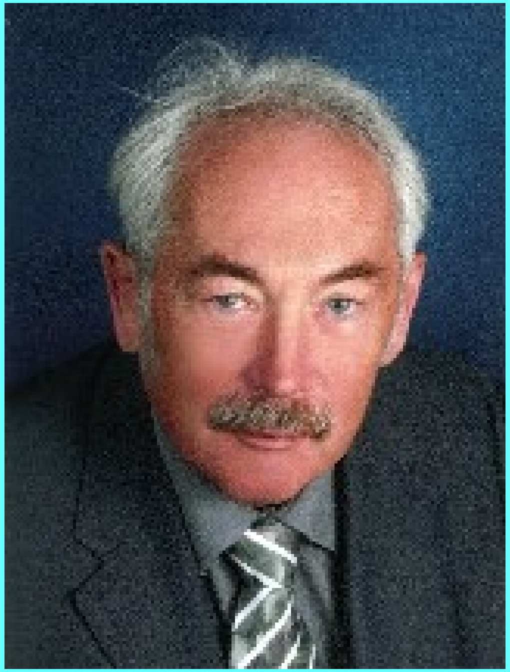
J Barnaś, Wydział Fizyki UAM w Poznaniu

Gigantyczny magnetoopór: Nagroda Nobla 2007 dla Alberta Ferta i Petera Grunberga

"for the discovery of Giant Magnetoresistance"

Peter Grunberg
Research Center
Julich



Albert Fert,
Universite Paris Sud,
CNRS/Thales

http://motls.blogspot.com/2007/10/physics-nobel-prize-2007.html

PHYSICAL REVIEW B VOLUME 39, NUMBER 7 1 MARCH 1989

Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange

G. Binasch, P. Grünberg, F. Saurenbach, and W. Zinn
Institut für Festkörperforschung, Kernforschungsanlage Jülich G.m.b.H., Postfach 1913, D-5170 Jülich, West Germany
(Received 31 May 1988; revised manuscript received 12 December 1988)

The electrical resistivity of Fe-Cr-Fe layers with antiferromagnetic interlayer exchange increases when the magnetizations of the Fe layers are aligned antiparallel. The effect is much stronger than the usual anisotropic magnetoresistance and further increases in structures with more than two Fe layers. It can be explained in terms of spin-flip scattering of conduction electrons caused by the antiparallel alignment of the magnetization.

VOLUME 61, NUMBER 21 PHYSICAL REVIEW LETTERS 21 NOVEMBER 1988

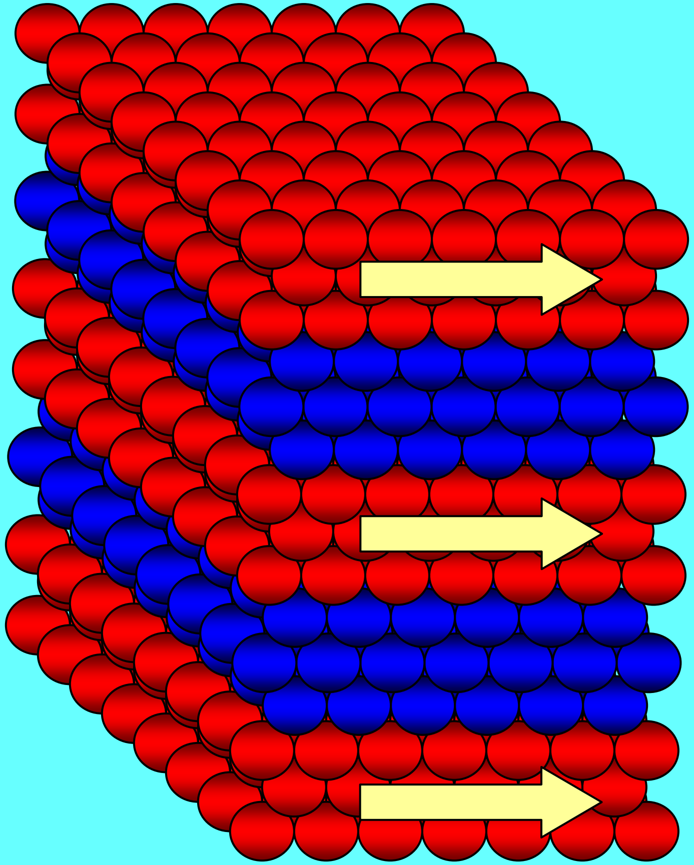
Giant Magnetoresistance of (001) Fe/(001) Cr Magnetic Superlattices

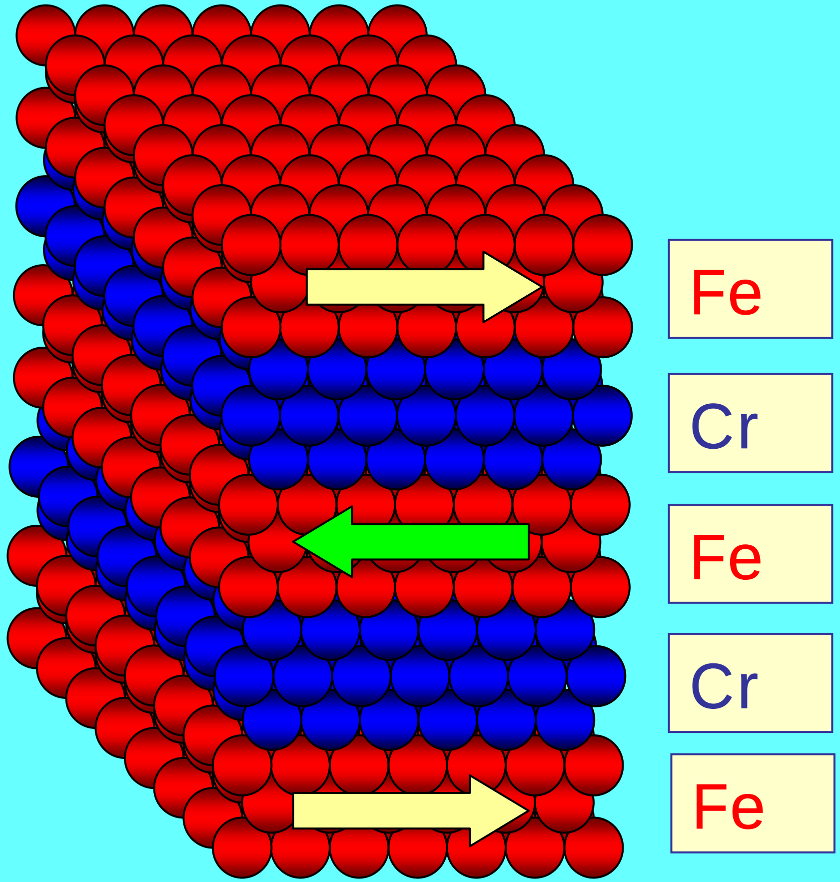
M. N. Baibich,[a] J. M. Broto, A. Fert, F. Nguyen Van Dau, and F. Petroff
Laboratoire de Physique des Solides, Université Paris-Sud, F-91405 Orsay, France

