# 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*

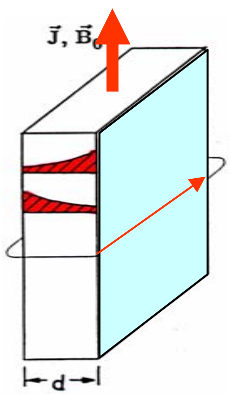
# May I introduce myself

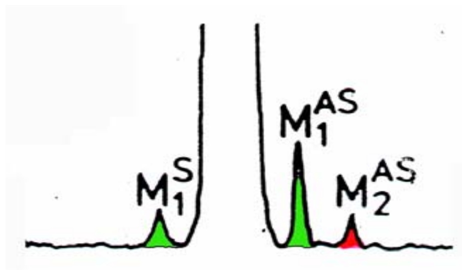
**1969: PhD in Darmstadt (Germany) with**
**„Optical Spectroscopy and Crystal Field Analysis in some Rare Earth Garnets“**
**Mentor K.H.Hellwege, Supervisor: St.Hüfner**

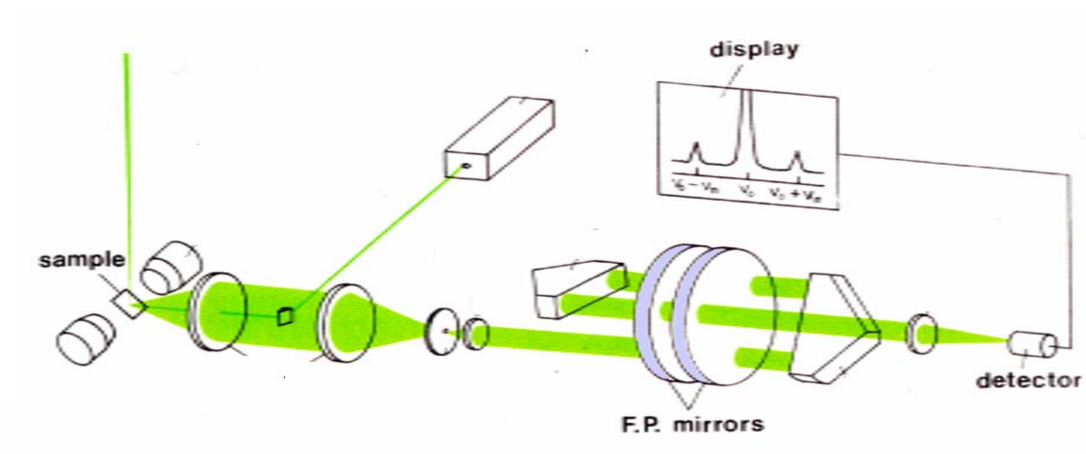
**1969-1972 postdoctoral fellow at Carleton University Ottawa Canada.**
**Raman Spectroscopy on electronic states and phonons**
**Supervisor: J. A.Koningstein**

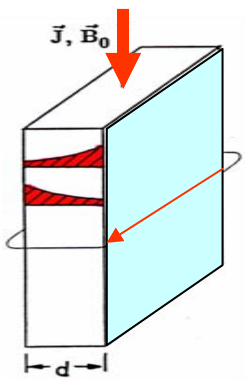
**since 1972 Research Center Jülich,**
**Institute for Magnetism founded in 1971**
**Investigation of magnetic semiconductors EuO, EuS**
**Fabrication, magnetic and transport properties of layered magnetic structures**
**Mentor: W.Zinn**

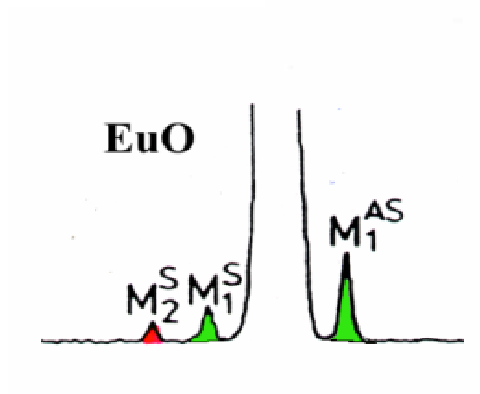
# Bulk and Surface Spinwaves in EuO




New instrumental development

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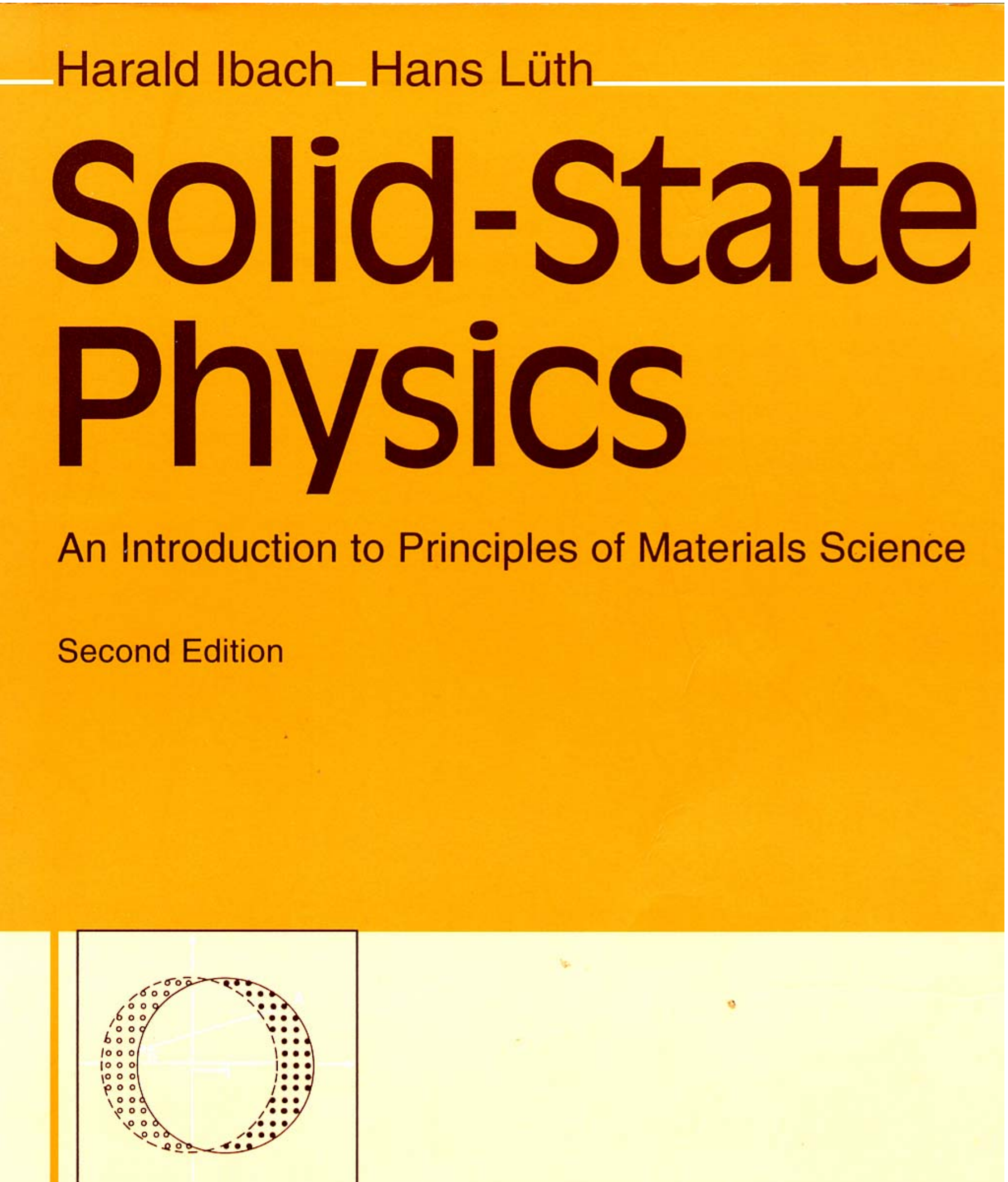


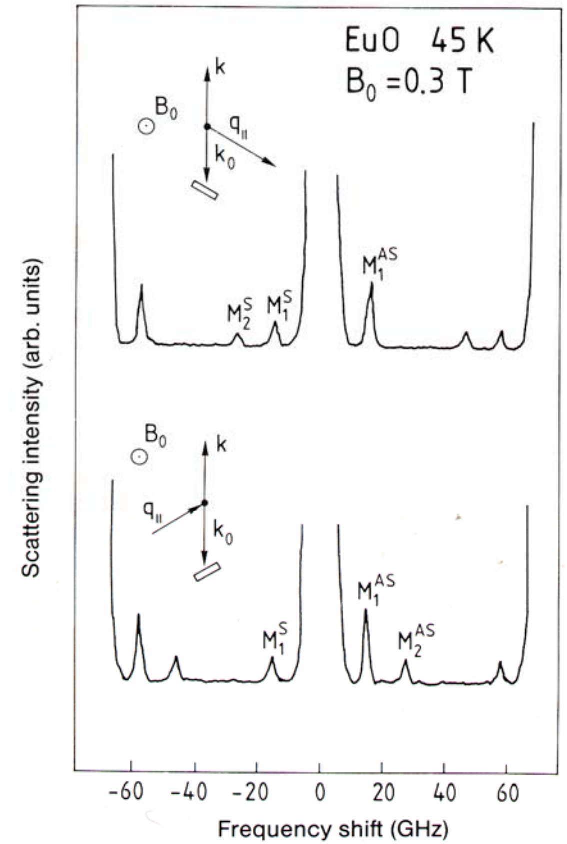
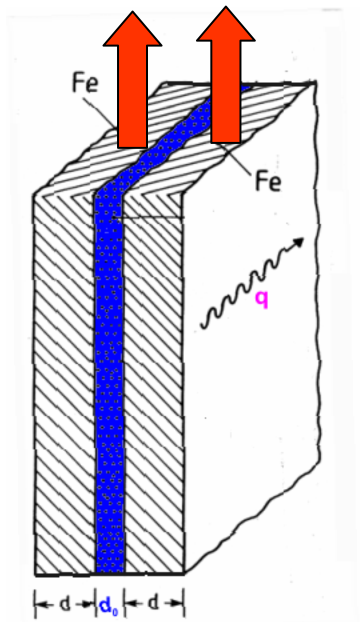



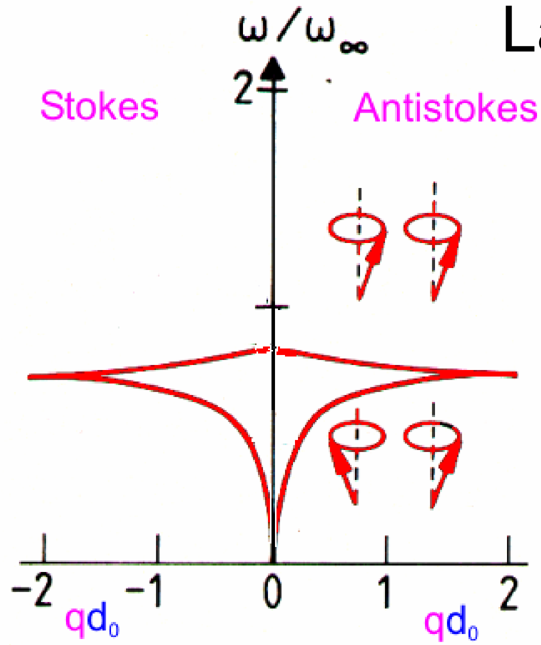

**Fig. VI.3.** Raman spectrum from EuO [VI.2]. According to the orientation of the sample one observes the Damon-Eshbach spin waves (labelled as $M_2$) as a Stokes line (*above*) or as an anti-Stokes line (*below*), while the volume spin waves appear with equal intensity in both geometries, although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

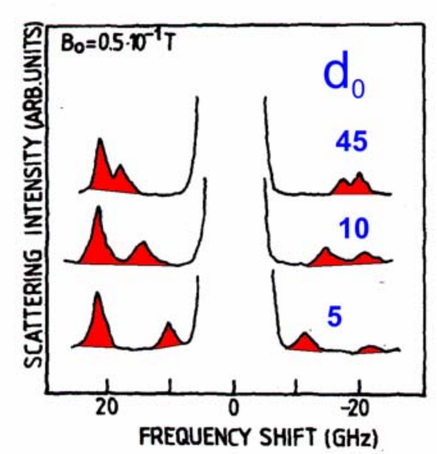
# Coupled Damon-Eshbach-Spinwaves

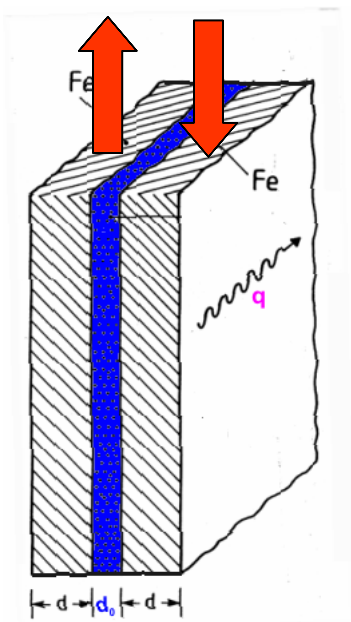
Landau Lifshitz equation

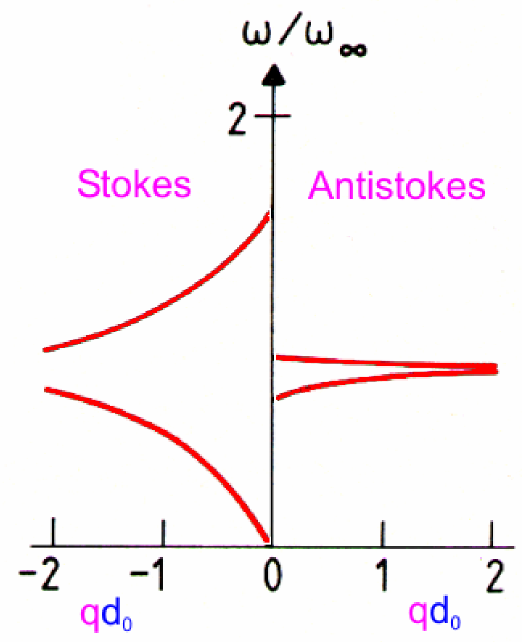
$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{\text{eff}}$$



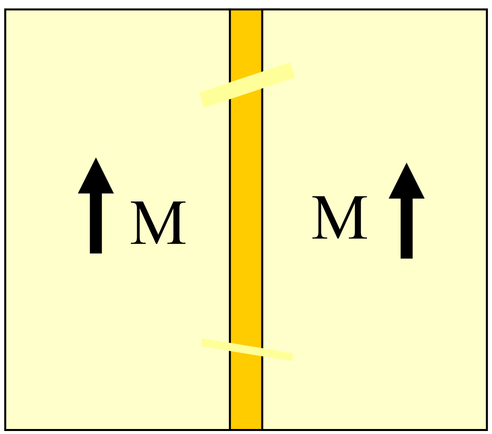



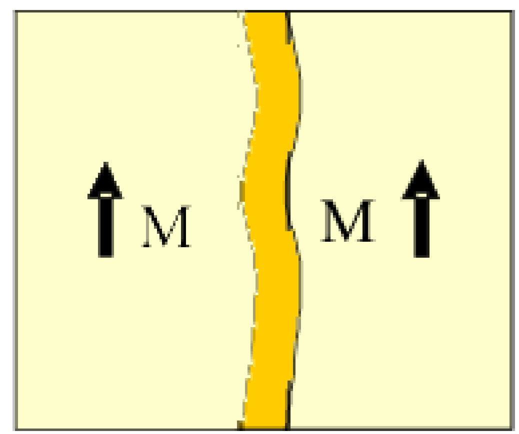

?

