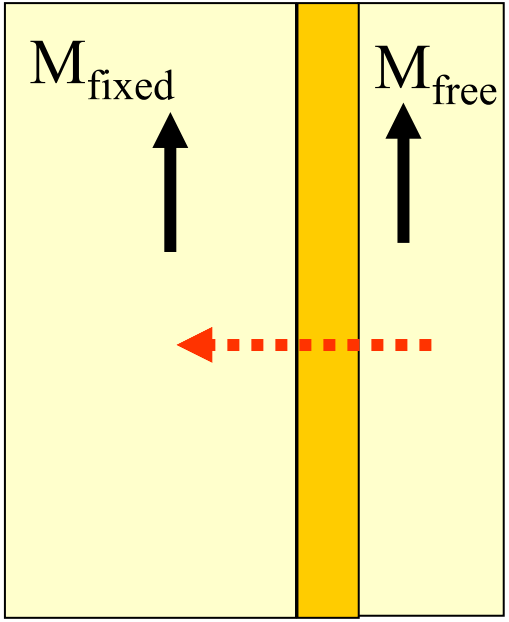
current induced magnetization switching and excitation of spinwaves proposed by J.Slonczewski and L.Berger in 1995

first experiment: J.A. Katine *et al.*, Phys. Rev. Lett. 84, 3149 (2000)

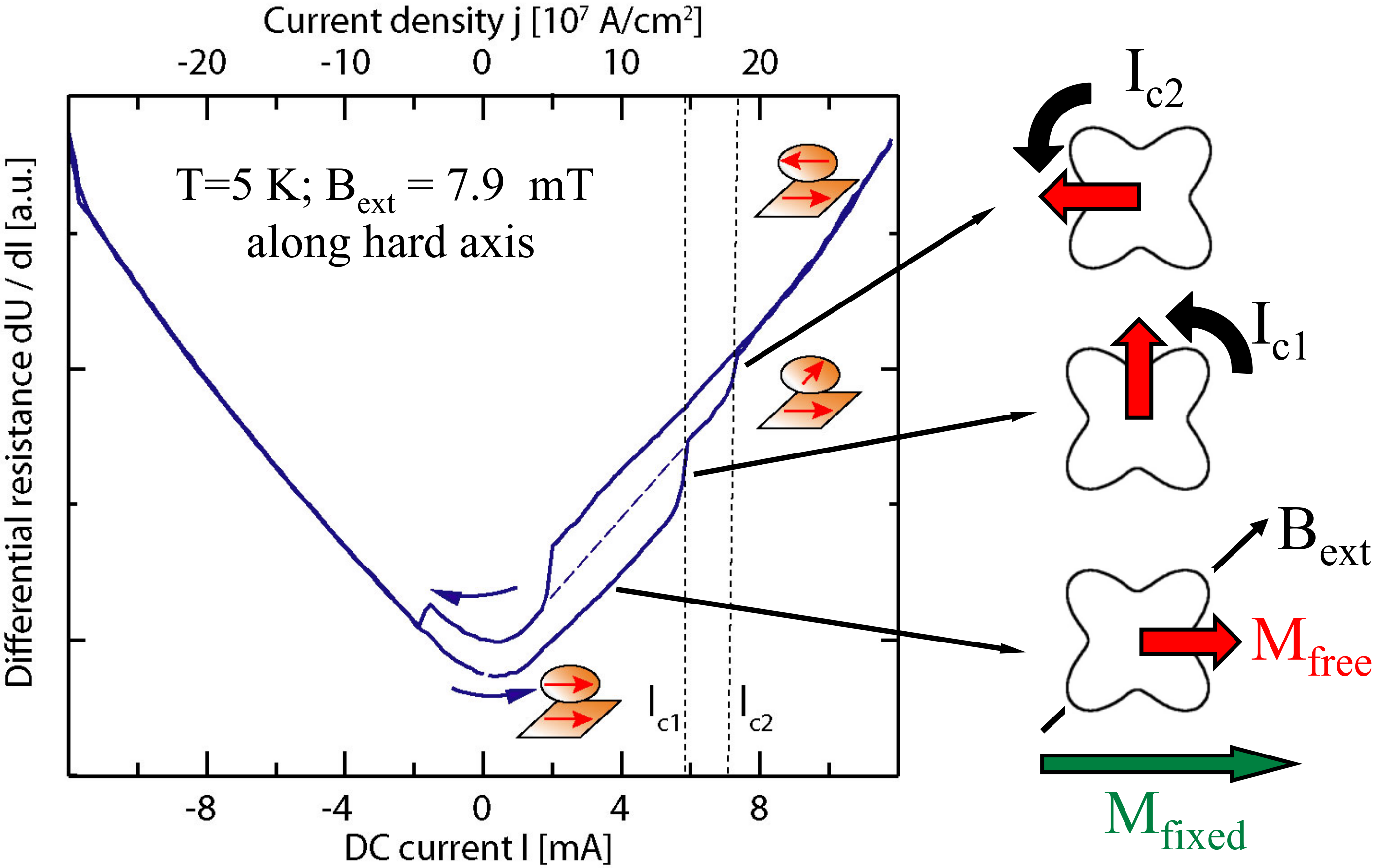
Start with ap alignment

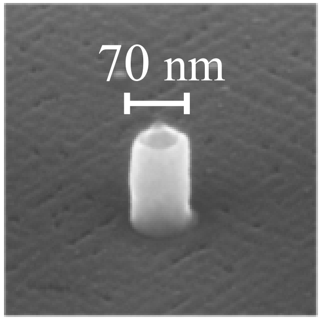


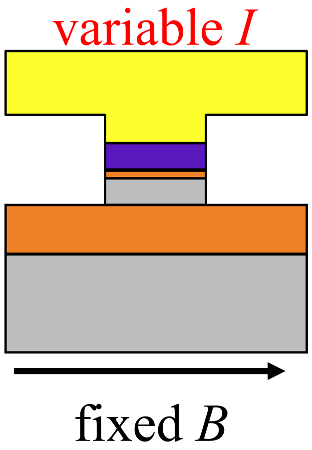
Start with par alignment



Two step CIMS in Fe/Ag/Fe





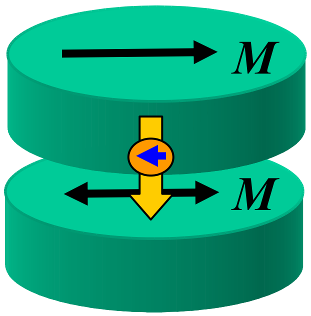


Four energetically nearly identical states give rise to two-step switching

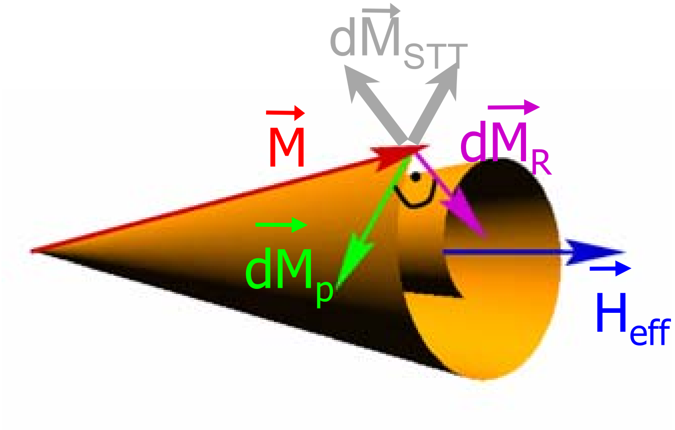
R.Lehndorf, D.Bürgler, C.Schneider, Jülich
2007