P. Eitenne, G. Creuzet, A. Friederich, and J. Chazelas
Laboratoire Central de Recherches, Thomson CSF, B.P. 10, F-91401 Orsay, France
(Received 24 August 1988)

We have studied the magnetoresistance of (001)Fe/(001)Cr superlattices prepared by molecular-beam epitaxy. A huge magnetoresistance is found in superlattices with thin Cr layers: For example, with $t_{Cr}=9$ Å, at $T=4.2$ K, the resistivity is lowered by almost a factor of 2 in a magnetic field of 2 T. We ascribe this giant magnetoresistance to spin-dependent transmission of the conduction electrons between Fe layers through Cr layers.

Struktury warstwowe Fe/Cr (P. Grunberg & A. Fert)





From A Fert

$H > H_s$

$H = 0$

VOLUME 57, NUMBER 19 PHYSICAL REVIEW LETTERS 10 NOVEMBER 1986

Layered Magnetic Structures: Evidence for Antiferromagnetic Coupling of Fe Layers across Cr Interlayers

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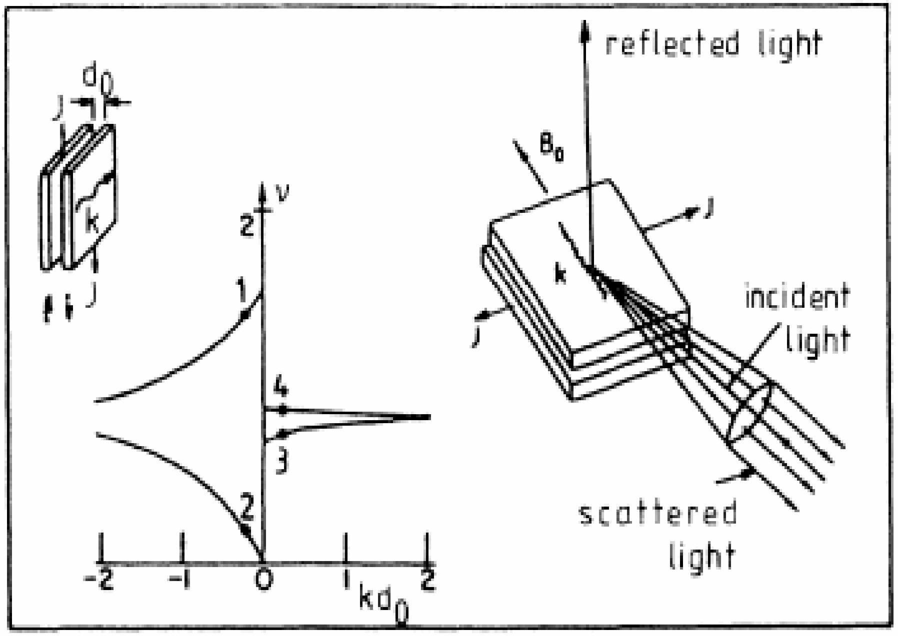
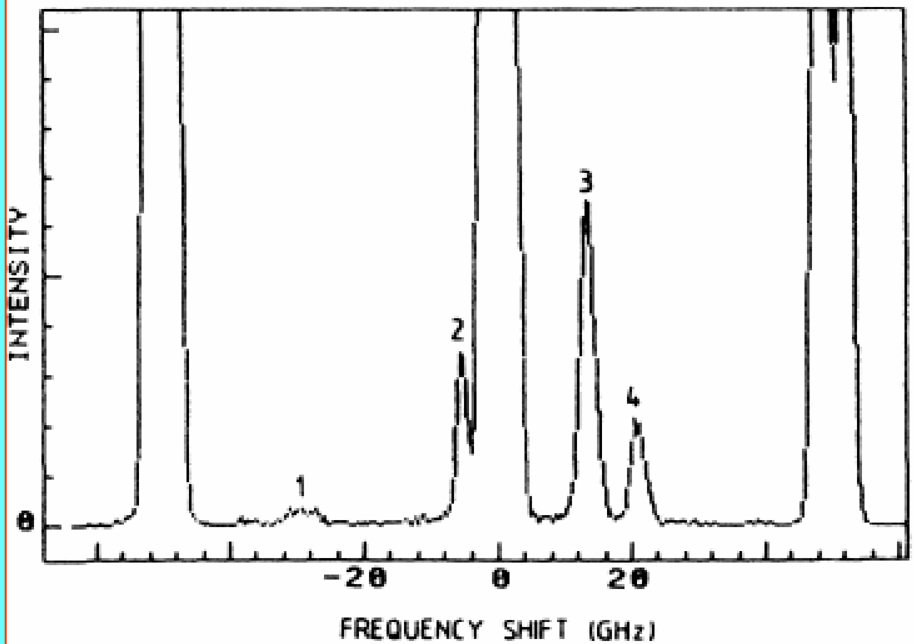
and