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

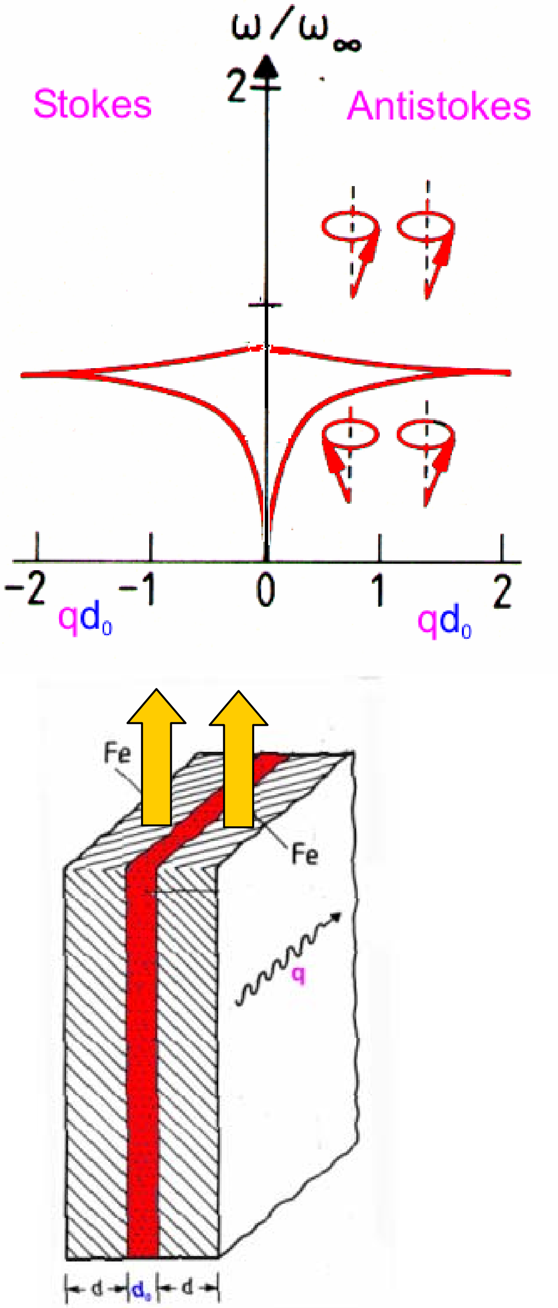
Pinhole coupling due to „magnetic bridges“

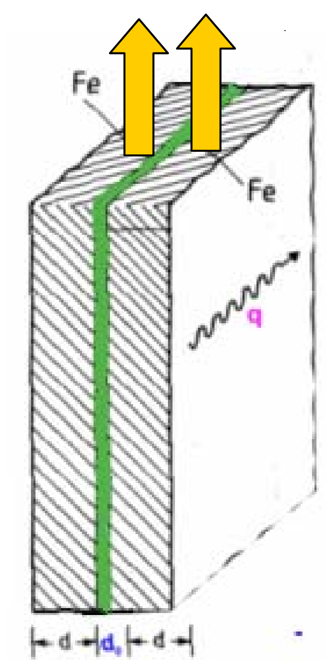


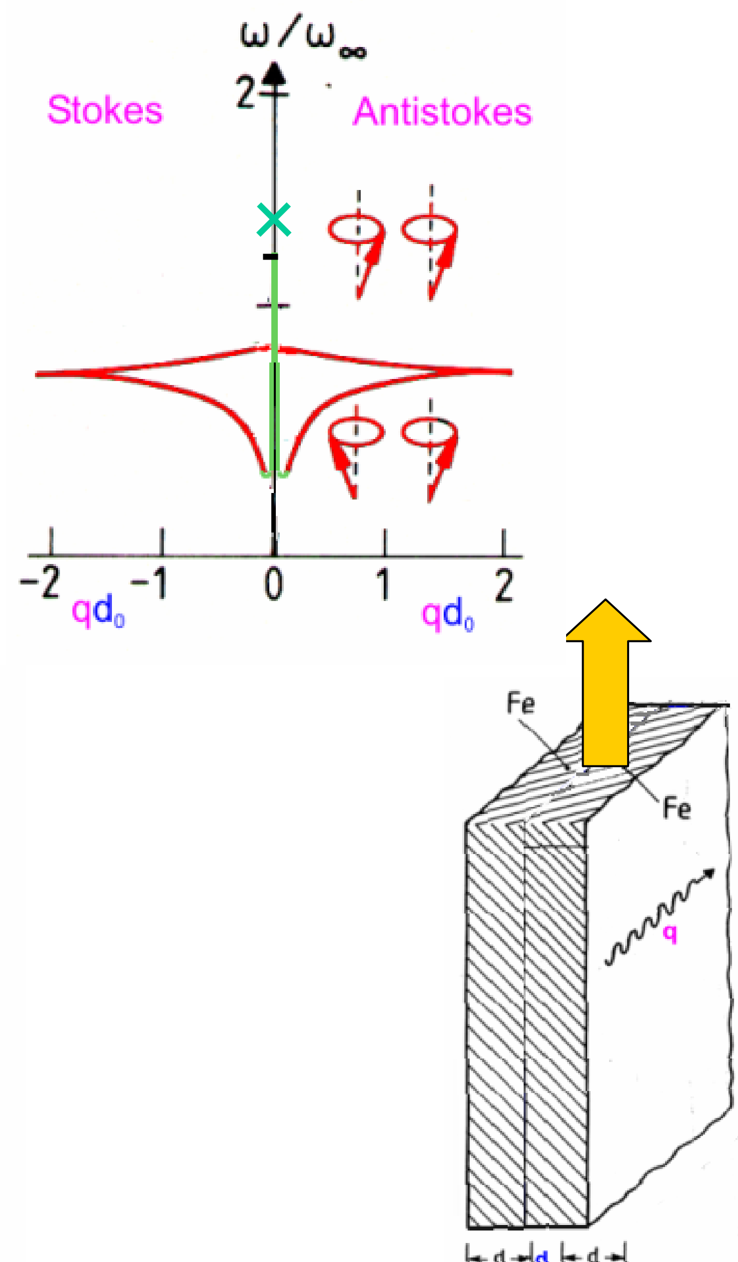

Orange peel or Neel type coupling caused by strayfields due to meandering interlayers