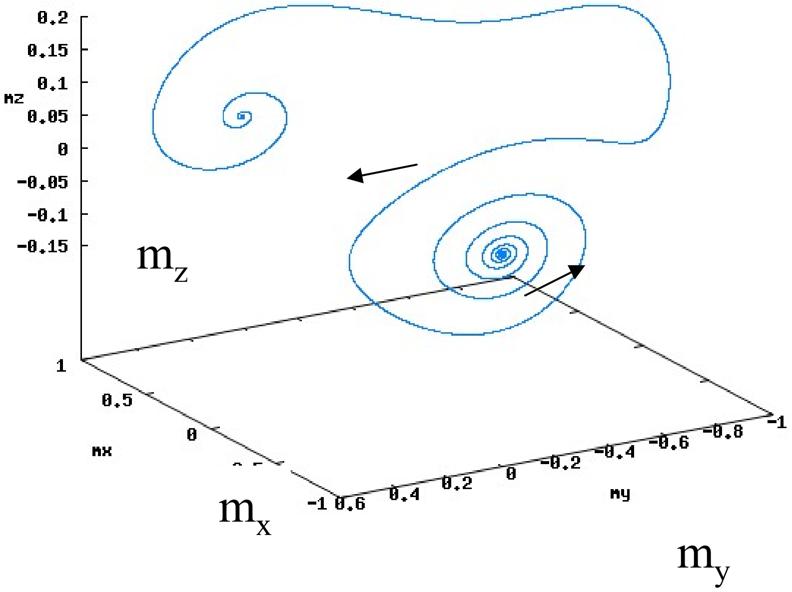
Magnetization reversal of a thin-film element by a spin-polarized current

spin-polarized electric current



$$\frac{\mathrm{d}\boldsymbol{m}}{\mathrm{d}t} = \underbrace{\boxed{-\gamma \boldsymbol{m} \times \boldsymbol{H}_{\mathrm{eff}}}}_{\text{precession}} + \underbrace{\boxed{\alpha \boldsymbol{m} \times \frac{\mathrm{d}\boldsymbol{m}}{\mathrm{d}t}}}_{\text{damping}} + \underbrace{\boxed{\chi \boldsymbol{m} \times (\boldsymbol{m} \times \boldsymbol{p})}}_{\text{spin-transfer torque}}$$

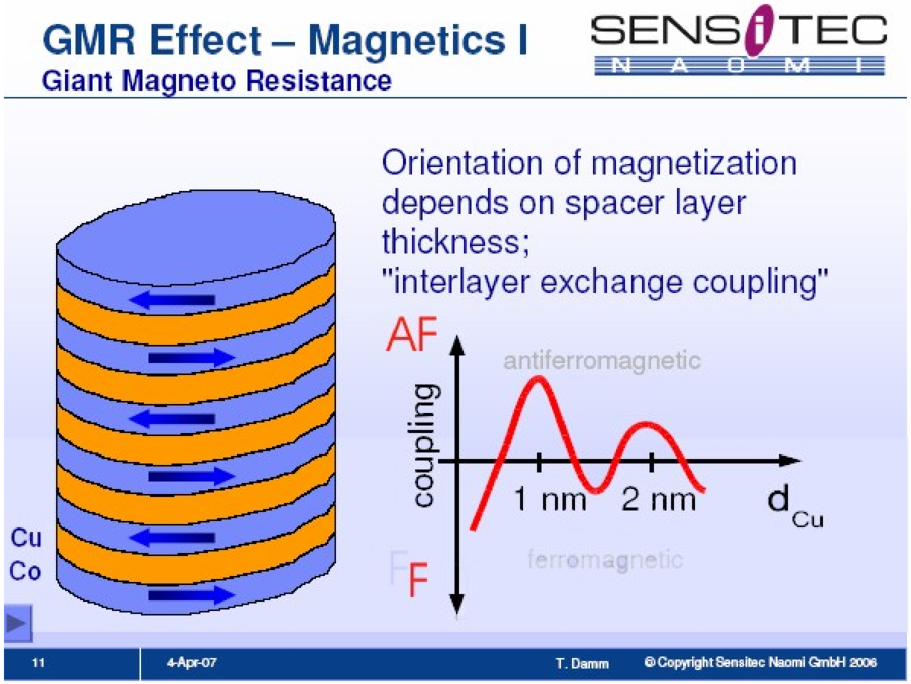




A. Kakay, R. Hertel, C.Schneider, IFF Jülich

Forschungszentrum Jülich
in der Helmholtz-Gemeinschaft

Applications



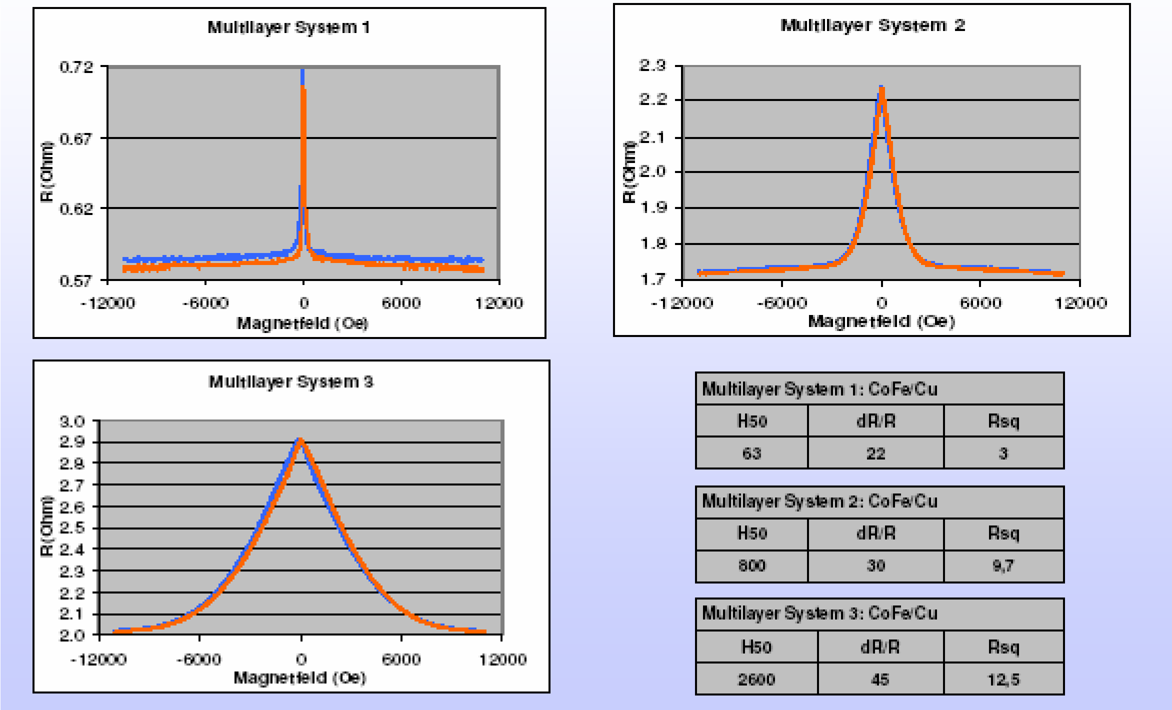
GMR Effect – Magnetics I

Giant Magneto Resistance

Orientation of magnetization depends on spacer layer thickness;
"interlayer exchange coupling"

11 4-Apr-07 T. Damm © Copyright Sensitec Naomi GmbH 2006

AF coupled multilayer:
large signal (22-44%)
easy tailoring of sensitivity
unipolar