M. B. Brodsky and H. Sowers
Argonne National Laboratory, Argonne, Illinois 60439

(Received 10 June 1986)



(a)



(b)

PHYSICAL REVIEW B VOLUME 39, NUMBER 16 1 JUNE 1989

Effect of interlayer exchange coupling on spin-wave spectra in magnetic double layers: Theory and experiment

M. Vohl, J. Barnaś,* and P. Grünberg
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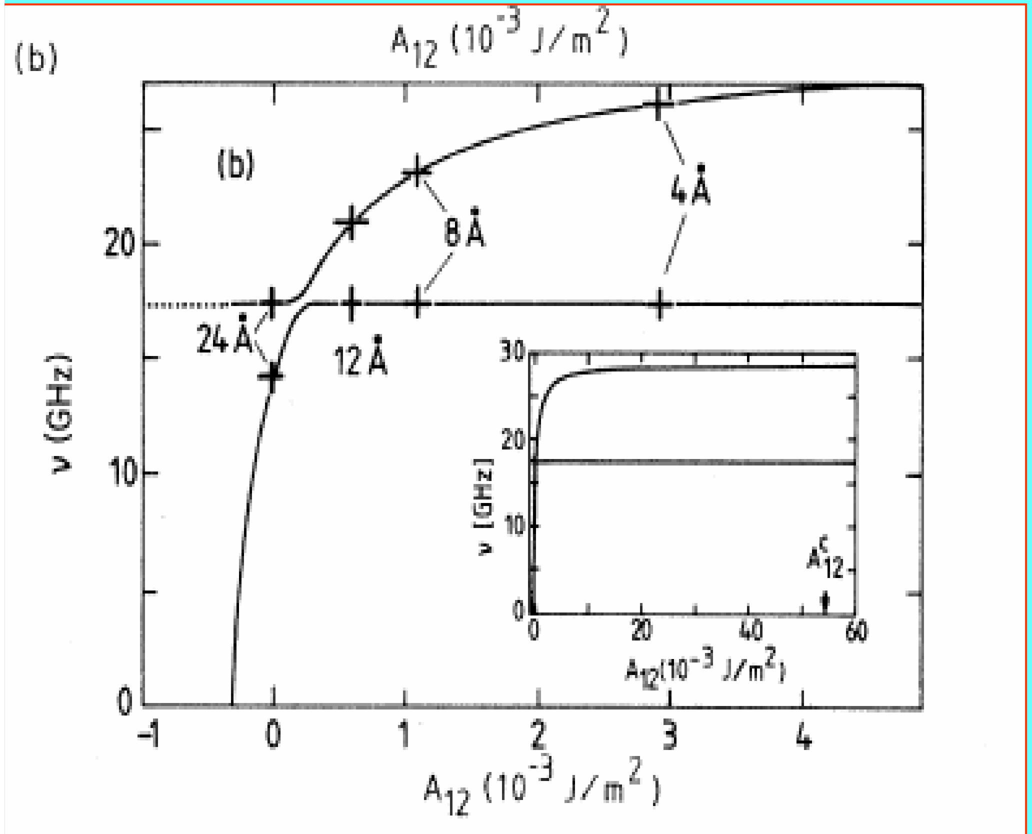
(Received 9 January 1989)



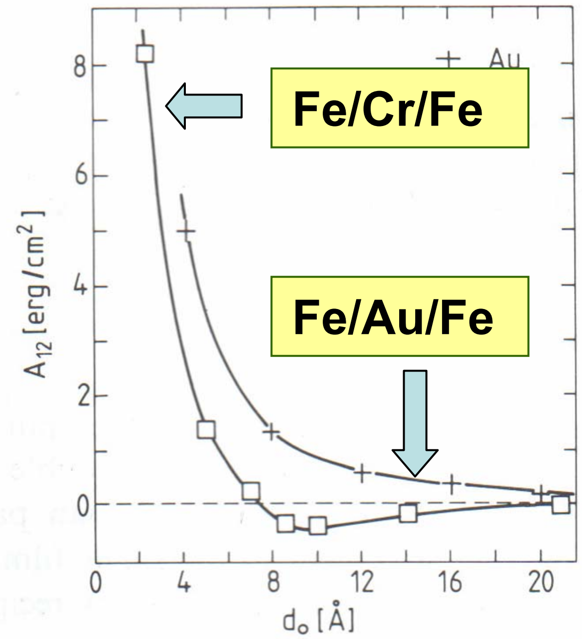
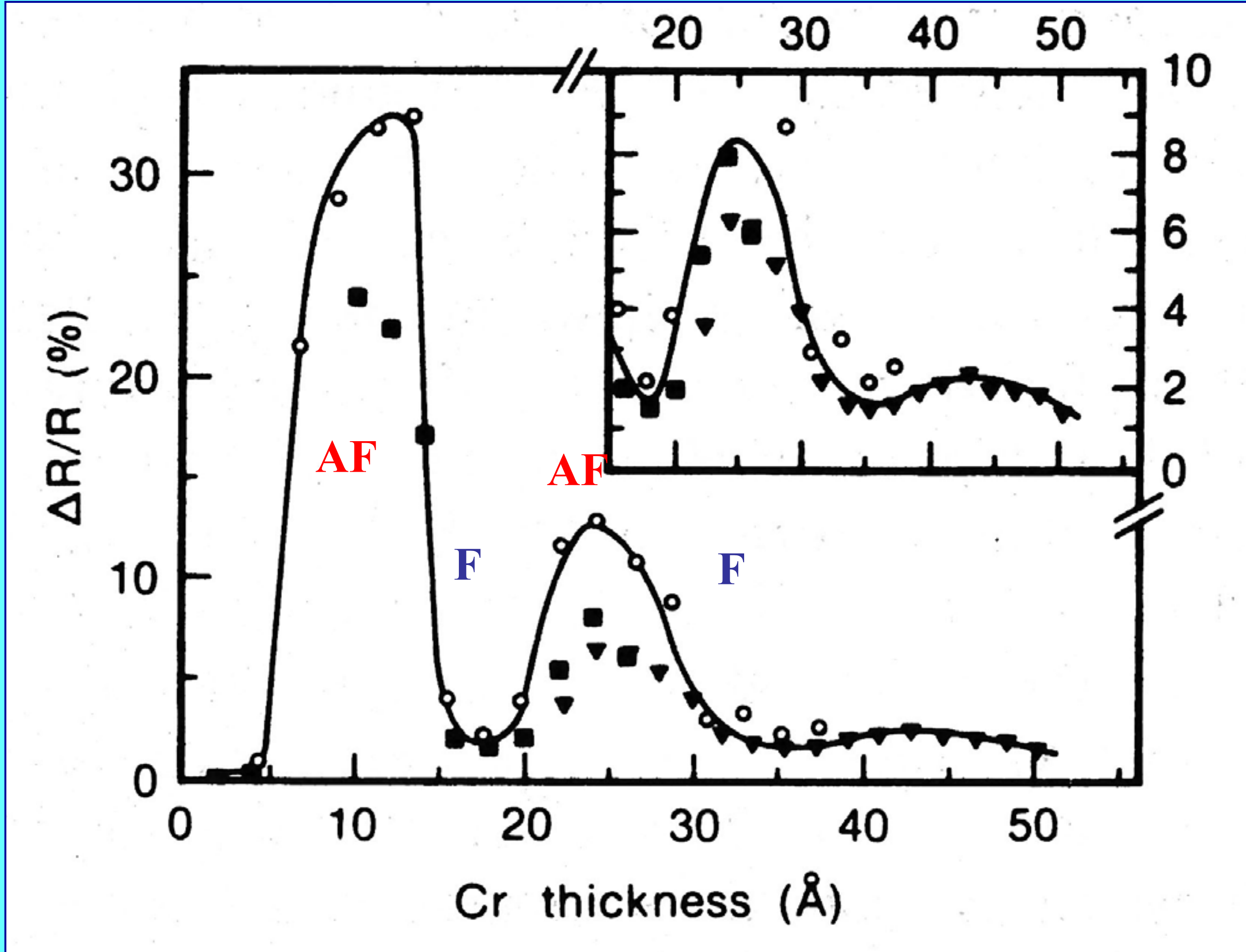