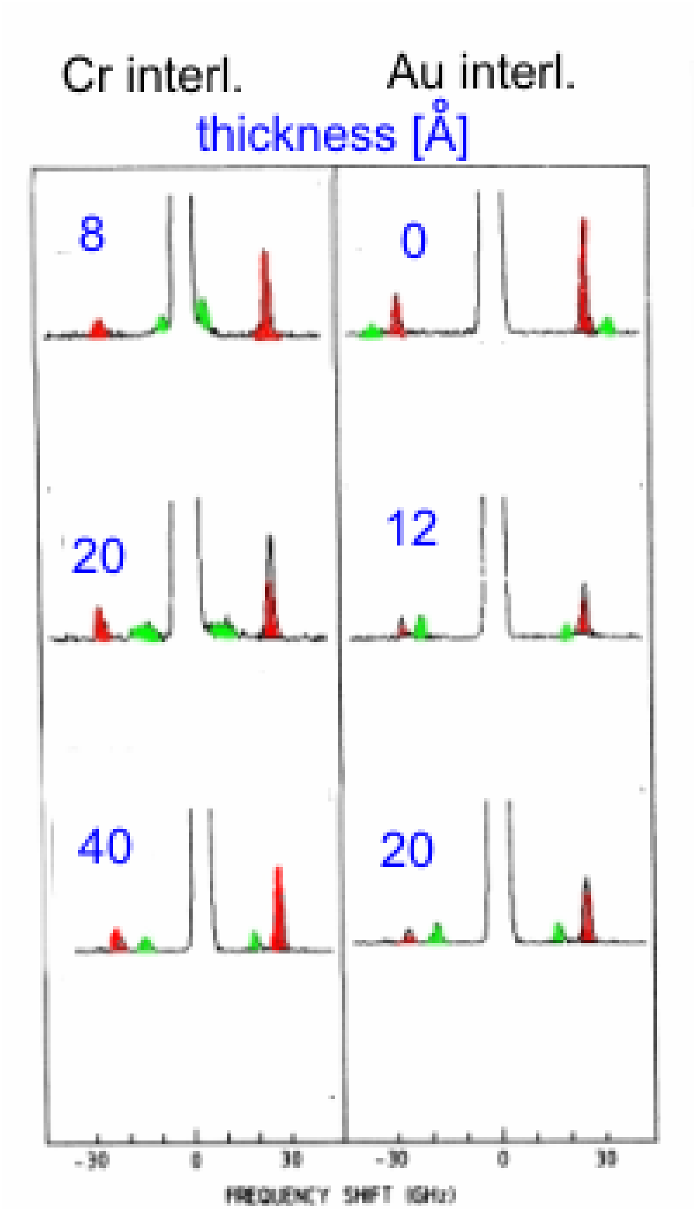
# Coupled Damon-Eshbach-Spinwaves

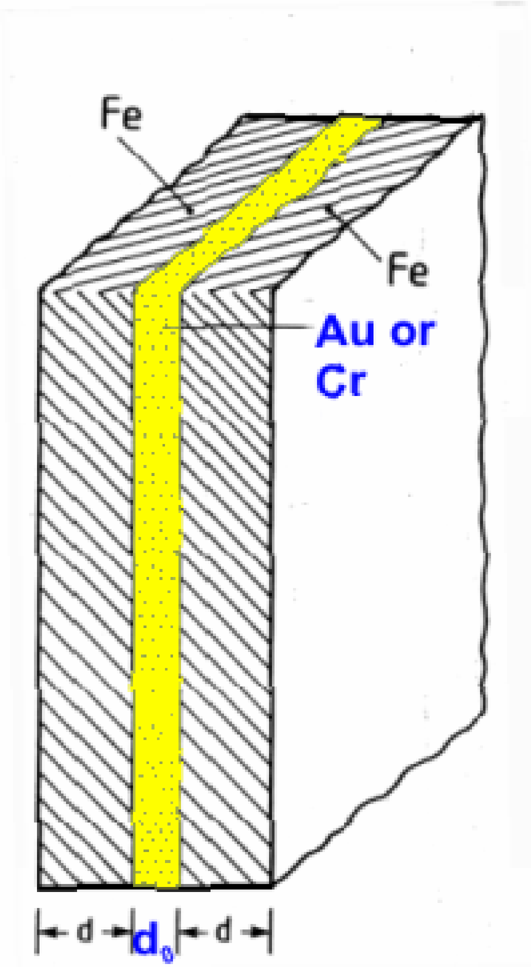


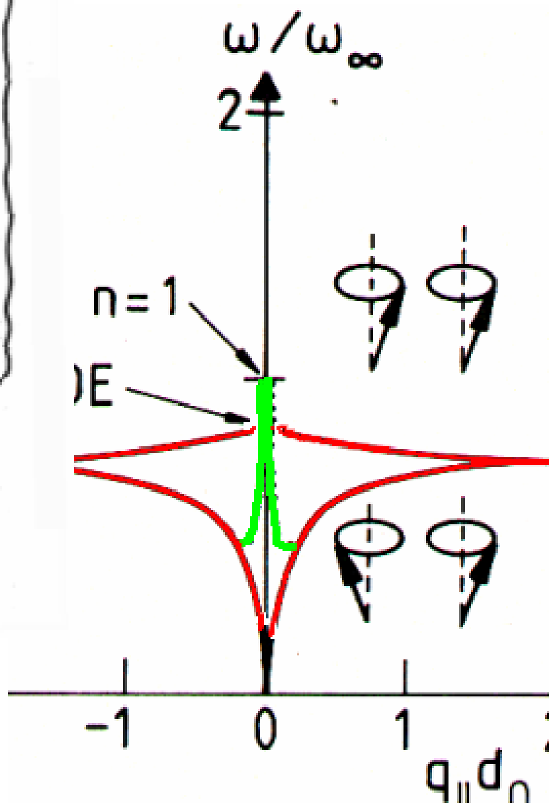



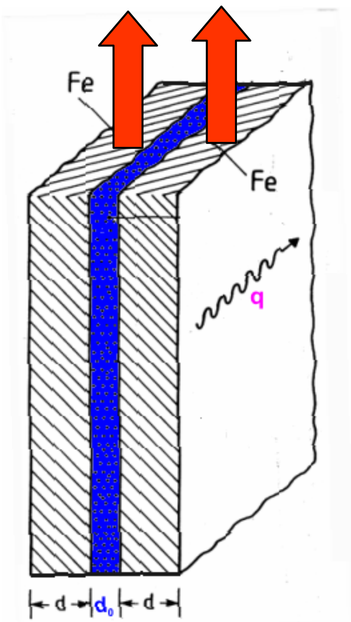
# Effect of exchange coupling

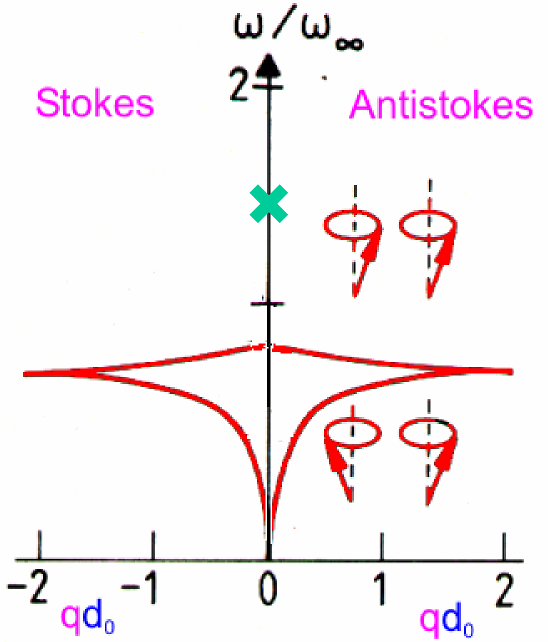


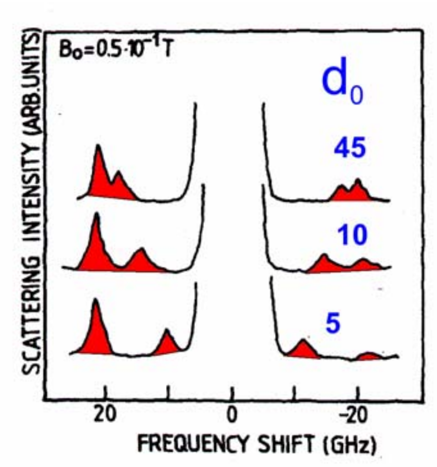



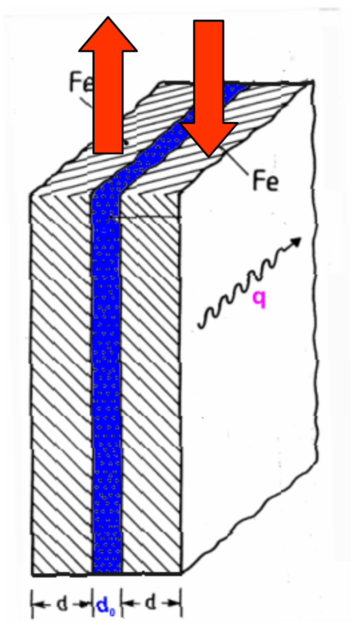



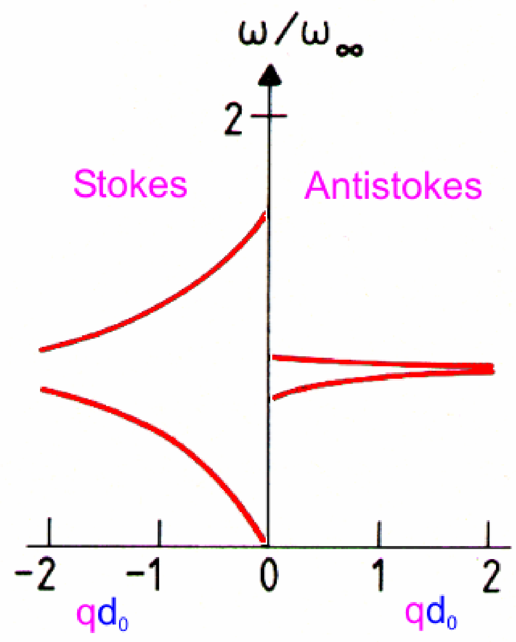
# Coupled Damon-Eshbach-Spinwaves

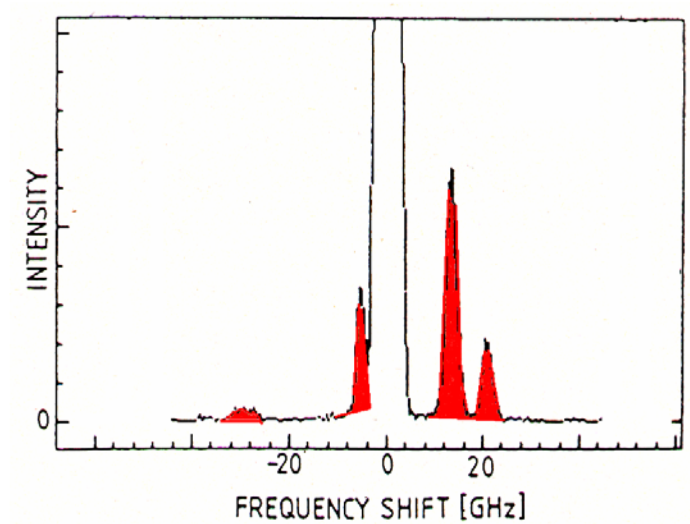


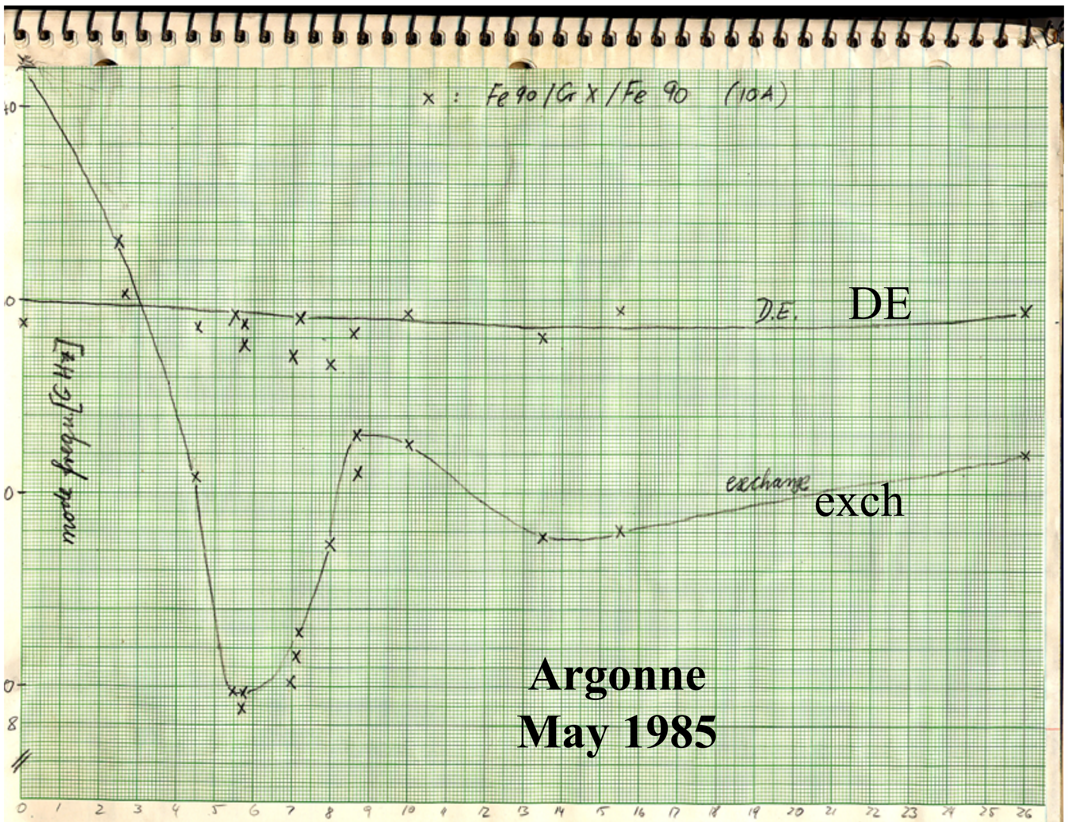



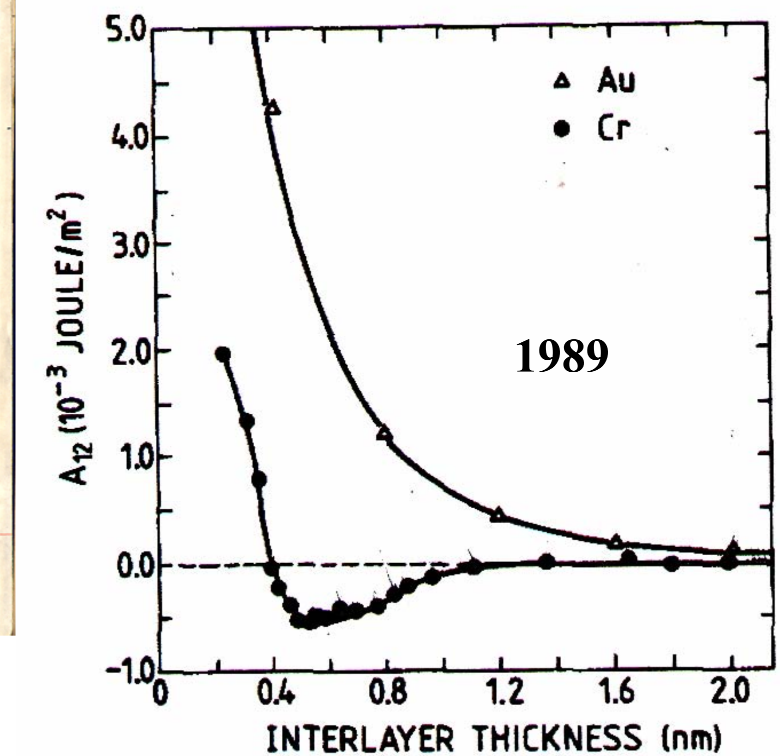



# First measurement of interlayer exchange coupling as a function of the interlayer thickness

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



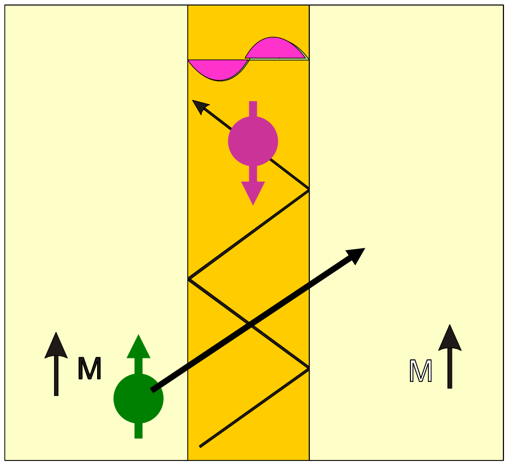
# Work on interlayer exchange coupling published in 1986

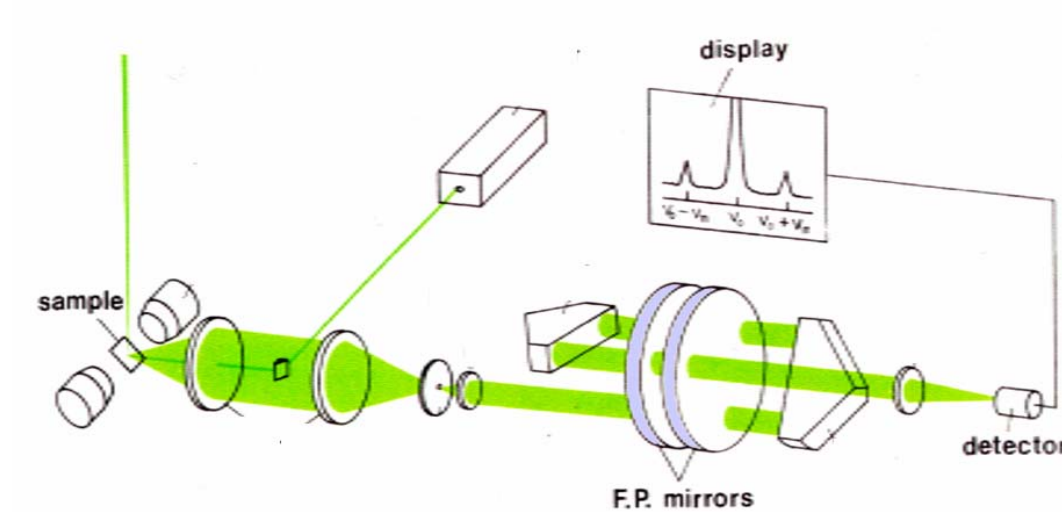
**Oscillatory coupling in Gd/Y multilayers (Majkrzak et al)**

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

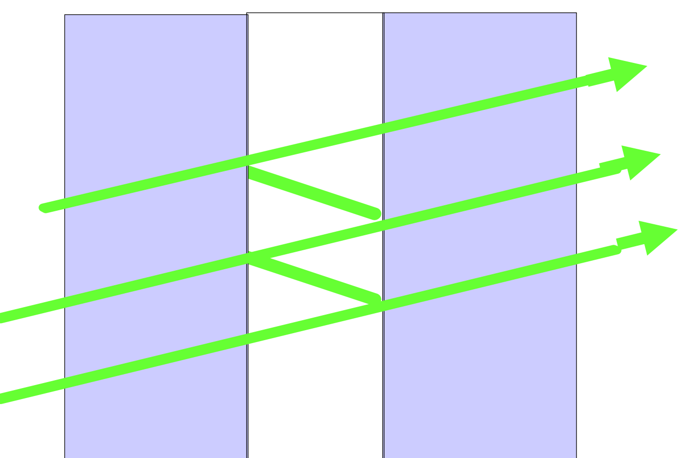
**AF coupling in Fe/Cr/Fe layered structures (Grünberg et al)**

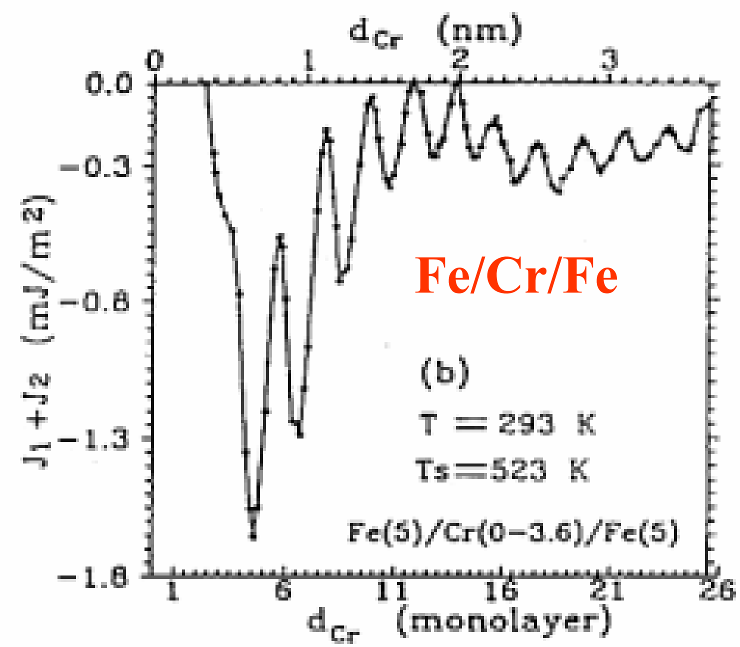
# Fabry Perot model of interlayer exchange coupling