Multilayer System 1: CoFe/Cu		
H50	dR/R	Rsq
63	22	3

Multilayer System 2: CoFe/Cu		
H50	dR/R	Rsq
800	30	9,7

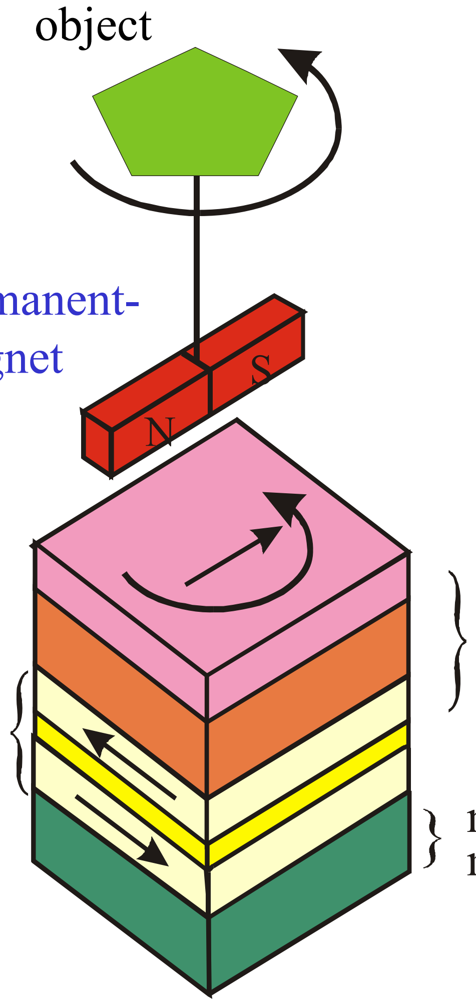
Multilayer System 3: CoFe/Cu		
H50	dR/R	Rsq
2600	45	12,5

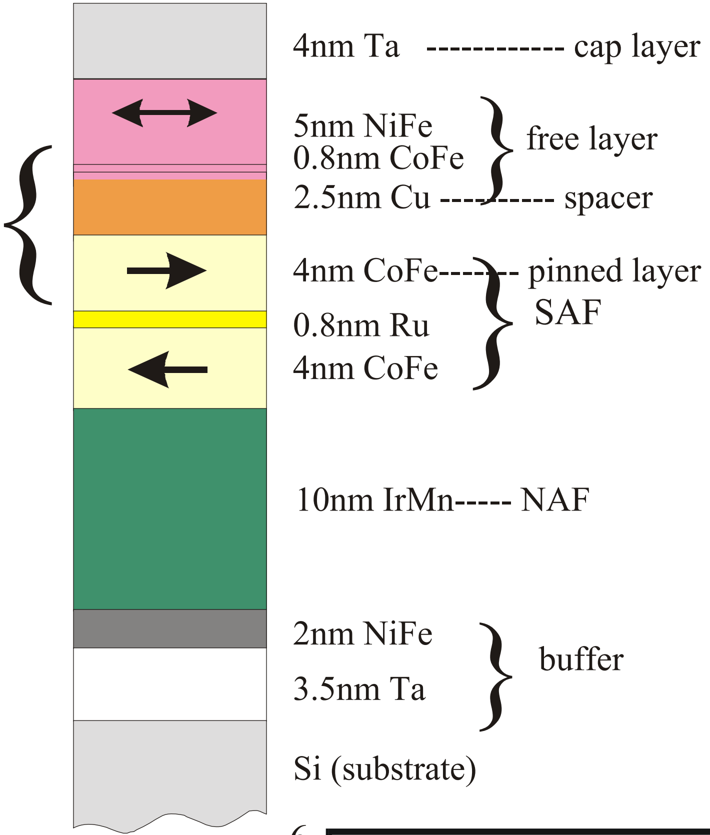
Fig.13 working principle and data for GMR sensor with AF coupled multilayer

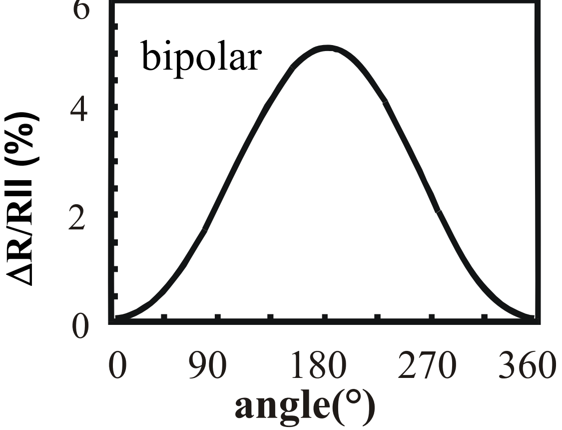
by courtesy of NAOMI-Sensitech, Germany

Spinvalves

Here to monitor mechanical rotations

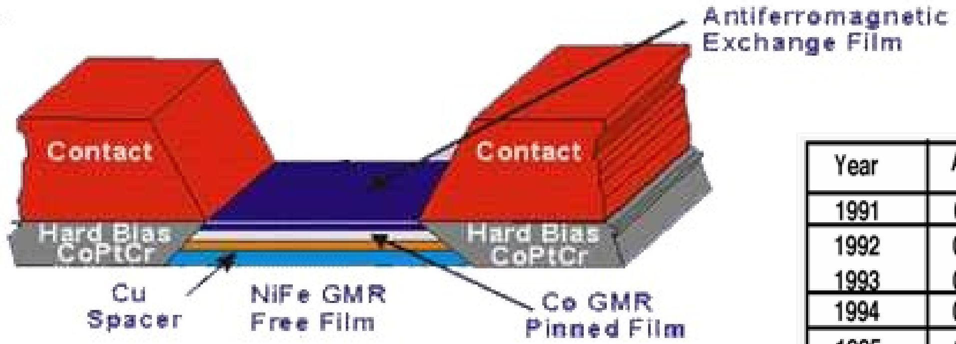






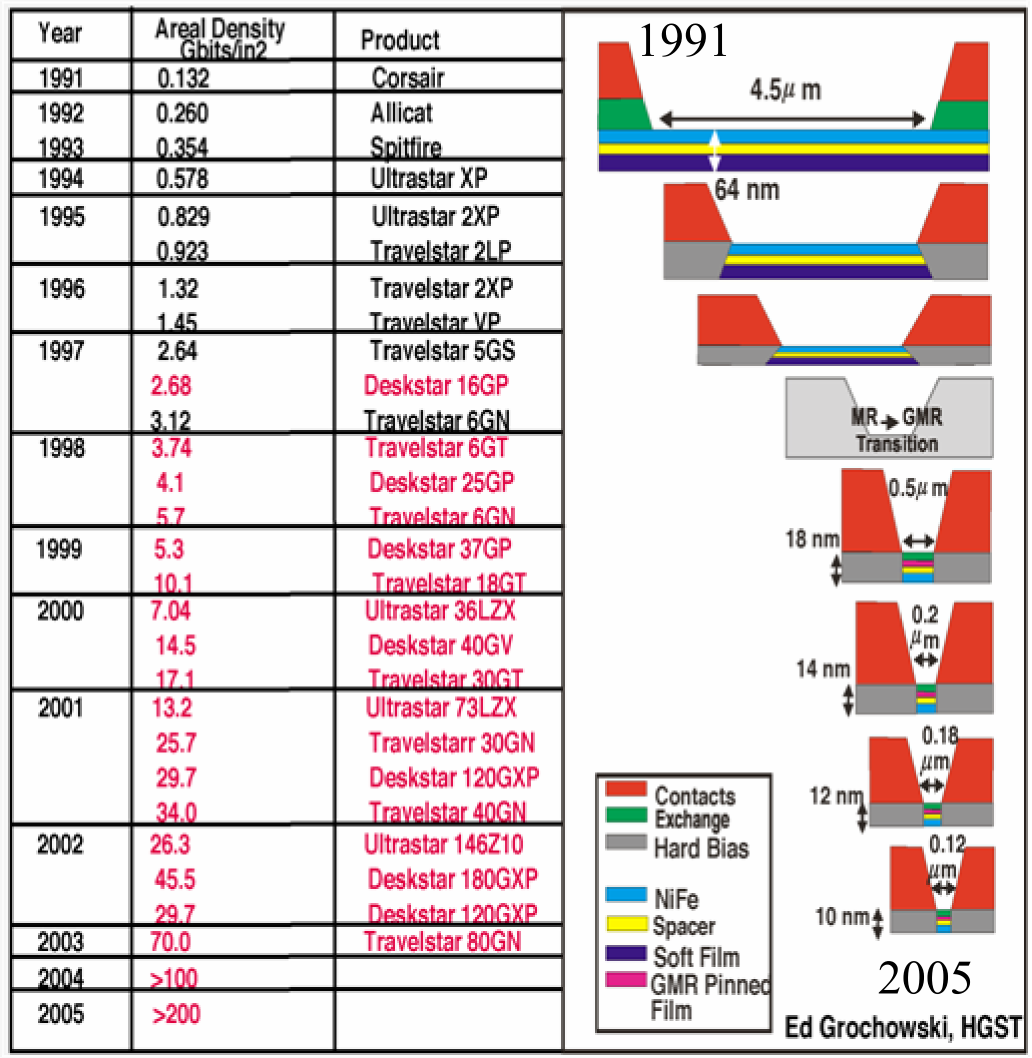
Used in ABS- and ESP-Systems for cars

GMR sensors in read-heads for hard-disk drives



Shipment of GMR-read-heads (1997-2007):