Fig. 6. The d_0 dependence of the interlayer exchange constant A_{12} for Fe/Au/Fe and Fe/Cr/Fe structures analyzed in this paper.

J Barnaś & P Grunberg, JMMM 1990

Oscylacje oddziaływania wymiennego z grubością warstwy niemagnetycznej (Fe/Cr)



S. S. P. Parkin, et al, Phys. Rev. Lett. **64**, 2304 (1990)

J. Appl. Phys. 76 (10), 15 November 1994

Magnetoresistance and magnetization oscillations in Fe/Cr/Fe trilayers

R. Schad, C. D. Potter, P. Beliën, G. Verbanck, V. V. Moshchalkov, and Y. Bruynseraede
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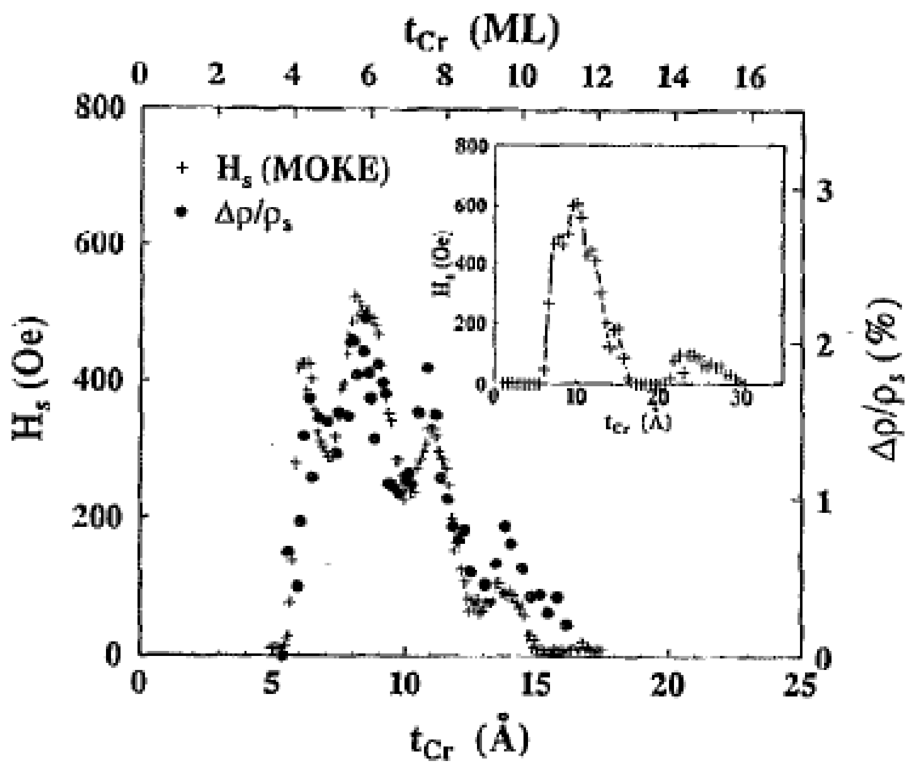
M. Schäfer, R. Schäfer, and P. Grünberg
IFF-FZ, Kernforschungsanlage Jülich, Postfach 1913, D-52425 Jülich, Germany



W strukturach metali przejściowych występują najczęściej dwa periody: krótki (około dwóch płaszczyzn atomowych) i długi (rzędu 5-10 płaszczyzn)

PHYSICAL REVIEW B VOLUME 39, NUMBER 7 1 MARCH 1989

Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange

G. Binasch, P. Grünberg, F. Saurenbach, and W. Zinn

Institut für Festkörperforschung, Kernforschungsanlage Jülich G.m.b.H., Postfach 1913, D-5170 Jülich, West Germany

(Received 31 May 1988; revised manuscript received 12 December 1988)

The electrical resistivity of Fe-Cr-Fe layers with antiferromagnetic interlayer exchange increases when the magnetizations of the Fe layers are aligned antiparallel. The effect is much stronger than the usual anisotropic magnetoresistance and further increases in structures with more than two Fe layers. It can be explained in terms of spin-flip scattering of conduction electrons caused by the antiparallel alignment of the magnetization.