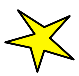

analogy: optical Fabry Perot interferometer

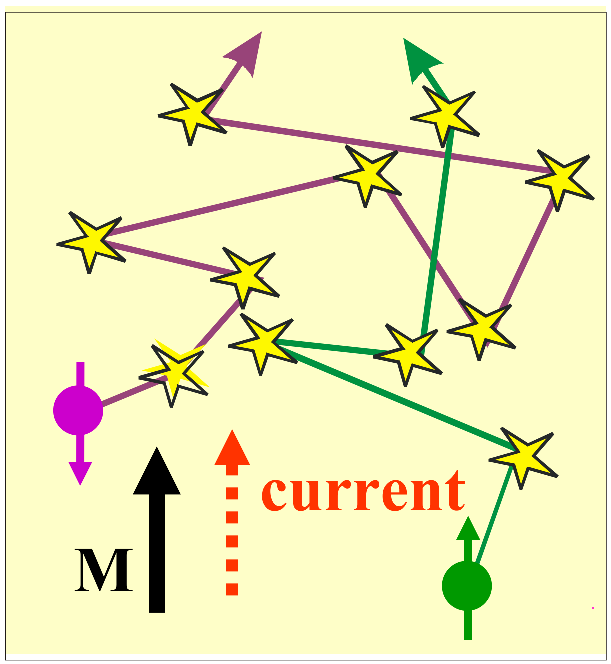




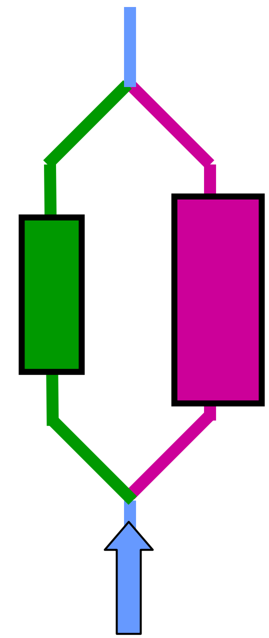

Short period oscillations after improvement of growth

# Mott`s two current model

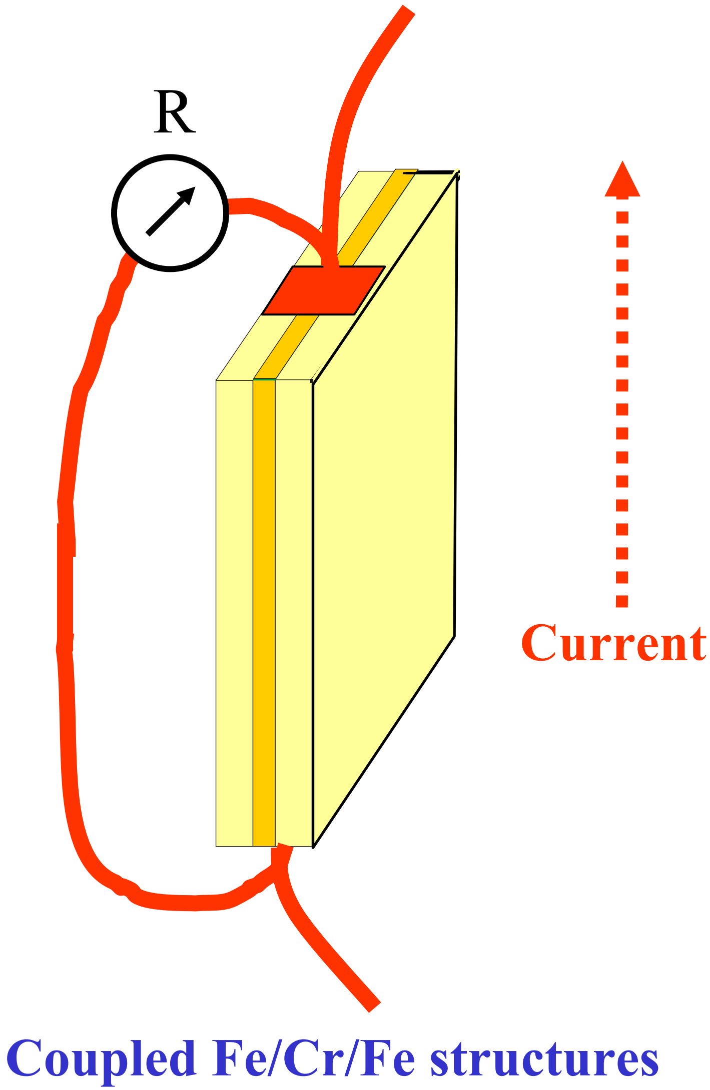

Scattering event

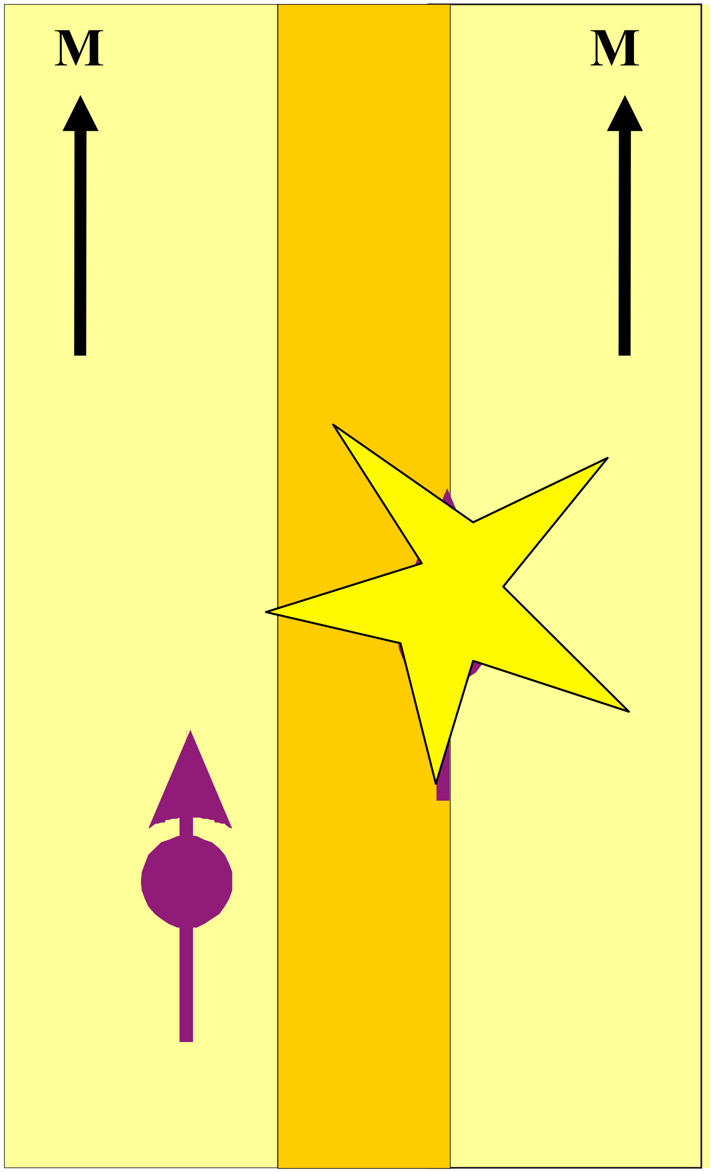


ferromagnetic alloy


Equivalent circuit

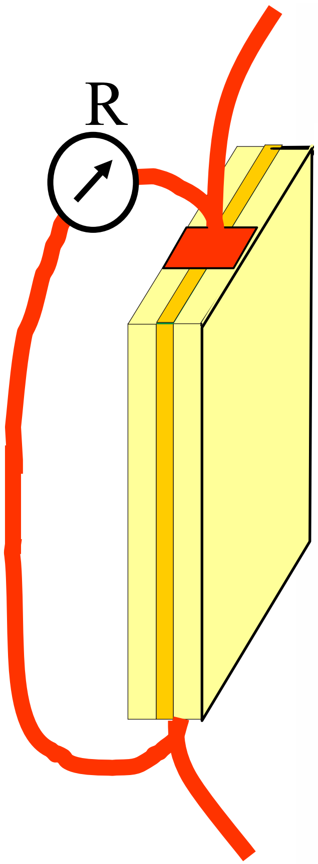
# What can we expect in magnetic multilayers?

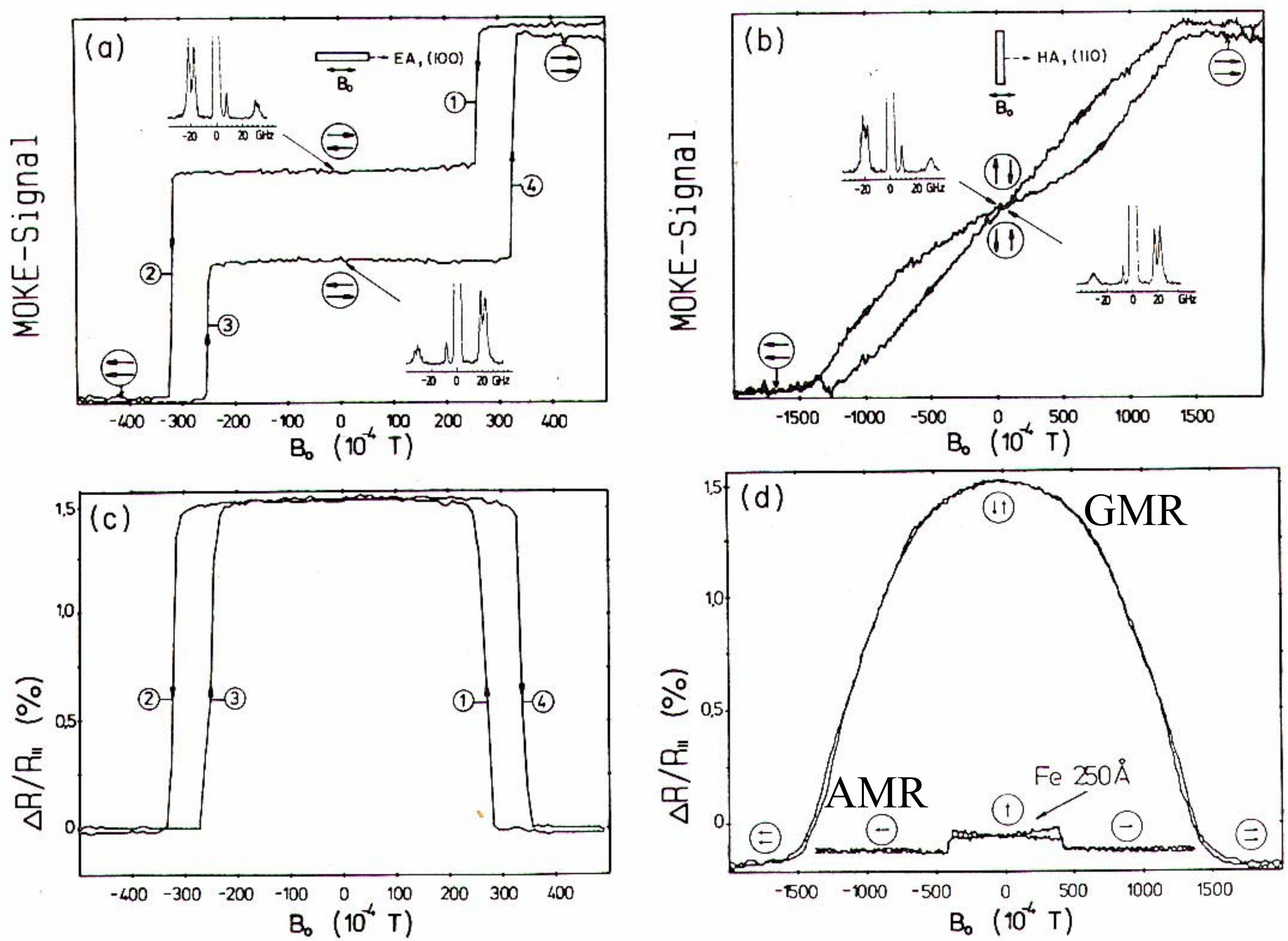


Phys. Rev. B 39, P. 4828, 1989

# First measurement of GMR




Filing a patent: april 1988

**Le Creusot, August 1988**

# First measurements of GMR in Fe/Cr/Fe

Orsay

Jülich

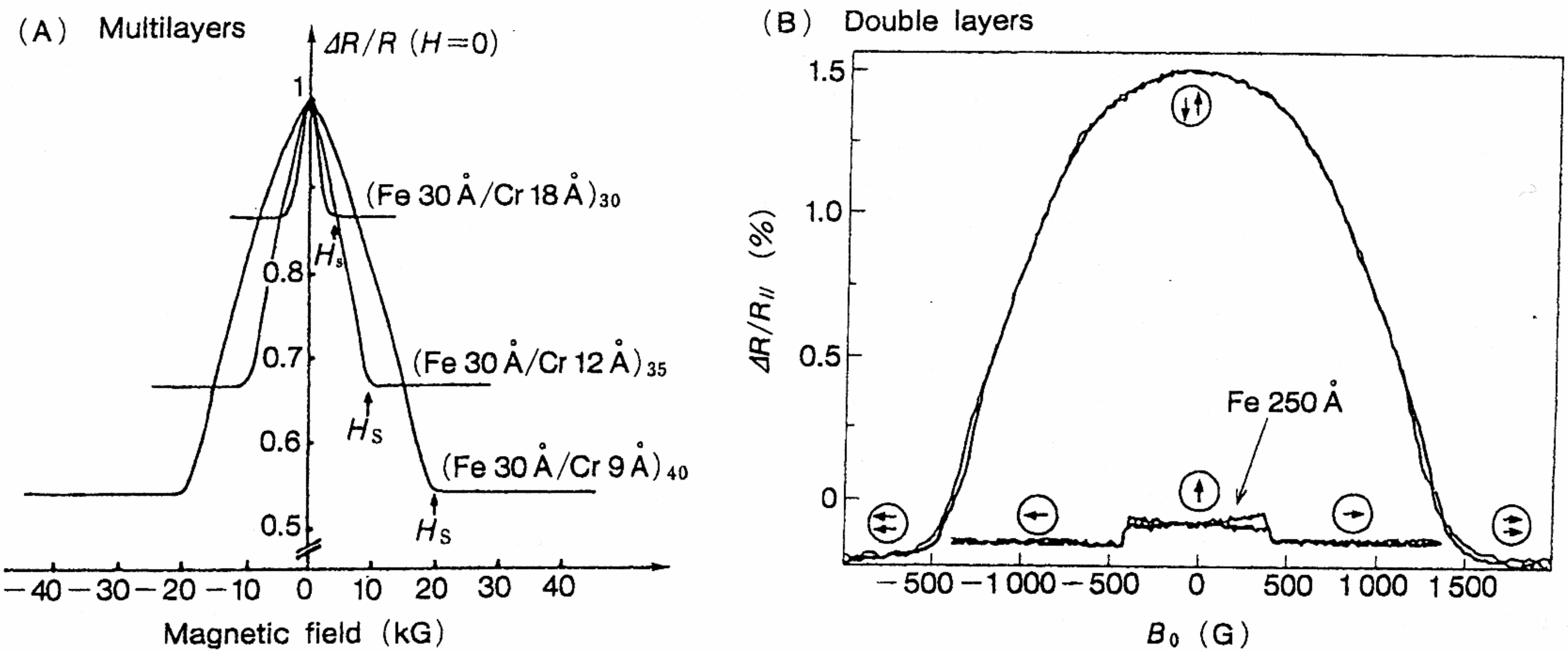



Fig. 5. GMR effect in a multilayer (A) and a double layer (B) of Fe interspaced by Cr. (B) The AMR effect in a single film of Fe with thickness 250 Å is also shown for comparison.

# 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)

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

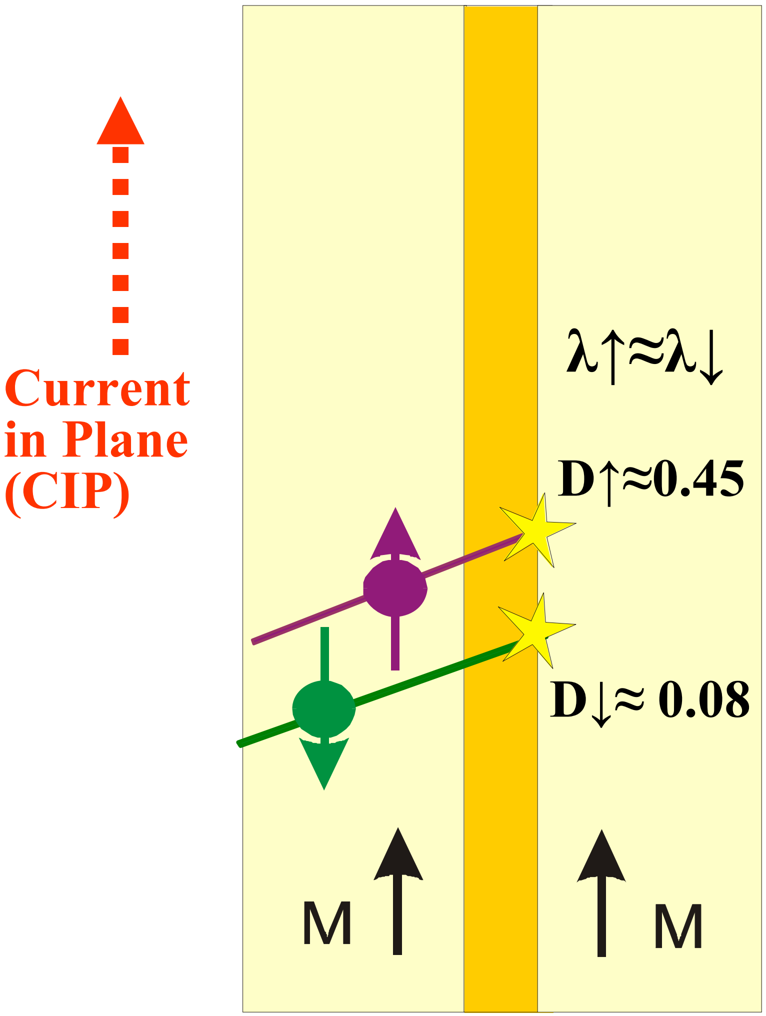
**Boltzmann transport equation: Camley-Barnas model**

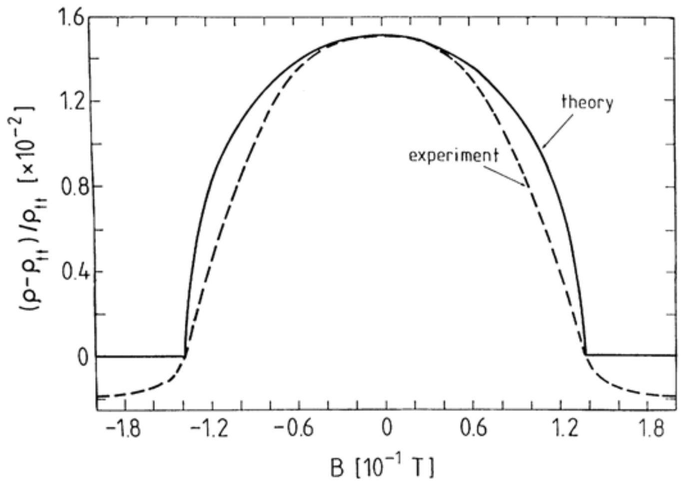
PHYSICAL REVIEW B VOLUME 42, NUMBER 13 1 NOVEMBER 1990

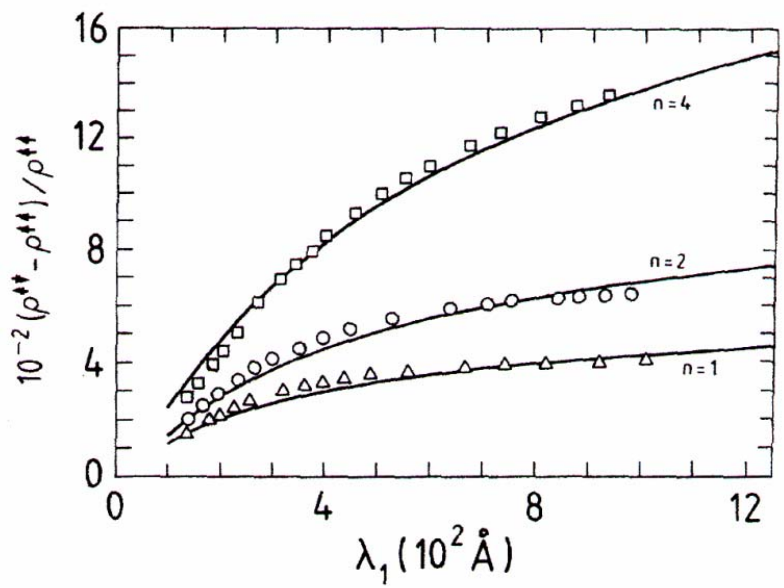
**Novel magnetoresistance effect in layered magnetic structures: Theory and experiment** page 8110