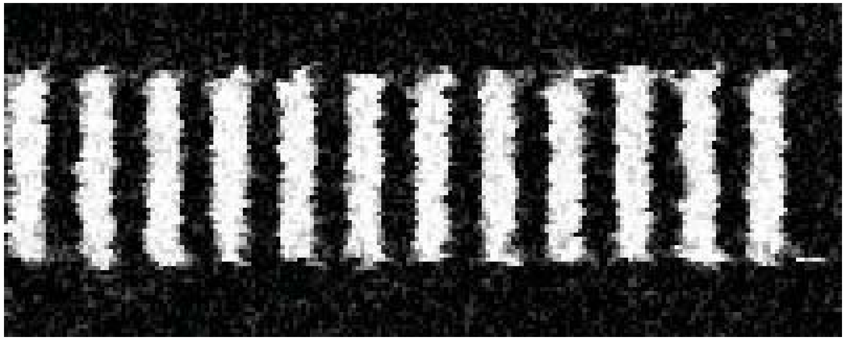
5 billion (10^9)

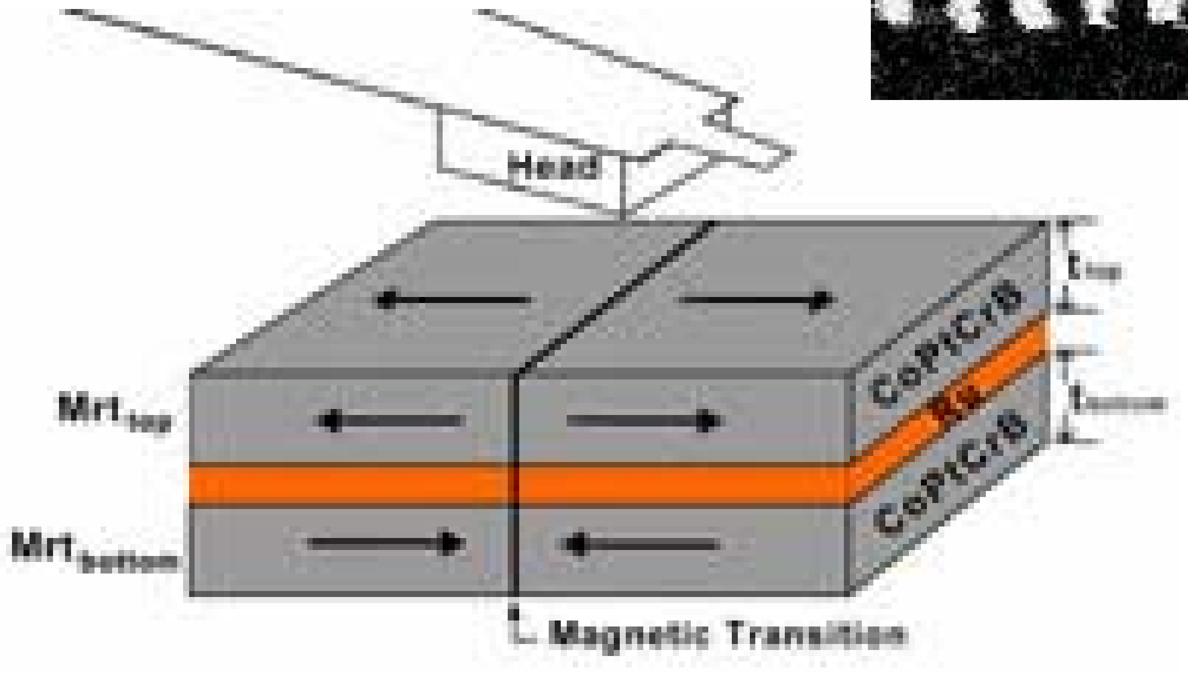


Year	Areal Density Gbits/in2	Product
1991	0.132	Corsair
1992	0.260	Allicat
1993	0.354	Spitfire
1994	0.578	Ultrastar XP
1995	0.829	Ultrastar 2XP
	0.923	Travelstar 2LP
1996	1.32	Travelstar 2XP
	1.45	Travelstar VP
1997	2.64	Travelstar 5GS
	2.68	Deskstar 16GP
	3.12	Travelstar 6GN
1998	3.74	Travelstar 6GT
	4.1	Deskstar 25GP
	5.7	Travelstar 6GN
1999	5.3	Deskstar 37GP
	10.1	Travelstar 18GT
2000	7.04	Ultrastar 36LZX
	14.5	Deskstar 40GV
	17.1	Travelstar 30GT
2001	13.2	Ultrastar 73LZX
	25.7	Travelstarr 30GN
	29.7	Deskstar 120GXP
	34.0	Travelstar 40GN
2002	26.3	Ultrastar 146Z10
	45.5	Deskstar 180GXP
	29.7	Deskstar 120GXP
2003	70.0	Travelstar 80GN
2004	>100	
2005	>200	

Ed Grochowski, HGST

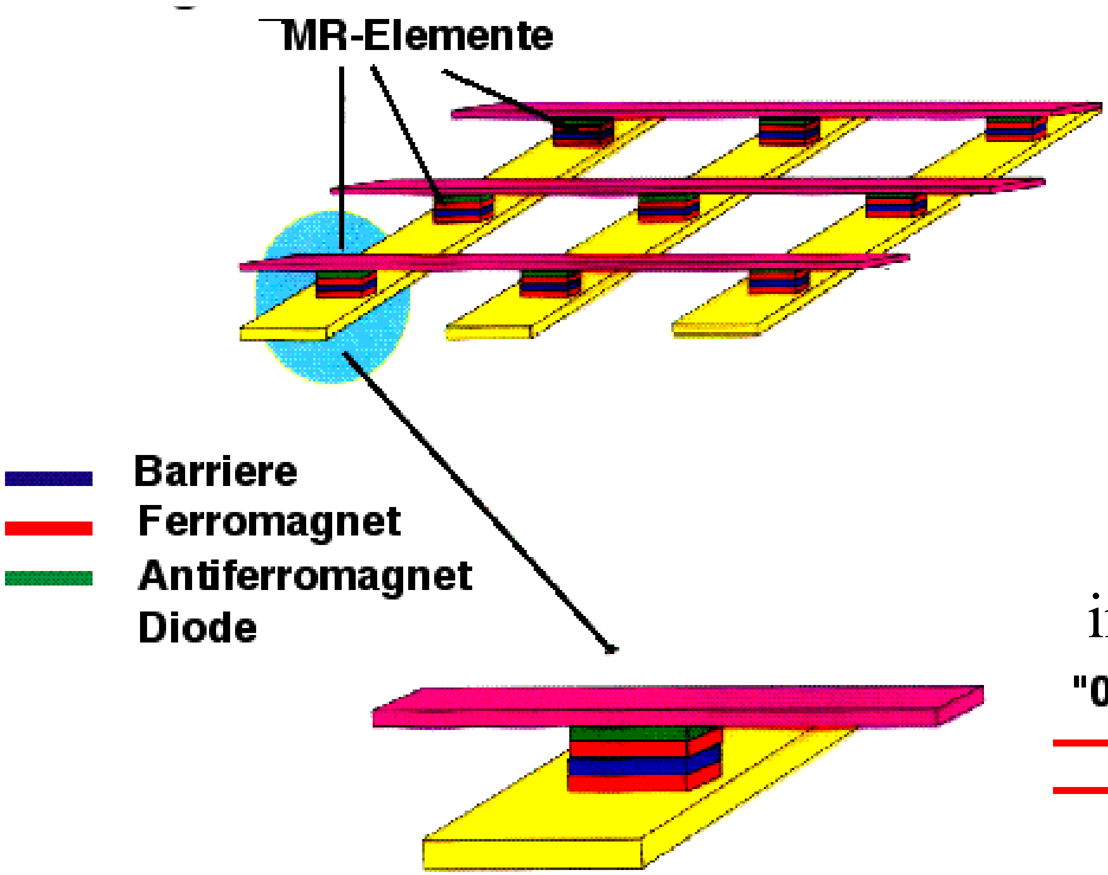
AFC media



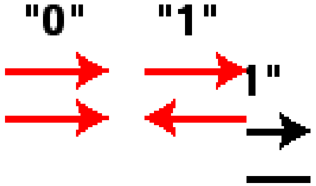


AFC stabilising magnetic domains on hard disc

TMR and MRAM
(magnetic random access memory)