Current flowing in the film plane (CIP)

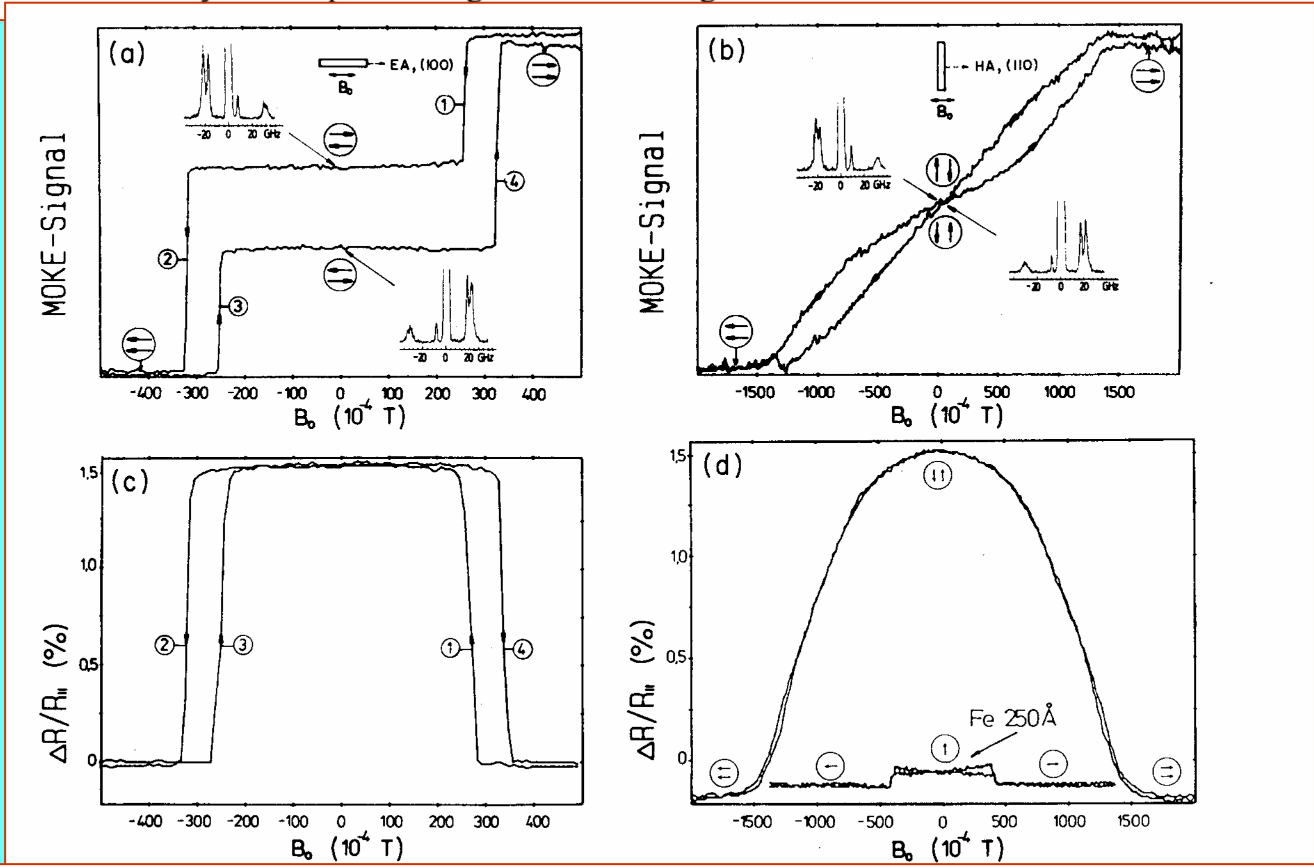


FIG. 2. (a)–(b) MOKE hysteresis curves and (c)–(d) magnetoresistance $\Delta R/R_{\parallel} = (R - R_{\parallel})/R_{\parallel}$ from Fe double layers with antiferromagnetic coupling. Also, (d) displays the anisotropic MR effect of a 250-Å-thick Fe film.

Giant Magnetoresistance of (001) Fe/(001) Cr Magnetic Superlattices

M. N. Baibich,[a] J. M. Broto, A. Fert, F. Nguyen Van Dau, and F. Petroff
Laboratoire de Physique des Solides, Université Paris-Sud, F-91405 Orsay, France

P. Eitenne, G. Creuzet, A. Friederich, and J. Chazelas
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(Received 24 August 1988)

We have studied the magnetoresistance of (001)Fe/(001)Cr superlattices prepared by molecular-beam epitaxy. A huge magnetoresistance is found in superlattices with thin Cr layers: For example, with $t_{Cr}=9$ Å, at $T=4.2$ K, the resistivity is lowered by almost a factor of 2 in a magnetic field of 2 T. We ascribe this giant magnetoresistance to spin-dependent transmission of the conduction electrons between Fe layers through Cr layers.