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

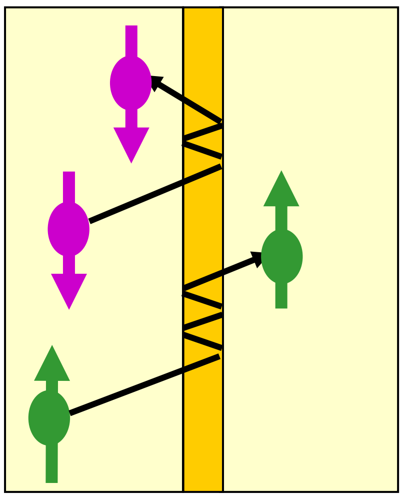
# Theory and Experiment



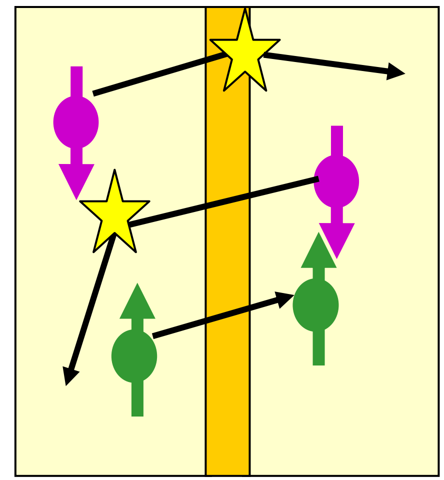



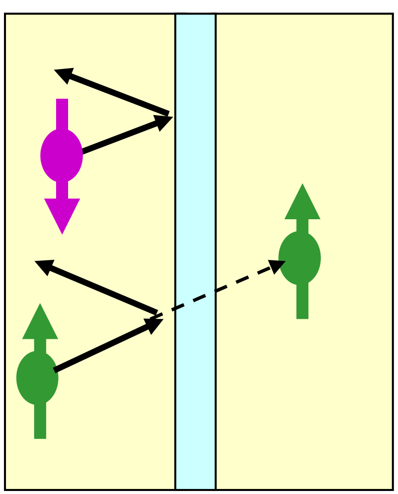
# Spin dependent transfer phenomena in layered magnetic structures



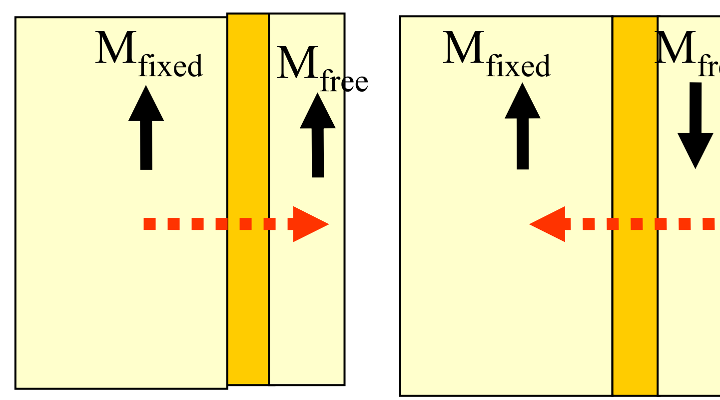
osc. Interlayer exchange coupling



Giant Magneto-resistance (GMR)



Tunnelingmagn-etoresistance (TMR)



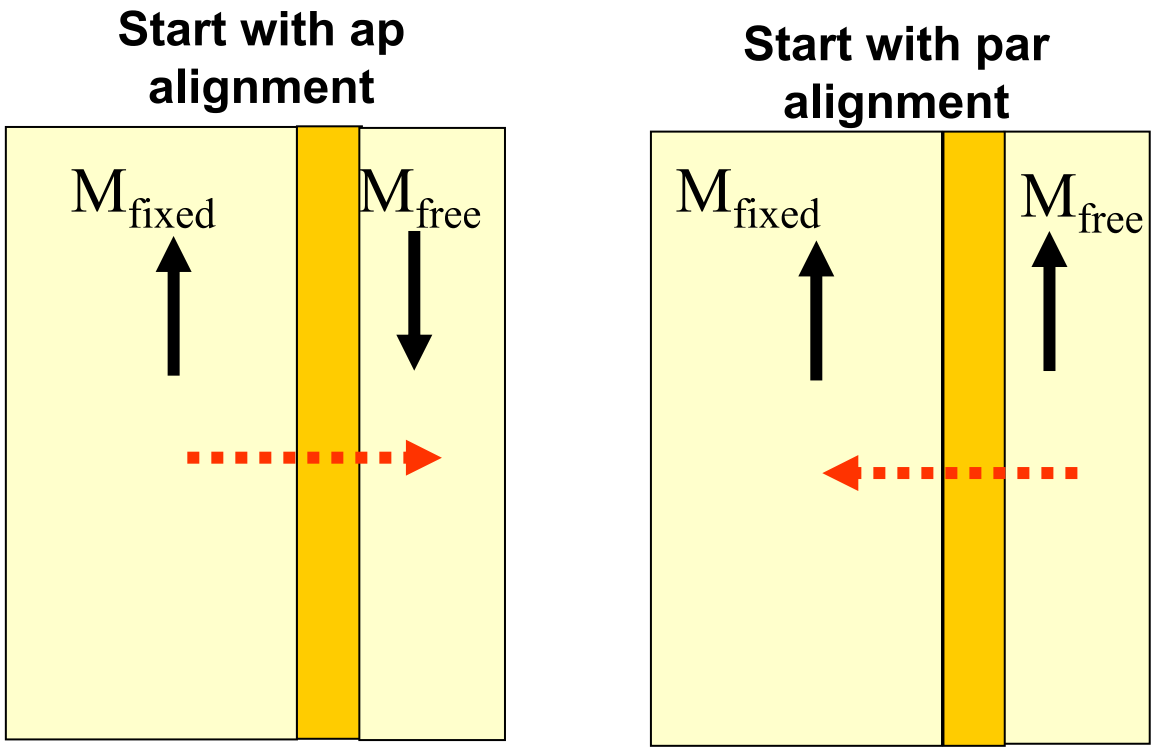

current induced magnetic excitations and switching (CIMS)

# CIMS – advanced magnetic switching concept

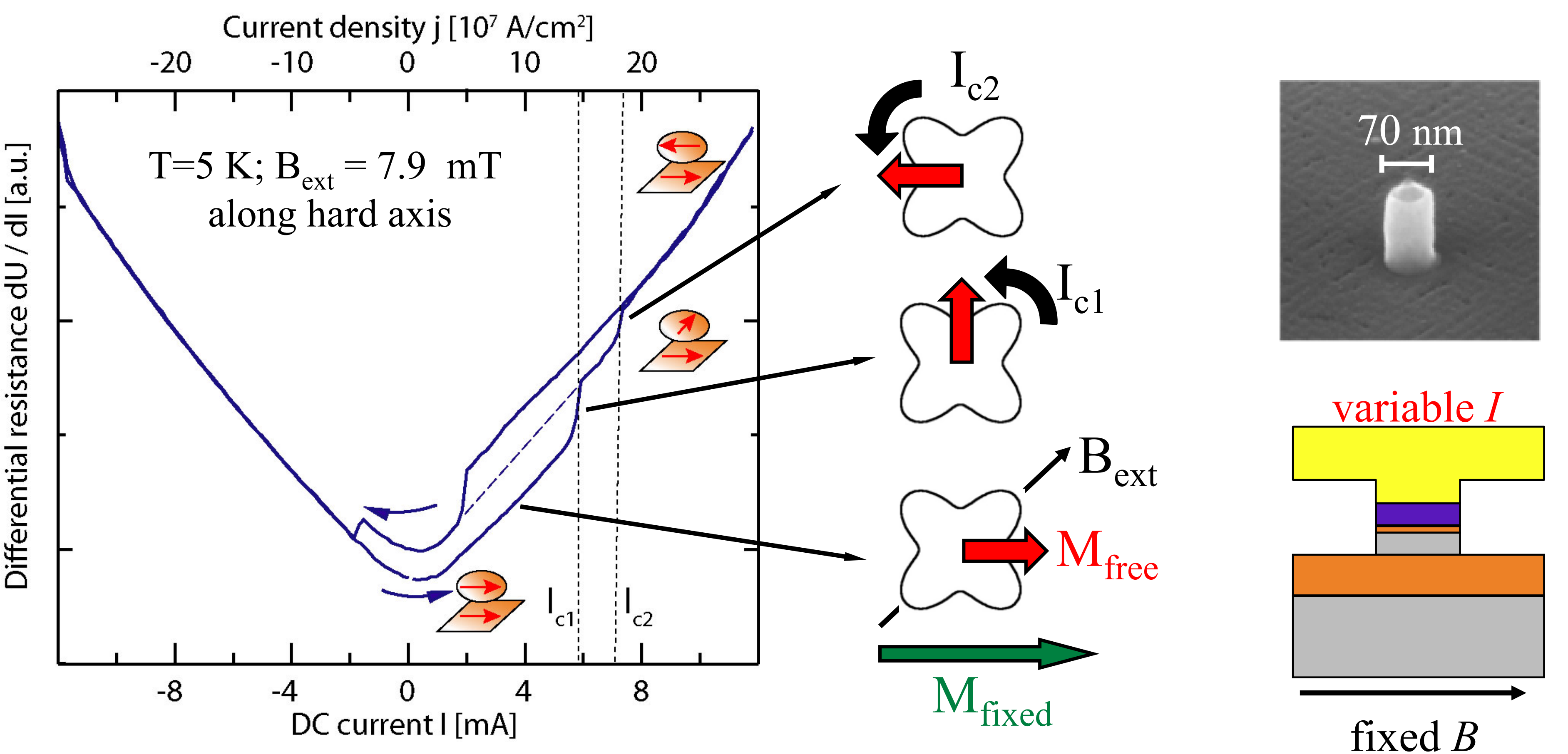
**due to spin polarized currents**

**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)**



# Two step CIMS in Fe/Ag/Fe

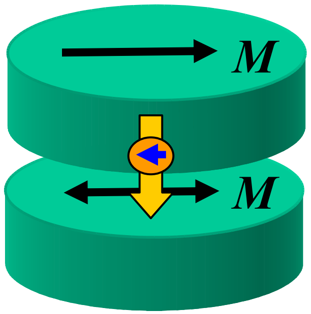



Four energetically nearly identical states give rise to two-step switching

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

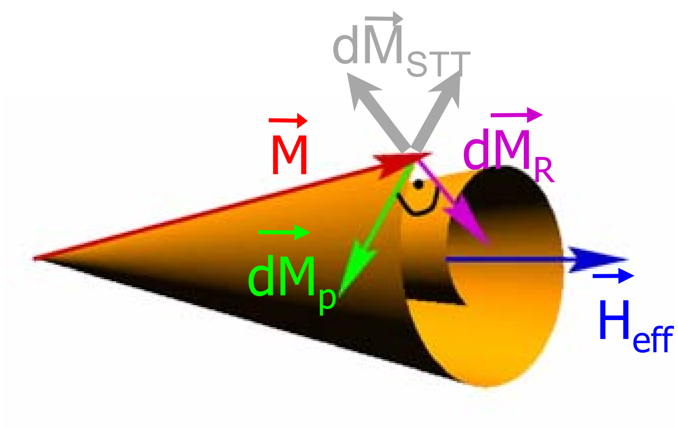
# Magnetization reversal of a thin-film element by a spin-polarized current

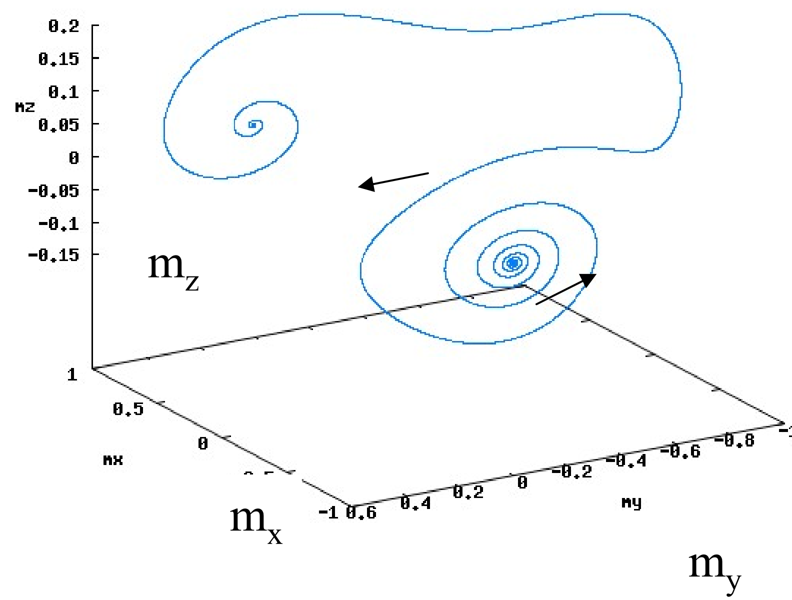
**spin-polarized electric current**




$$\frac{\mathrm{d}\boldsymbol{m}}{\mathrm{d}t} = -\gamma \boldsymbol{m} \times \boldsymbol{H}_{\mathrm{eff}} + \alpha \boldsymbol{m} \times \frac{\mathrm{d}\boldsymbol{m}}{\mathrm{d}t} + \chi \boldsymbol{m} \times (\boldsymbol{m} \times \boldsymbol{p})$$

precession — damping — spin-transfer torque

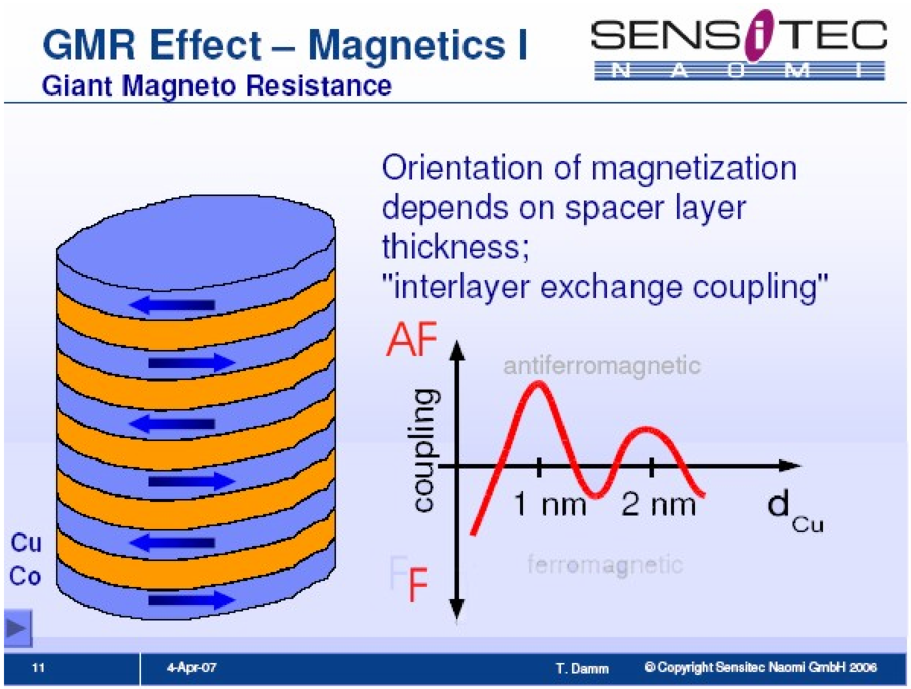


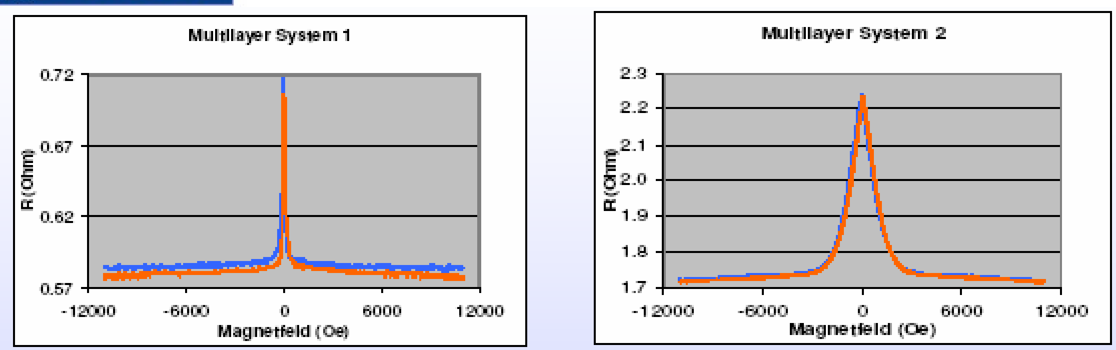

A. Kakay, R. Hertel, C.Schneider, IFF Jülich

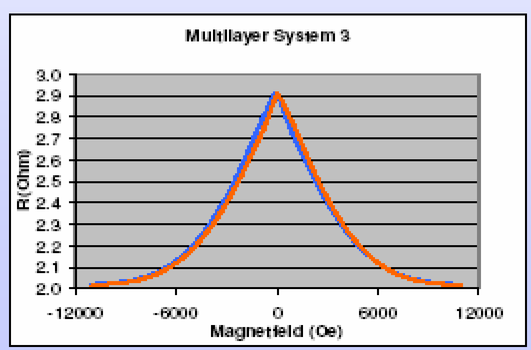
Forschungszentrum Jülich
in der Helmholtz-Gemeinschaft