information:



nonvolatile

Conventional: writing by Oersted fields
Advanced: writing by CIMS

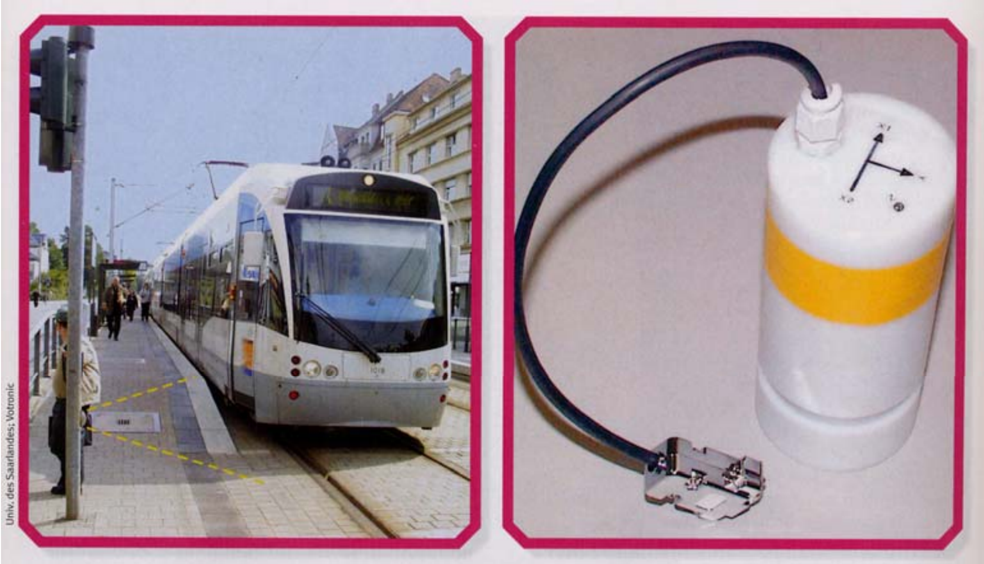
AMR-and GMR-Sensor Applications
e.g. als Electronic Compass Combined with a Mobile GPS System

there are already mobiles on the market which include GPS, in future also compasses

- measurement of the Earth‘s magnetic field in 2 or 3 axis
- accuracy of 1°
- low power consumption **(2 years battery life)**

For continous, retardation free alignment of map or direction of motion.

Traffic Control Sensors



Univ. des Saarlandes; Votronic

most vehicles contain parts of ferromagnetic materials

traffic control

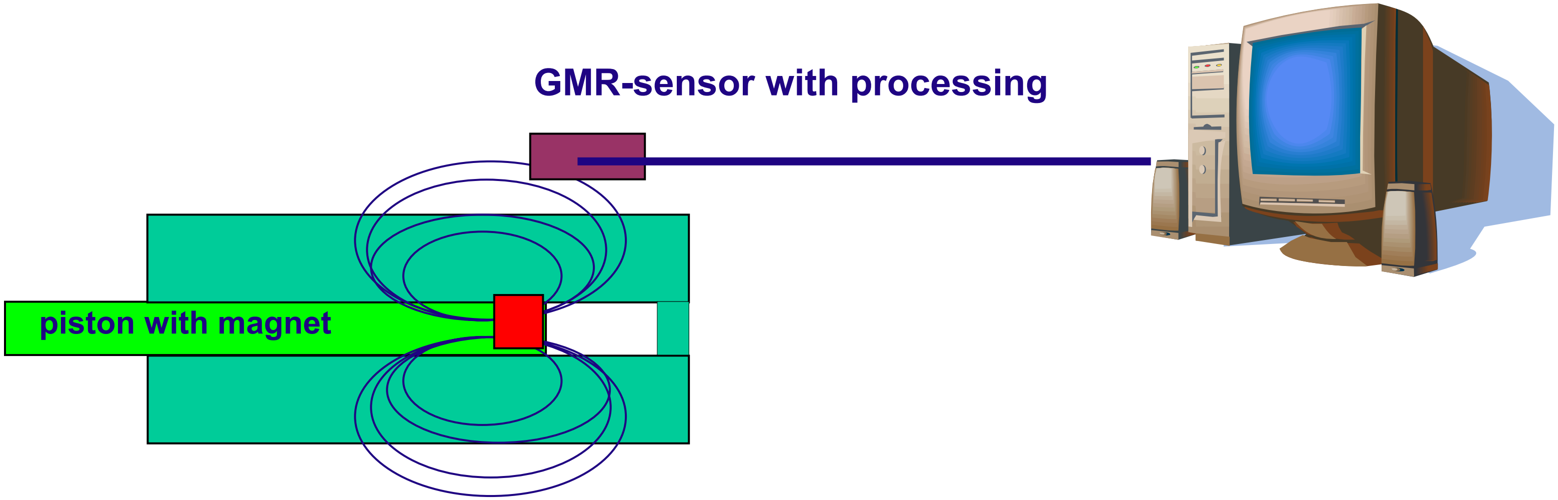
indicate free parking lots on a display at the entrance of parkhouses

Spirit and Opportunity

The motion of „Spirit and Opportunity“ on Mars are monitored by AMR sensors.