Current flowing in the film plane (CIP)

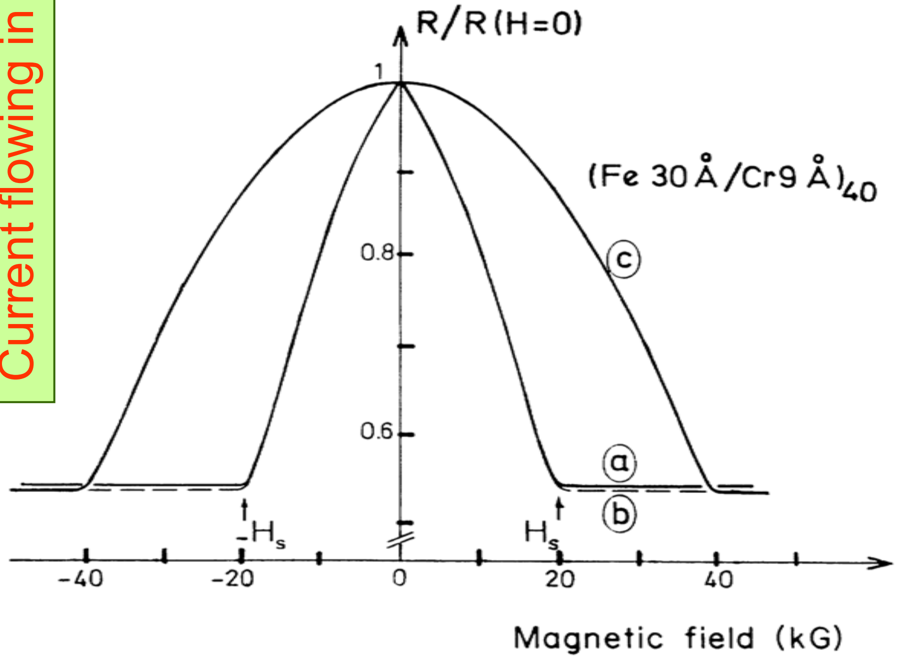

FIG. 2. Magnetoresistance of a $[(\text{Fe } 30\text{ Å})/(\text{Cr } 9\text{ Å})]_{40}$ superlattice of 4.2 K. The current is along [110] and the field is in the layer plane along the current direction (curve *a*), in the layer plane perpendicular to the current (curve *b*), or perpendicular to the layer plane (curve *c*). The resistivity at zero field is 54 $\mu\Omega$ cm. There is a small difference between the curves in increasing and decreasing field (hysteresis) that we have not represented in the figure. The superlattice is covered by a 100-Å Ag protection layer. This means that the magnetoresistance of the superlattice alone should be slightly higher.

RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 37, NUMBER 1 1 JANUARY 1988

Enhanced magnetoresistance of ultrathin $(Au/Co)_n$ multilayers with perpendicular anisotropy

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D. Renard
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J. P. Renard and J. Seiden
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(Received 20 July 1987)

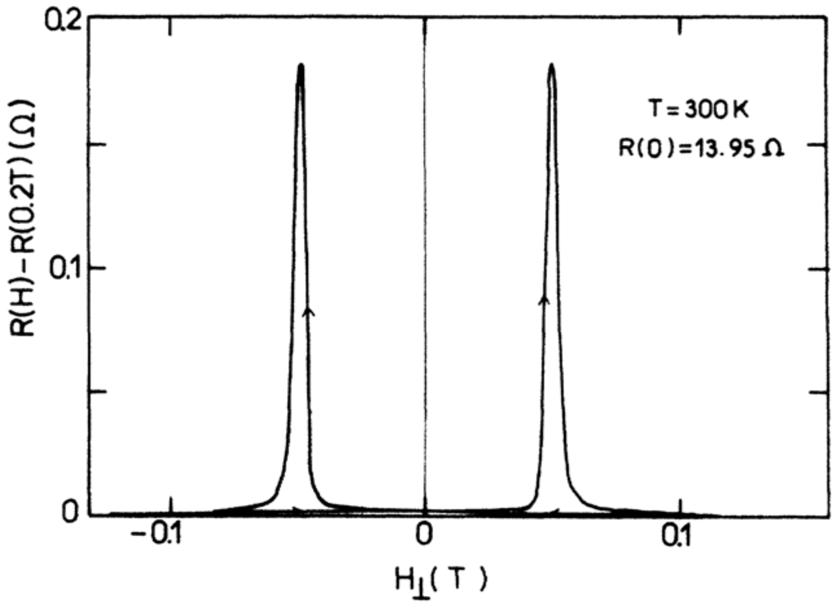

FIG. 3. Room-temperature perpendicular magnetoresistance of sample 3: Au/Co (0.76 nm)/Au (3 nm)/Co (0.76 nm)/Au. The coercive field is H_c=493 G and $\delta R_c/R$=1.3%.

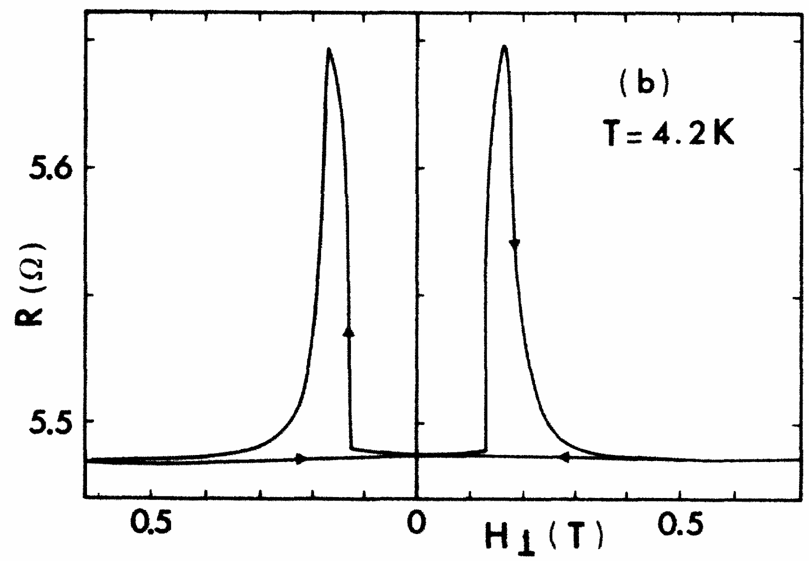

FIG. 4. Magnetoresistance of sample 3 at 4.2 K for (a) H_t and (b) $H_\perp$. Perpendicularly to the film, a coercive field of 2×10^3 G and a maximum magnetoresistance $\delta R_c/R$=3% are observed.