# Applications




**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 |

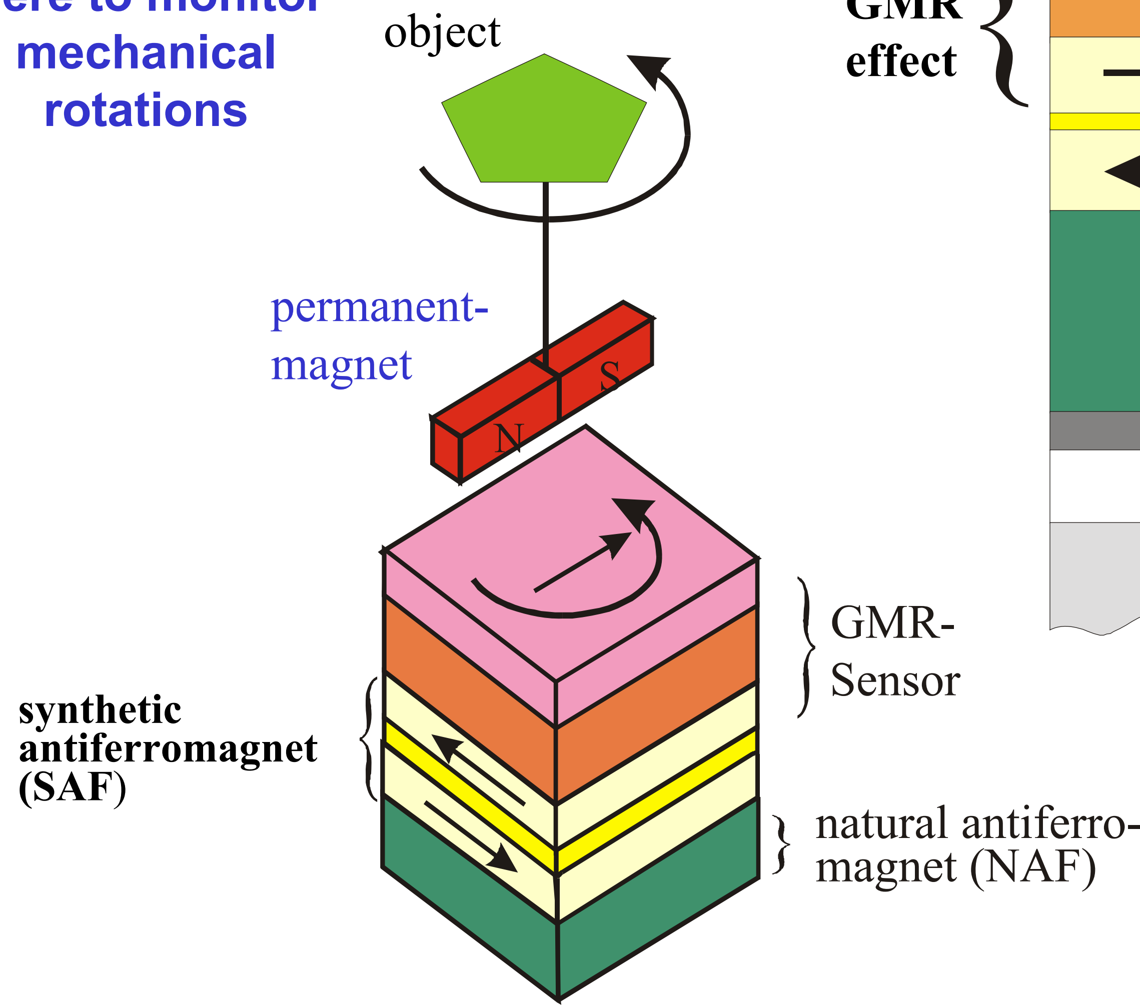
| Multilayer System 3: CoFe/Cu | | |
|---|---|---|
| H50 | dR/R | Rsq |
| 2600 | 45 | 12,5 |

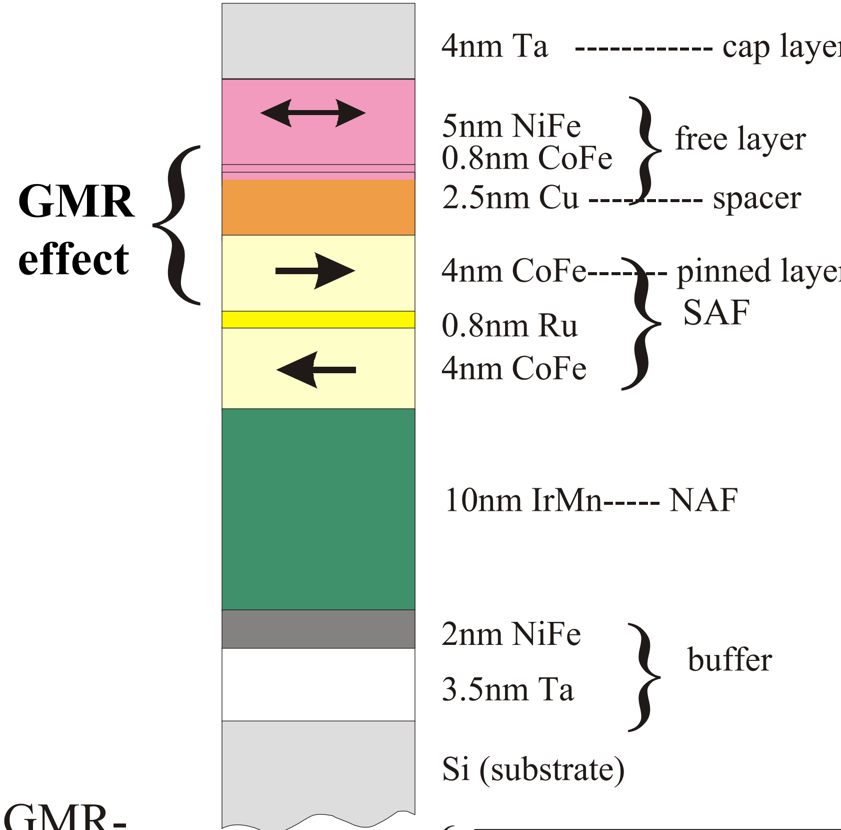
**Fig.13 working principle and data for GMR sensor with AF coupled multilayer**

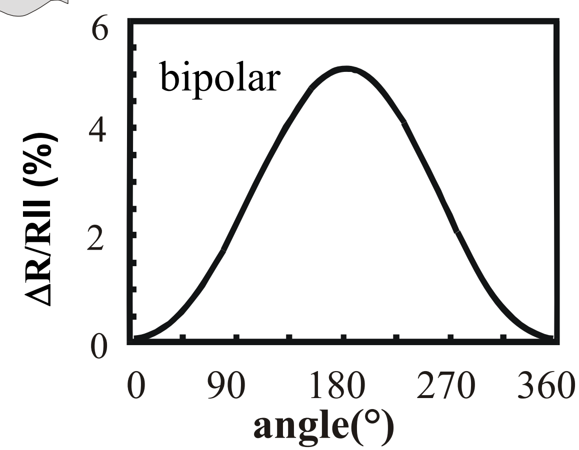
**by courtesy of NAOMI-Sensitech, Germany**

# Spinvalves

**Here to monitor mechanical rotations**

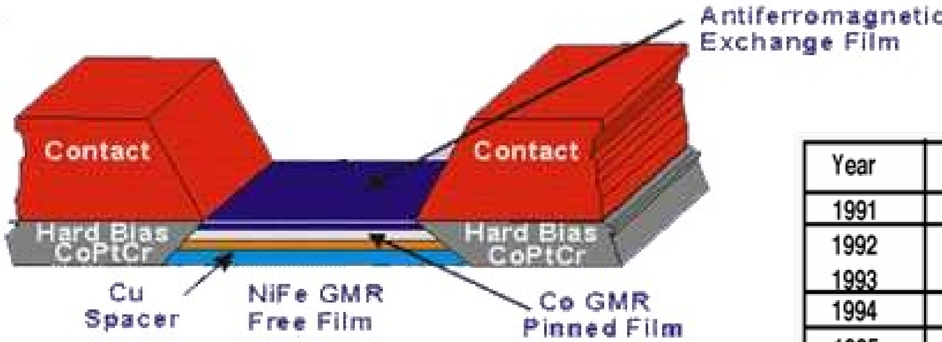



**Used in ABS- and ESP-Systems for cars**

# GMR sensors in read-heads for hard-disk drives

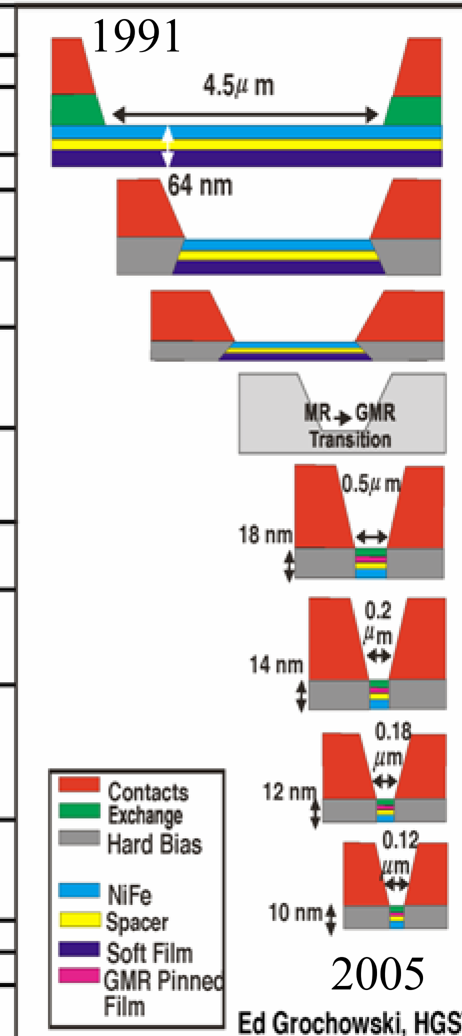




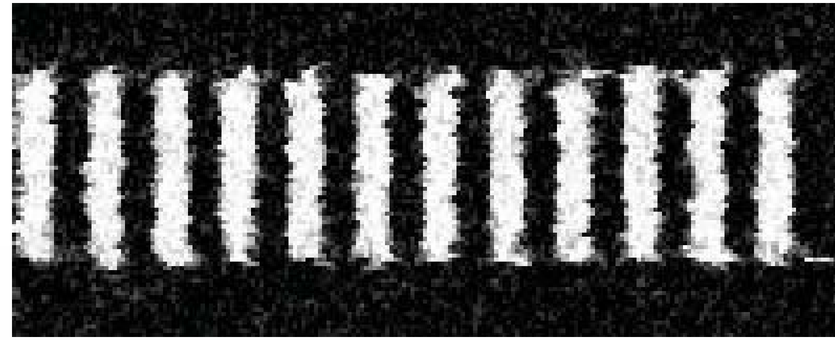
Shipment of GMR-read-heads (1997-2007):

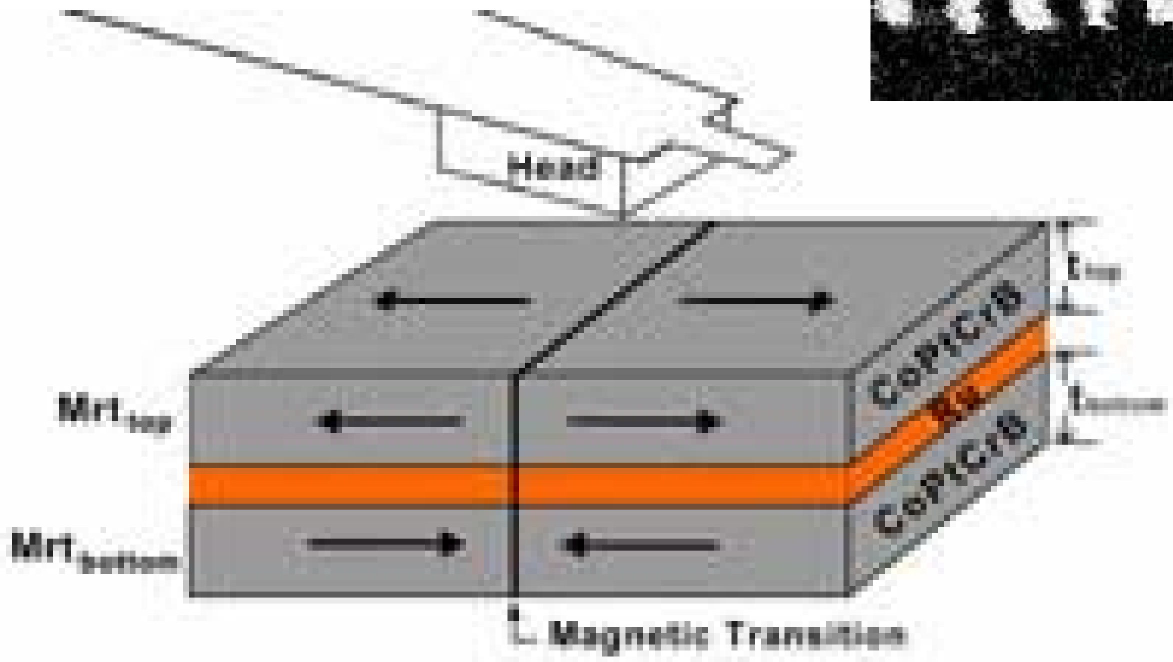
5 billion ($10^9$)