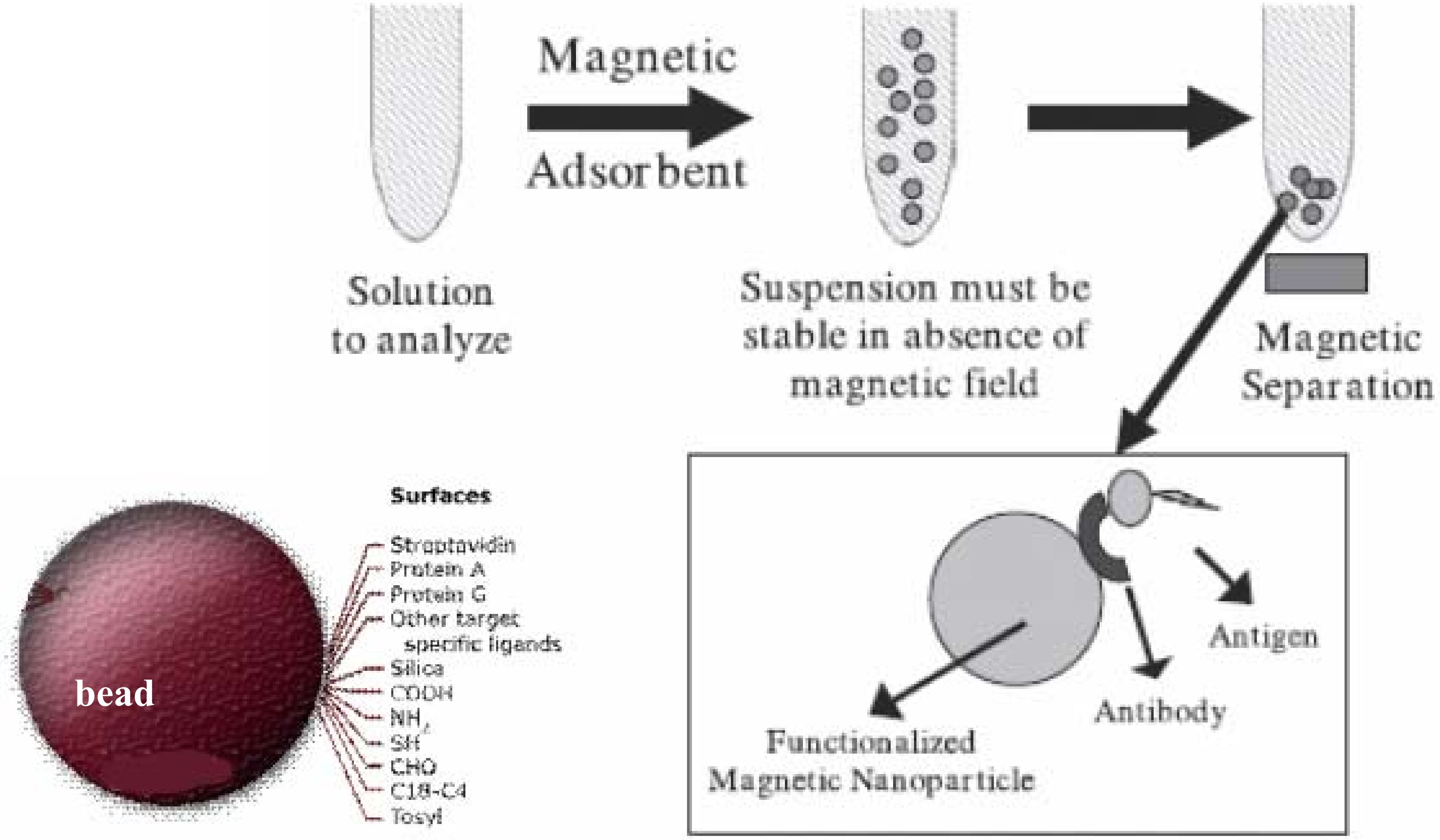
GMR-Field Sensor Applications

e.g. Detection of piston end positions

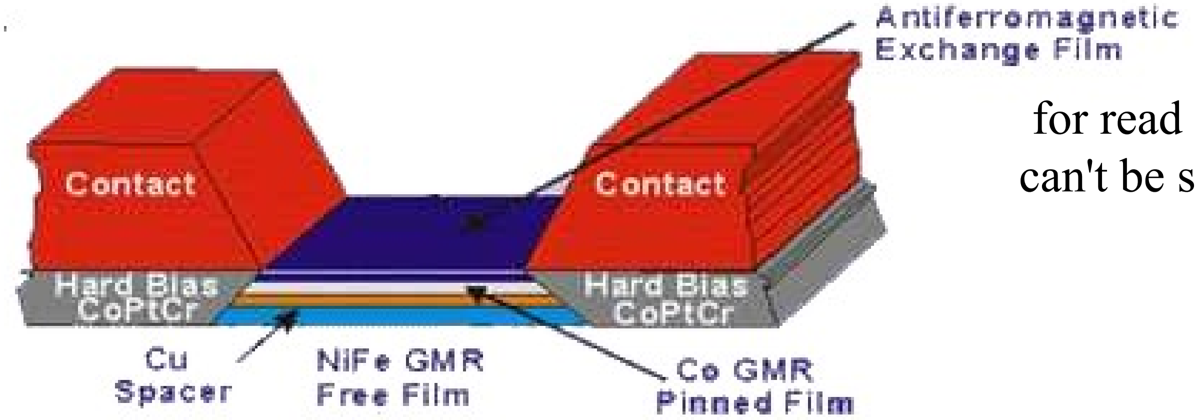


The GMR-sensor detects - due to its high magnetic sensitivity - the position of the piston even at large distances and different cylinder diameters.

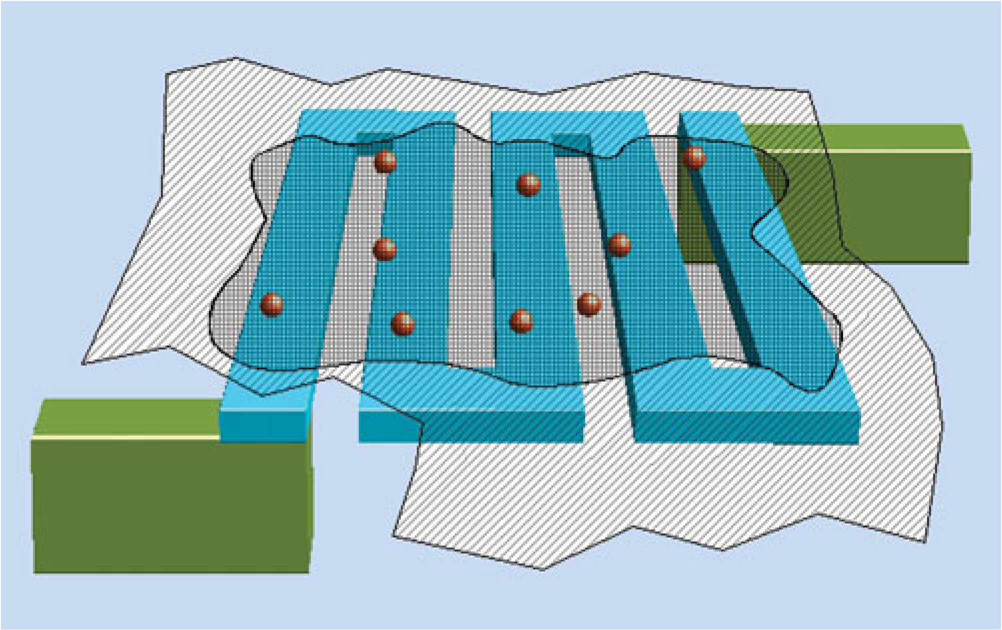
GMR in medicine and biology



New applications - New challenges



for read out in HDD
can't be small enough



for detecting magnetic beads:
can't be large
enough

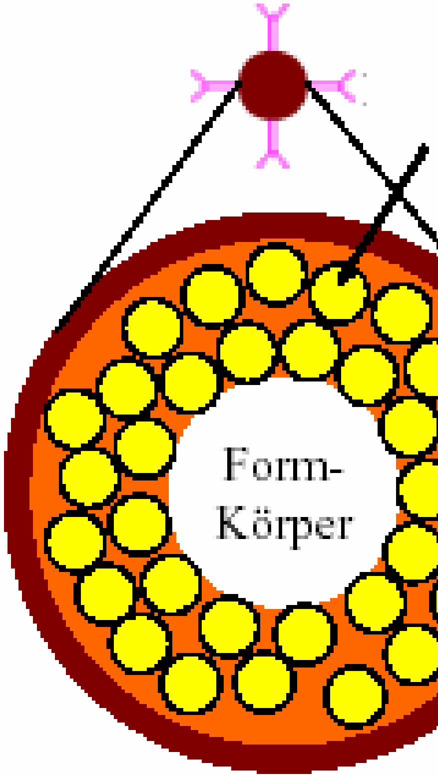
Hydra in tbe Greek mythology: cut one head, two new grow