VOLUME 63, NUMBER 6 PHYSICAL REVIEW LETTERS 7 AUGUST 1989

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

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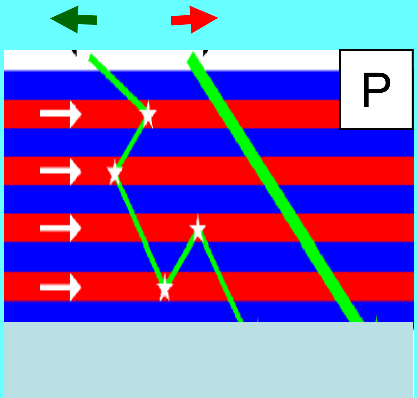
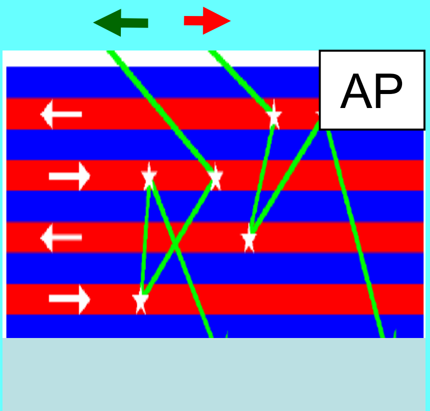
(Received 30 March 1989)

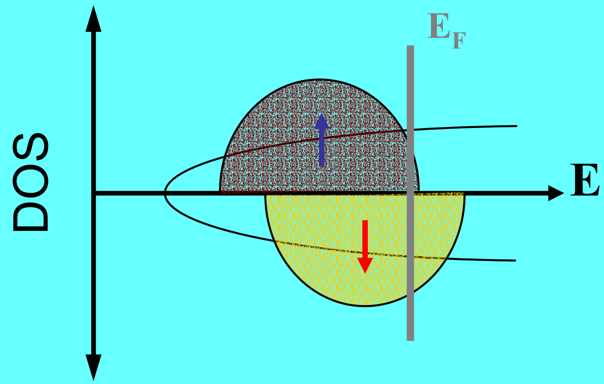




- Dwa dobrze zdefiniowane kanały spinowe
- Silna zależność od spinu parametrów transportowych

$$\rho_{\pm} = 2\rho^{*}(1 \mp \beta)$$

$$\rho_{\sigma}^{-1} = \frac{n_{\sigma} e^{2} \tau_{\sigma}}{m_{\sigma}}$$



$$\tau_{\sigma}^{-1} \sim \left| V_{\sigma} \right|^{2} N_{\sigma}(E_F)$$

Prąd ładunkowy związany jest z prądem spinowym

$$J_s = (J_+ - J_-)/e$$

Właściwości CIP GMR

1. **GMR spada eksponencjalnie z rosnącą grubością niemagnetycznej warstwy, z średnią drogą swobodną jako charakterystyczną długością zaniku**
2. **Zależność od grubości warstw magnetycznych jest bardziej złożona - z maksimum przy pewnej grubości.**
3. **GMR rośnie z liczbą warstw w układzie (do łącznej grubości porównywalnej z długością dyfuzji spinu)**
4. **Defekty strukturalne typu 'bulk' i na granicach dają wkład do GMR**
5. **Oddziaływanie wymienne nie jest konieczne do wystąpienia efektu.**
6. **Amplituda (maksimum) efektu nie zależy od oddziaływania wymiennego**

PHYSICAL REVIEW B VOLUME 42, NUMBER 13 1 NOVEMBER 1990

Novel magnetoresistance effect in layered magnetic structures: Theory and experiment

J. Barnaś,* A. Fuss, R. E. Camley,† P. Grünberg, and W. Zinn
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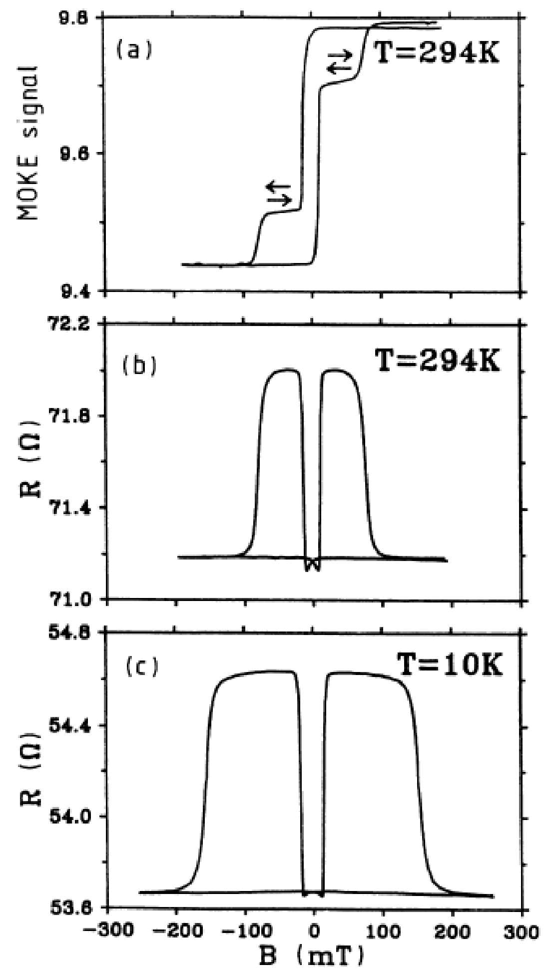
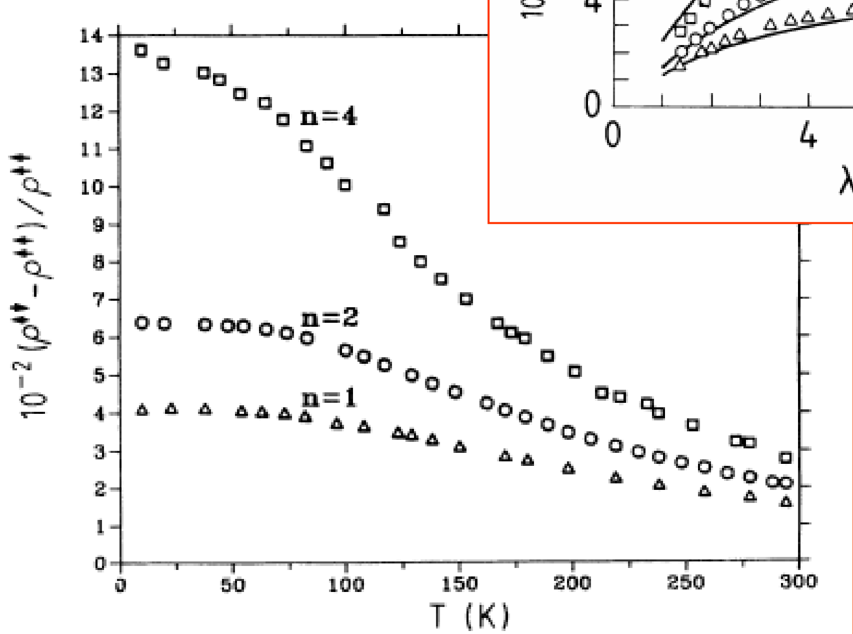
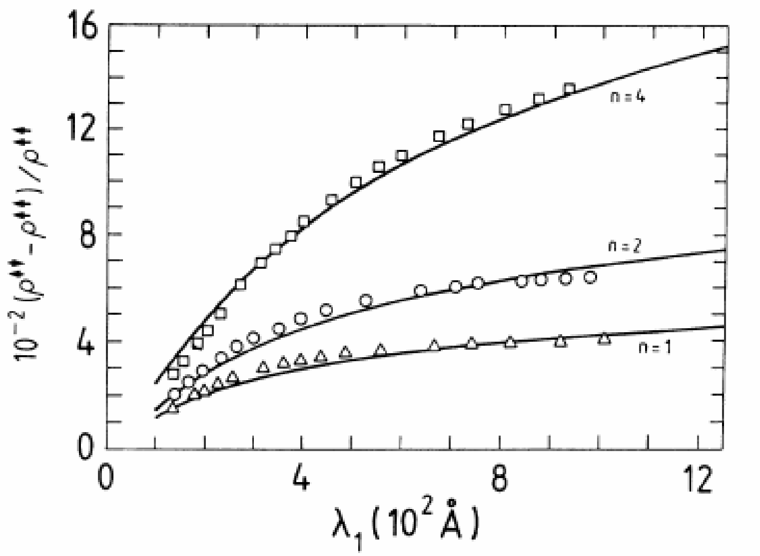
(Received 7 November 1989; revised manuscript received 26 April 1990)