| 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 | |



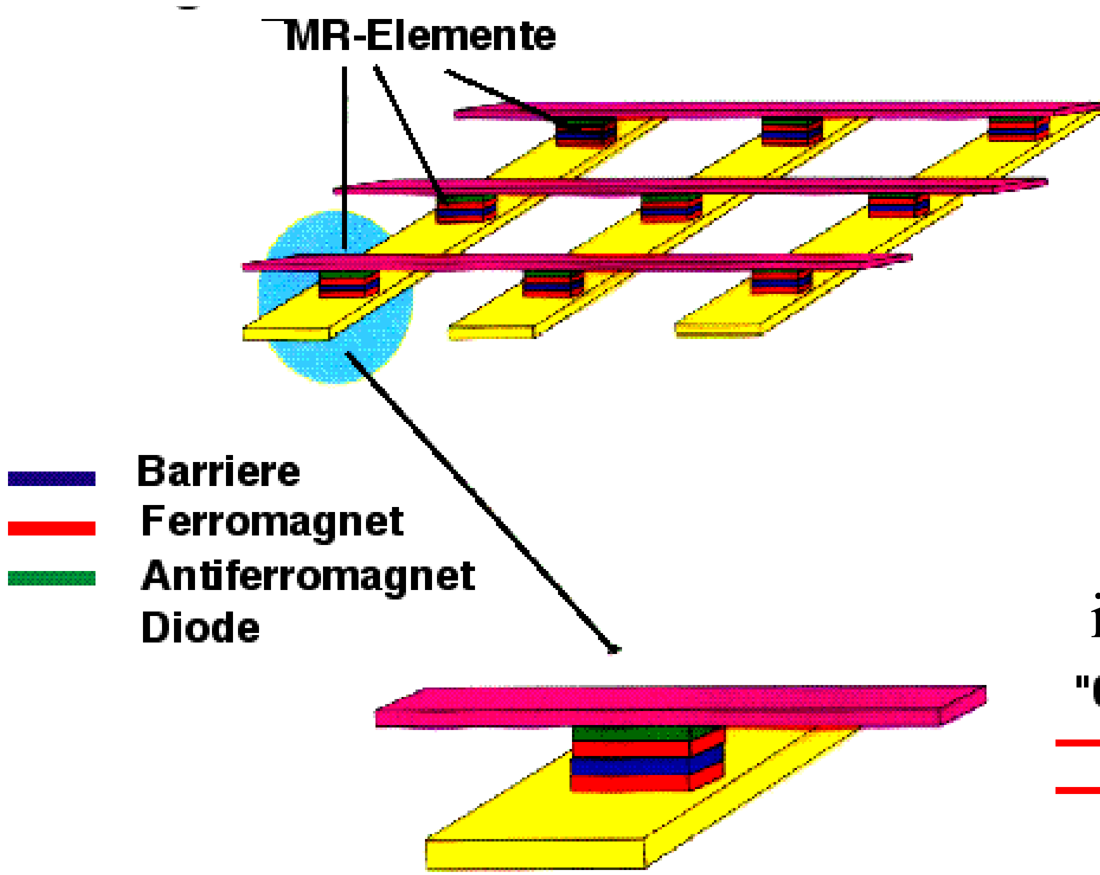
# AFC media



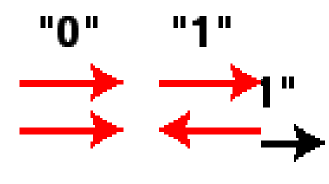



AFC stabilising magnetic domains on hard disc

# 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


most vehicles contain parts of ferromagnetic materials

→ traffic control

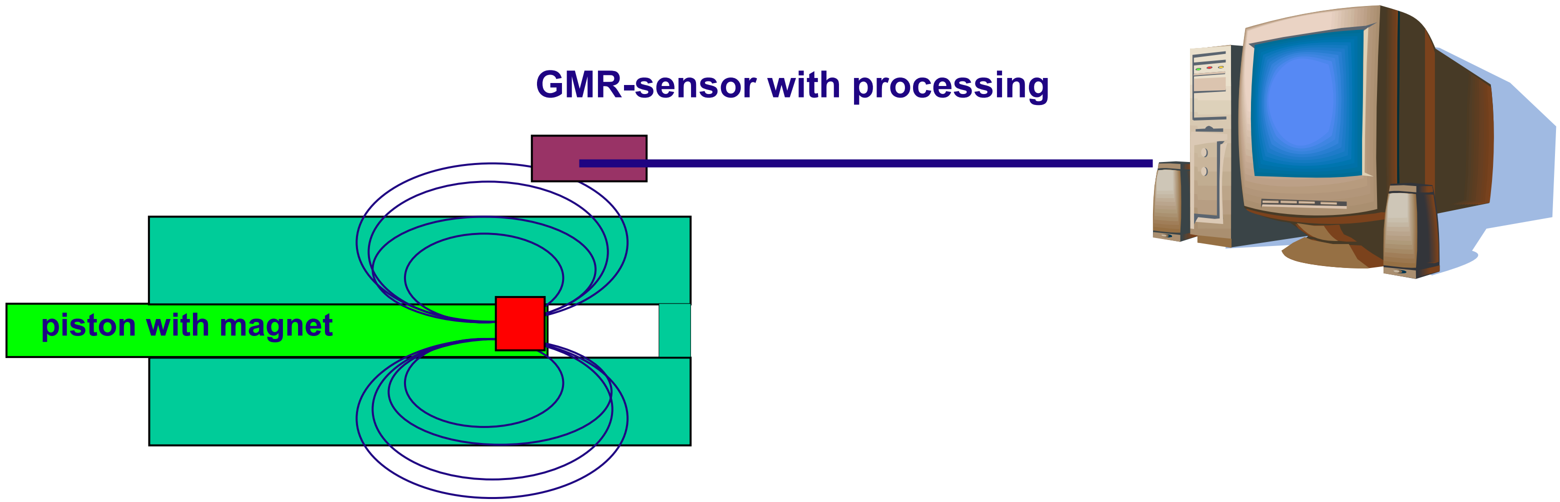
→ indicate free parking lots on a display at the entrance of parkhouses

# Spirit and Opportunity

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

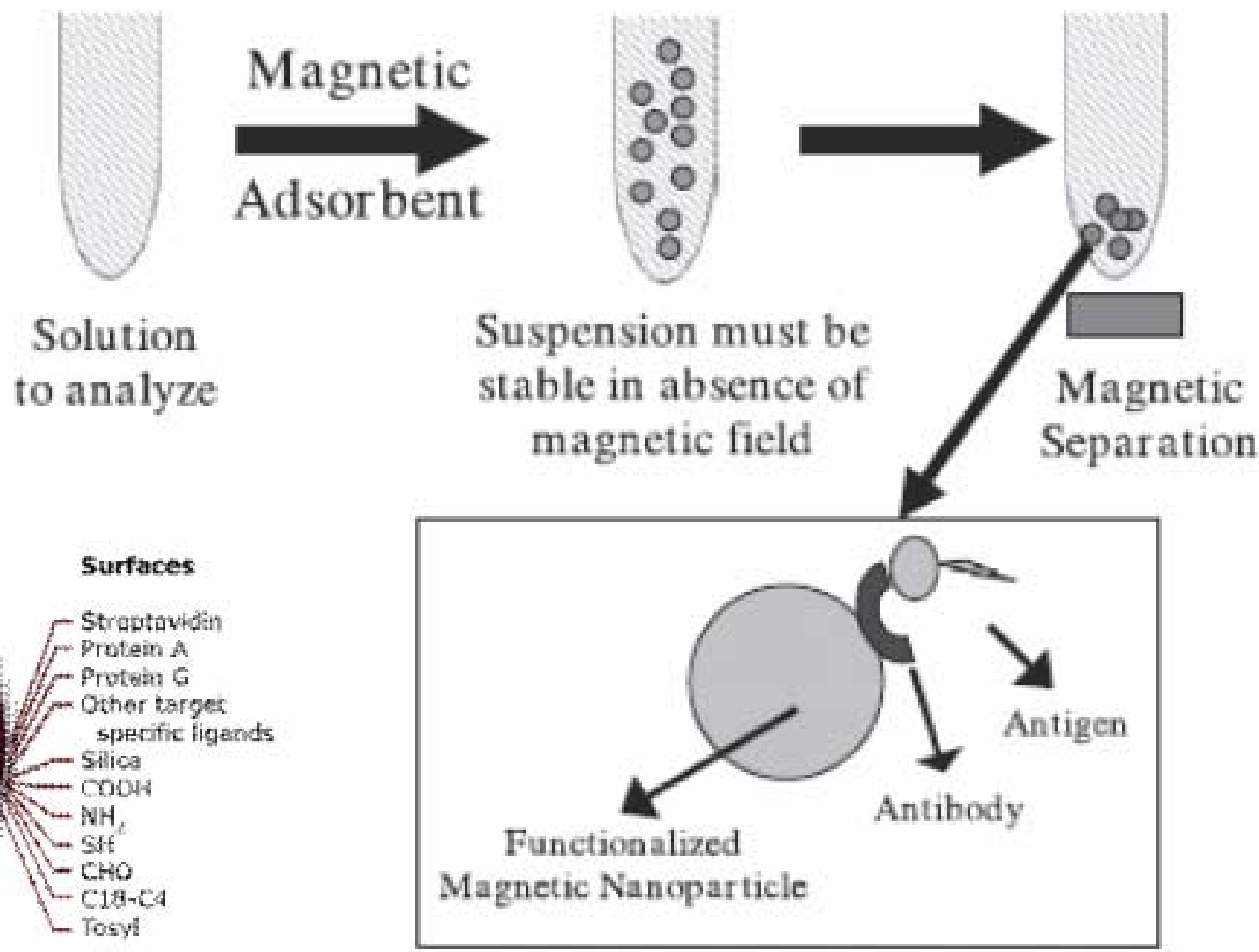
# GMR-Field Sensor Applications

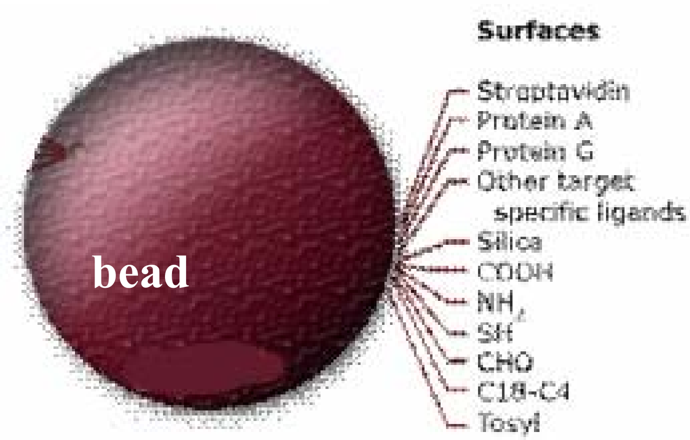
## e.g. Detection of piston end positions



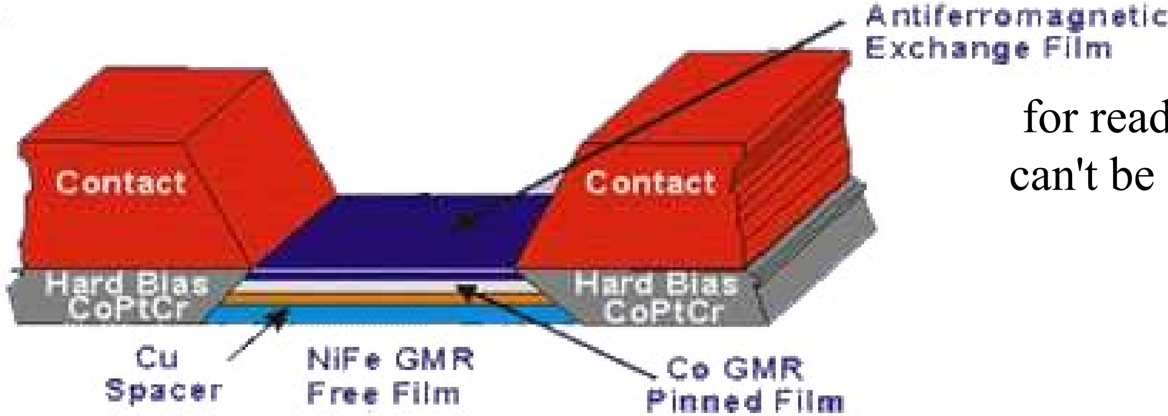

**The GMR-sensor detects - due to its high magnetic sensitivity - the position of the piston even at large distances and different cylinder diameters.**

# GMR in medicine and biology



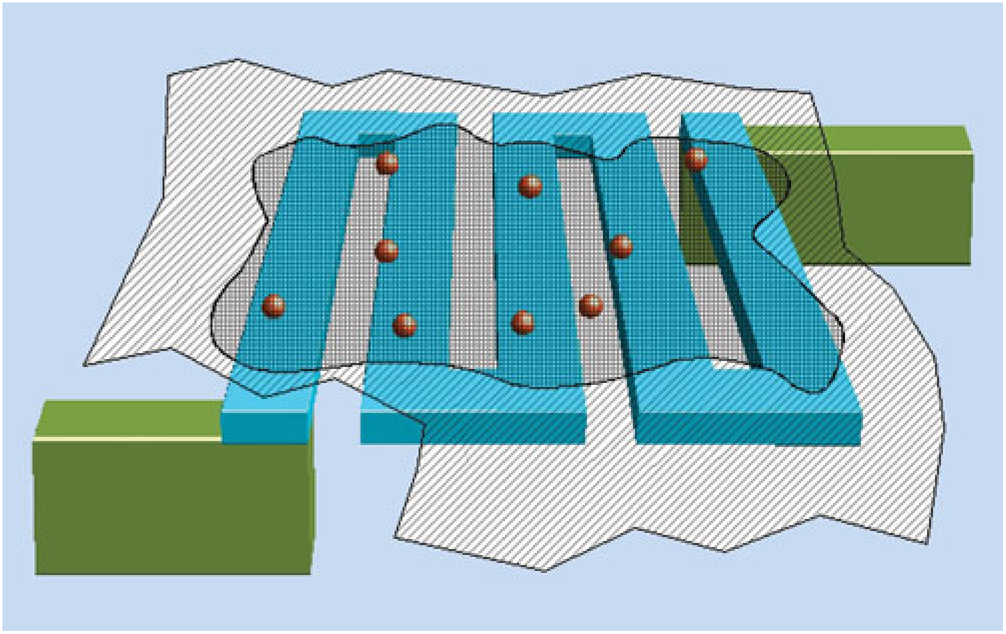



# New applications - New challenges




for read out in HDD
can't be small enough

for detecting magnetic beads:
can't be large
enough



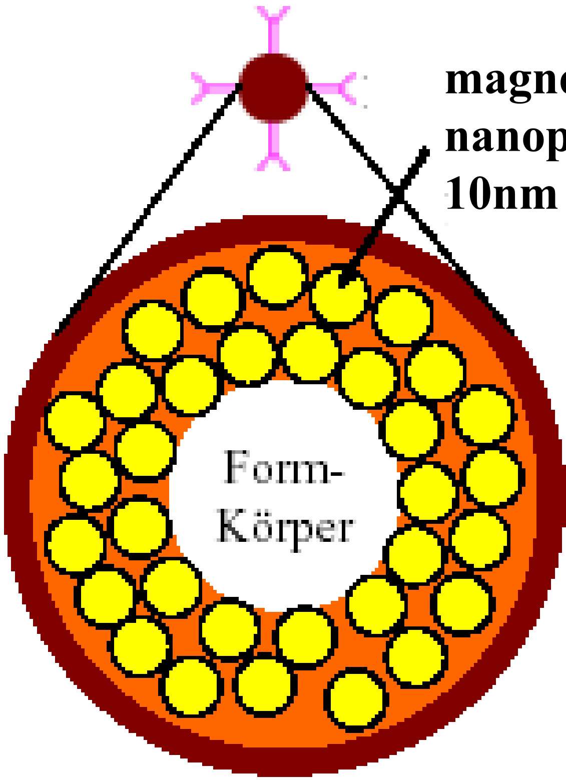
## Hydra in tbe Greek mythology: cut one head, two new grow


# Thank You

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

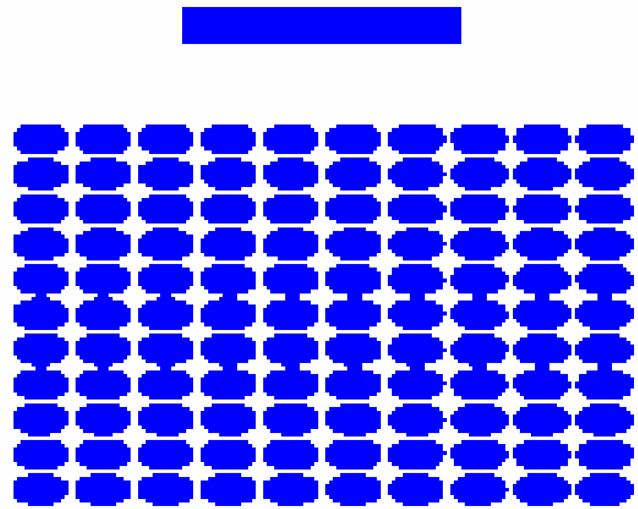
# Biosensor: important ingredients

magnetic beads 1µ




magnetic nanoparaticles 10nm

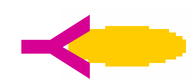
GMR- TMR-Sensor Array:
see also „MRAM“



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

antibodies
good guys

antigenes
bad guys

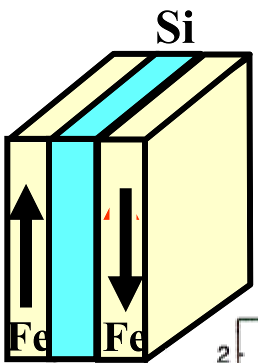


immune reaction

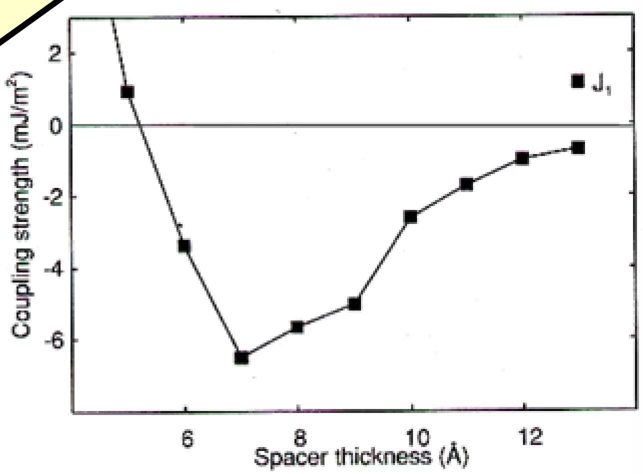
## Largest GMR values in trilayers and multi layers at room temp