Thank You

More Informations at
www.fz-juelich.de/gmr

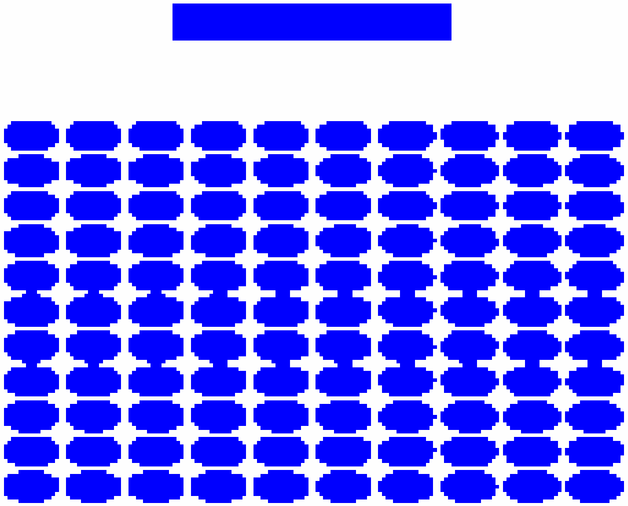
Biosensor: important ingredients

magnetic beads 1µ



magnetic
nanoparaticles
10nm

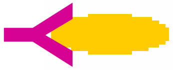
GMR- TMR-Sensor Array:
see also „MRAM“



10x10 Sensors on
0.1x0.1mm^2 area

Y antibodies
good guys

antigenes
bad guys

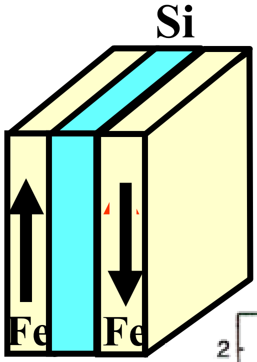


immune reaction

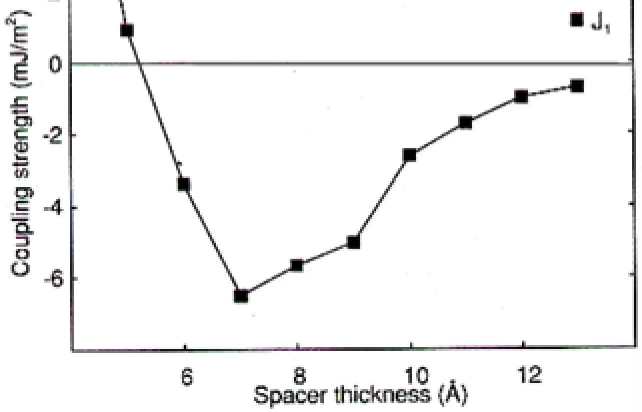
Largest GMR values in trilayers and multi layers at room temp

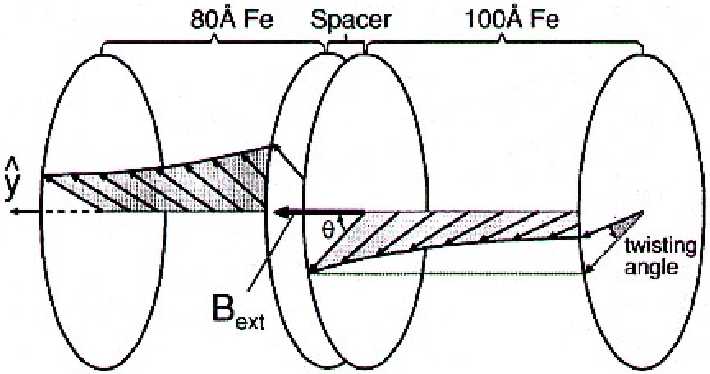
system	GMR[%]	t_{mag}[nm]	ref.
Fe/Cr/Fe	1.5	12	1)
Fe/Cr/Fe	2	5	2)
$[Fe/Cr(1.2nm)]_{50}$	42	.45	2)
Co/Au/Co	1.8	10	1)
Co/Cu/Co	2.0	10	1)
Fe/Cu/Fe	0.5	10	1)
Co/Cu/Co	15	3	3)
$[Co/Cu(0.9nm)]_{30}$	48	1.5	5)
$[Co/Cu(0.9)]_{16}$	65	1	6)

1) Grünberg et al.JMMM1991 2) Schad et al. JAP 1994 3)Egelhoff et al JAP79
4) Schad et al, Appl.Phys.Lett. 1994 5) Mosca et al JMMM 1991 6) Parkin Appl.Phys.Lett.1991

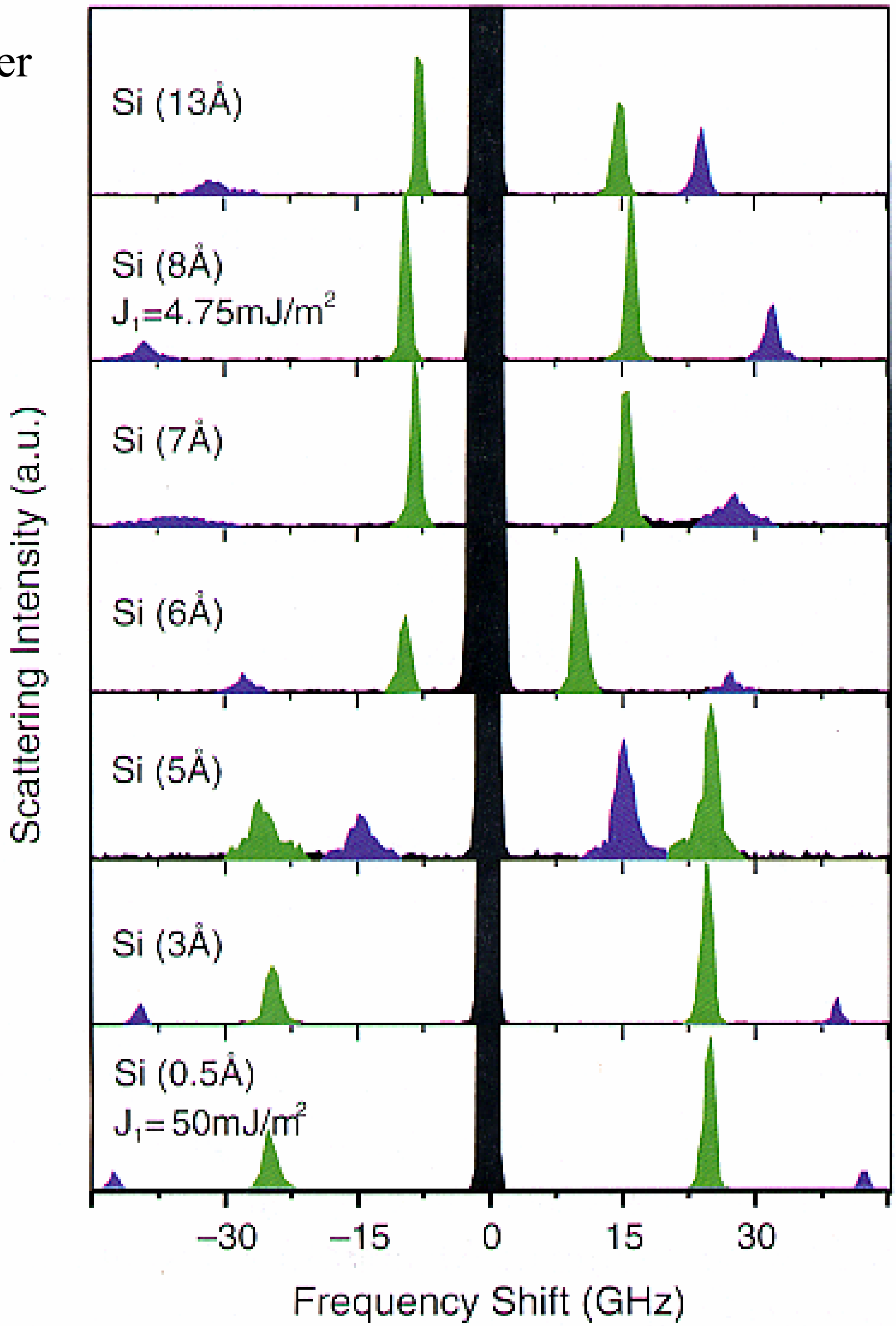


recent example: M.Buchmeier et al. PRB 67(2003)184404 and phD thesis, Juelich 2003