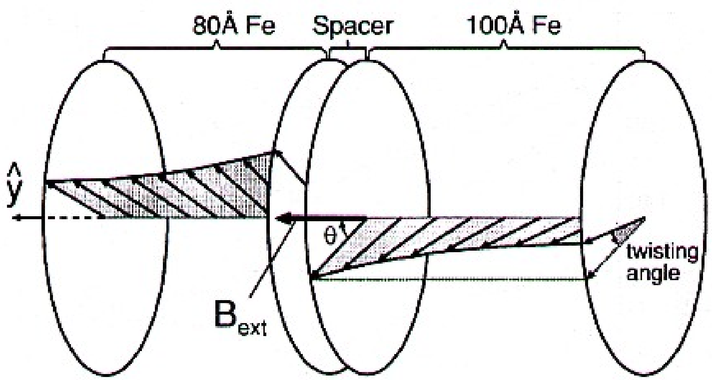
| system | GMR[%] | $t_{mag}$[nm] | ref. |
|---|---|---|---|
| Fe/Cr/Fe | 1.5 | 12 | 1) |
| Fe/Cr/Fe | 2 | 5 | 2) |
| $[Fe/Cr(1.2nm)]_{50}$ | 42 | .45 | 2) |
| Co/Au/Co | 1.8 | 10 | 1) |
| Co/Cu/Co | 2.0 | 10 | 1) |
| Fe/Cu/Fe | 0.5 | 10 | 1) |
| Co/Cu/Co | 15 | 3 | 3) |
| $[Co/Cu(0.9nm)]_{30}$ | 48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

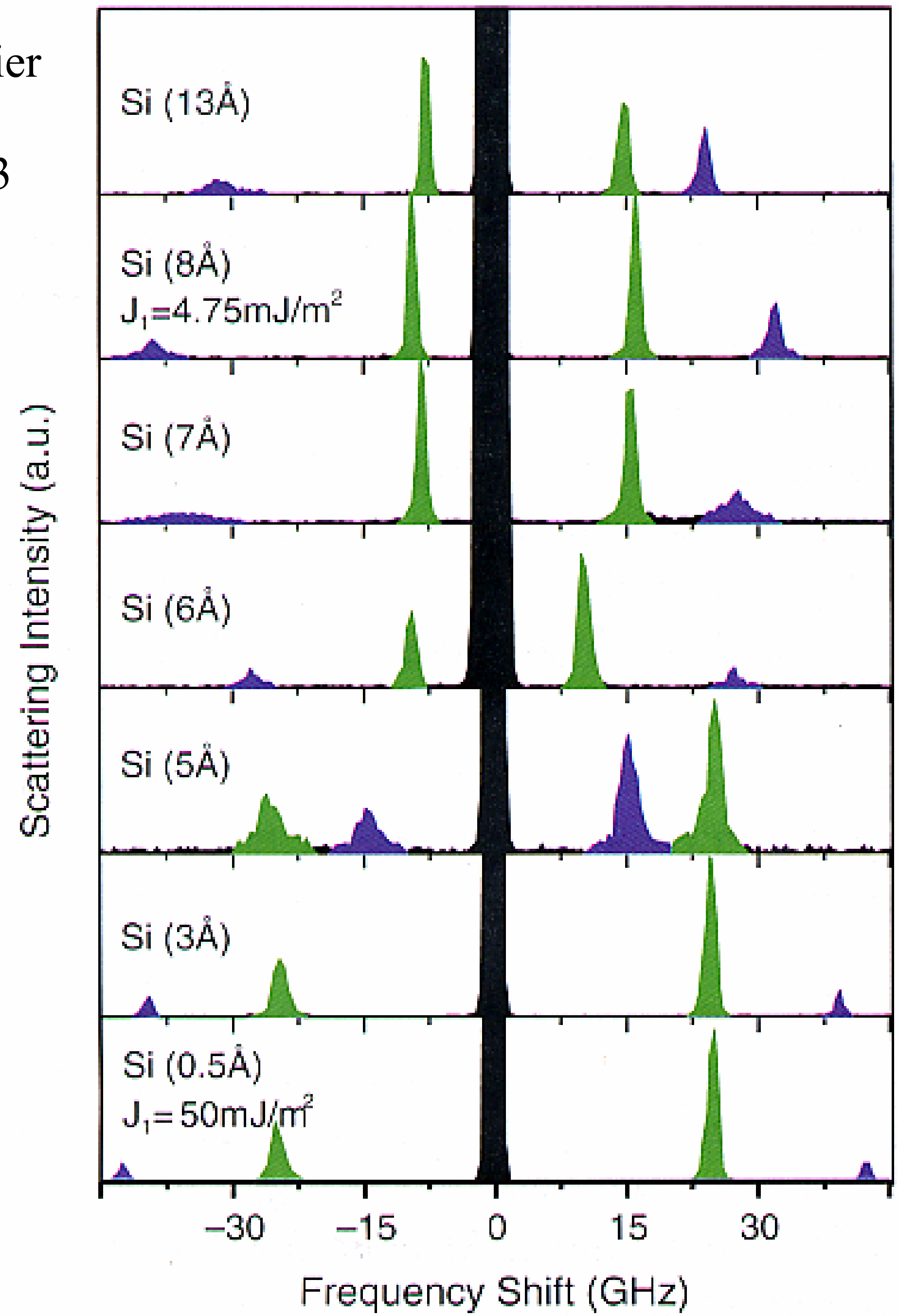



recent example: M.Buchmeier et al. PRB 67(2003)184404 and phD thesis, Juelich 2003



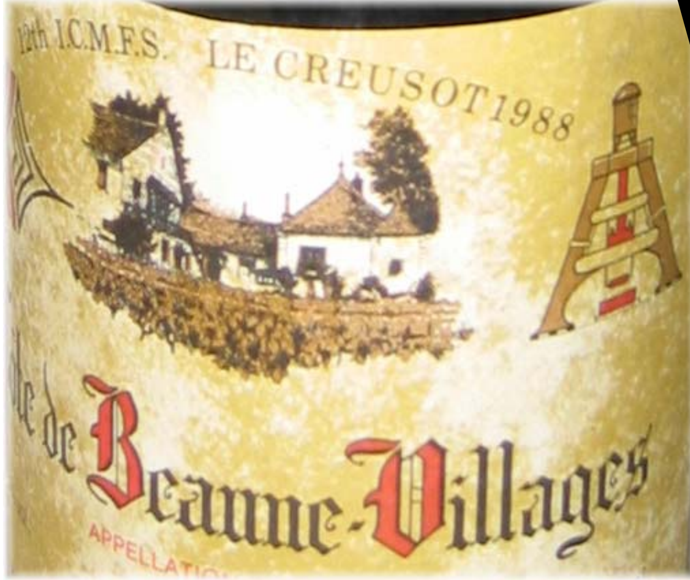

evaluation includes twisting of magnetization in the Fe films



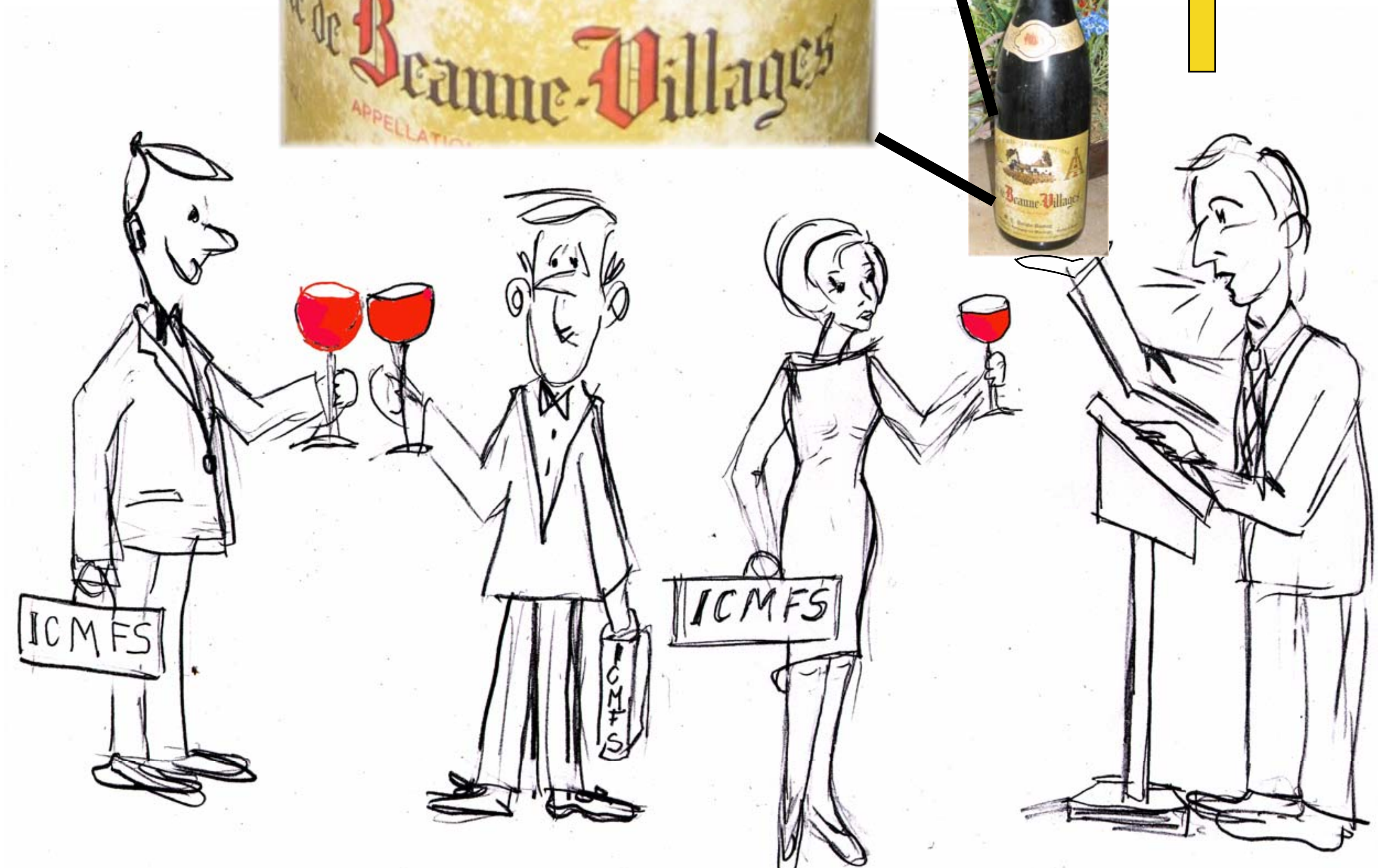
| Structure | Interlayer thickness [nm] | Coupling strength [mJ/$m^2$] | Reference |
|---|---|---|---|
| Fe/MgO/Fe | 0.5 | -0.26 | [12] |
| Fe/Si/Fe | 0.6 | -6.2 | [11] |
| Co/Ru/Co | <0.9 | -5 | [50] |
| Fe/Cr/Fe | 0.5 | -1.6 | [51] |

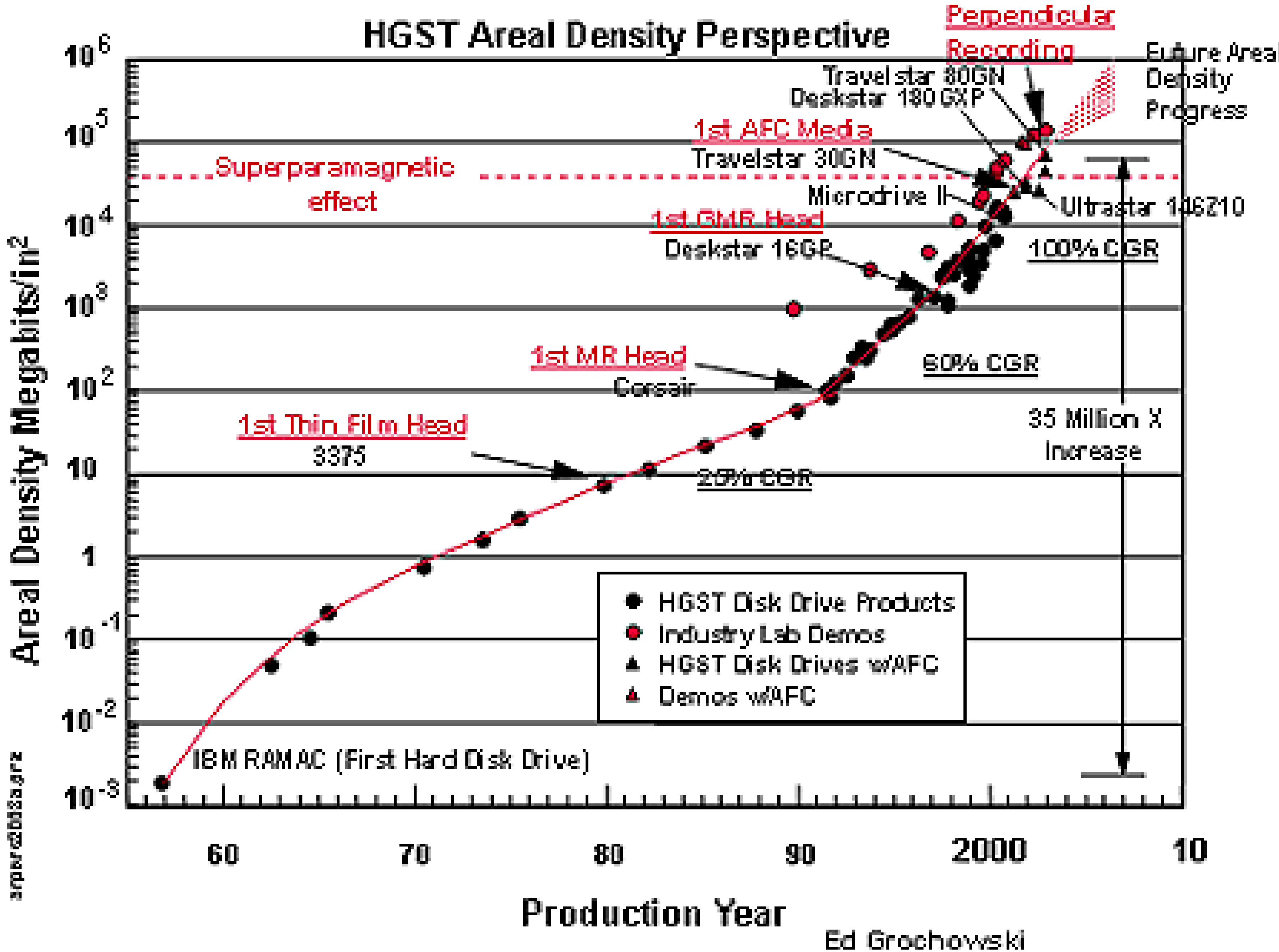
Table 1: Comparison of interlayer coupling strengths for some structures with insulating, semiconducting, and metallic interlayers.

Le Creusot 1988




Europe




HGST Areal Density Perspective
Perpendicular Recording
Future Areal Density Progress
Travelstar 80GN
Deskstar 180GXP
1st AFC Media
Travelstar 30GN
Superparamagnetic effect
Microdrive II
Ultrastar 146Z10
1st GMR Head
Deskstar 16GP
100% CGR
1st MR Head
Corsair
60% CGR
35 Million X Increase
1st Thin Film Head
3375
25% CGR
HGST Disk Drive Products
Industry Lab Demos
HGST Disk Drives w/AFC
Demos w/AFC
IBM RAMAC (First Hard Disk Drive)
Areal Density Megabits/in²
Production Year
60
70
80
90
2000
10
Ed Grochowski