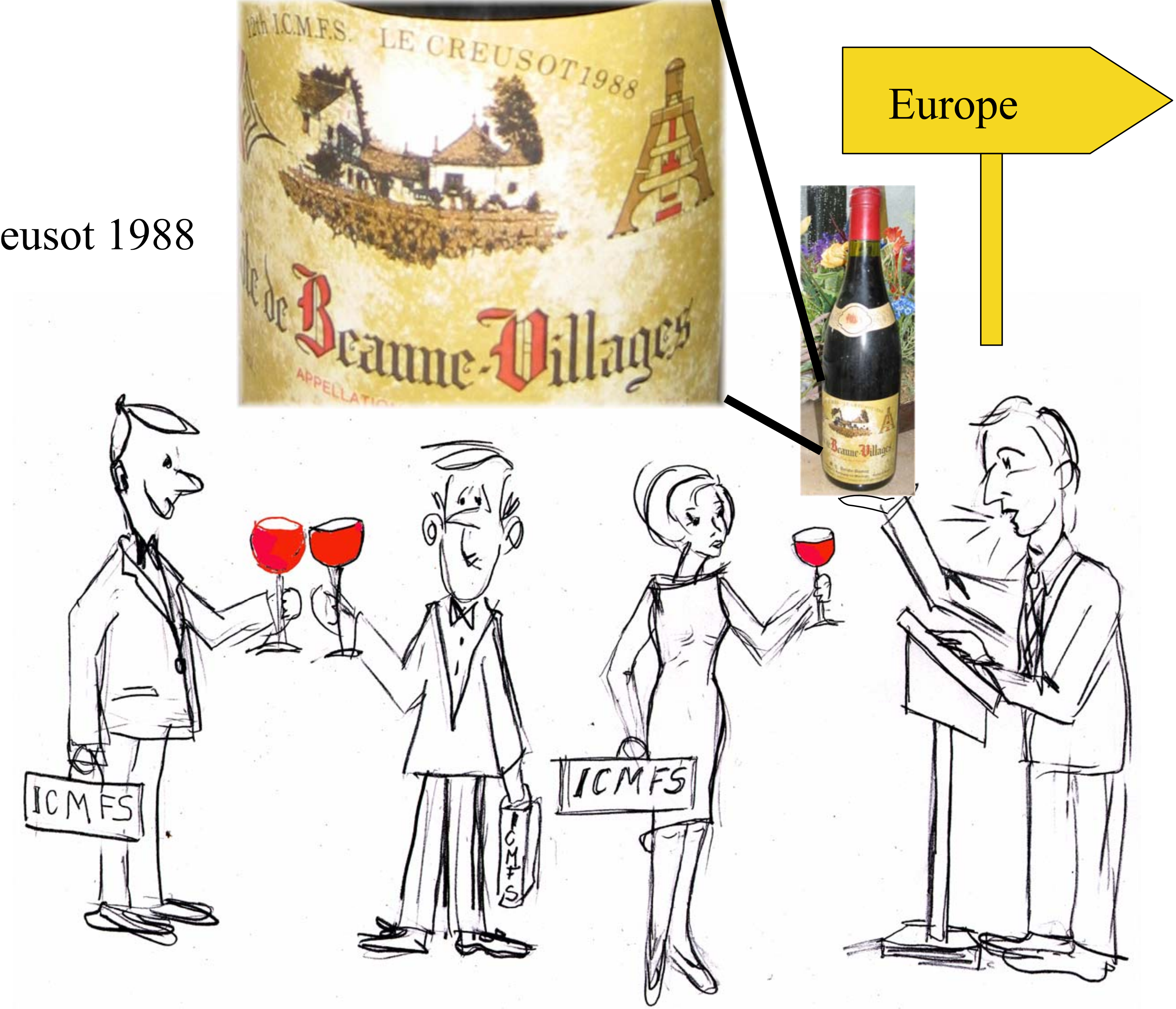
evaluation includes twisting of magnetization in the Fe films

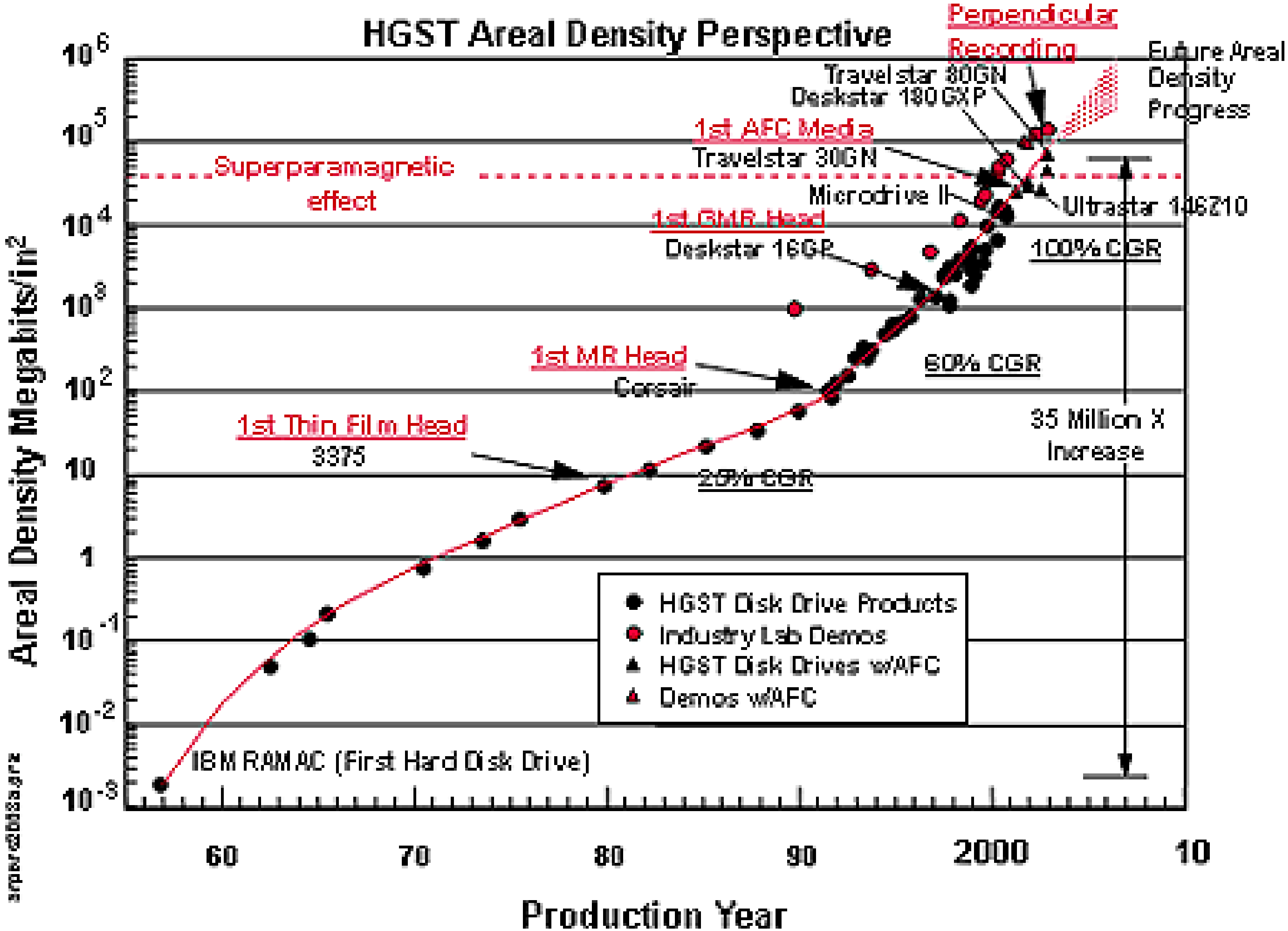


Structure	Interlayer thickness [nm]	Coupling strength [mJ/m^2]	Reference
Fe/MgO/Fe	0.5	-0.26	[12]
Fe/Si/Fe	0.6	-6.2	[11]
Co/Ru/Co	<0.9	-5	[50]
Fe/Cr/Fe	0.5	-1.6	[51]

Table 1: Comparison of interlayer coupling strengths for some structures with insulating, semiconducting, and metallic interlayers.

Le Creusot 1988





Ed Grochowski