Co/Au/Co





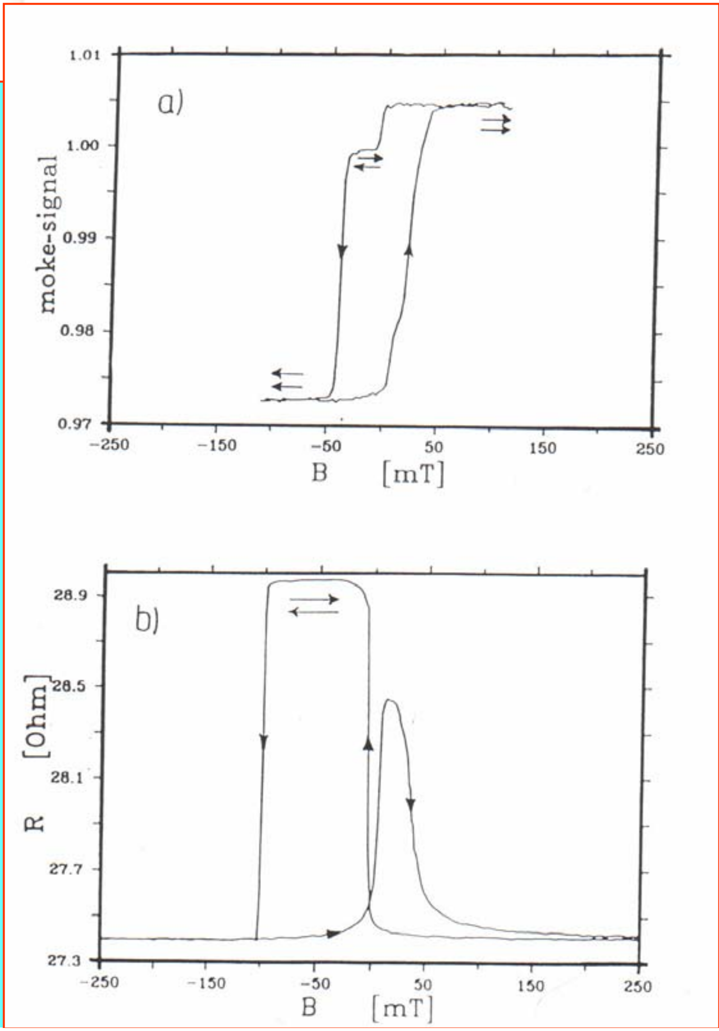
Fe/Cr/Fe

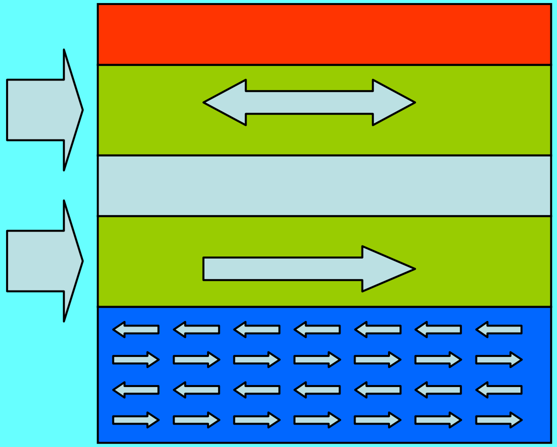
Vacuum/volume 41/numbers 4–6/pages 1241 to 1243/1990
Printed in Great Britain

0042–207X/90$3.00 + .00

Layered magnetic structures: magnetoresistance due to antiparallel alignment

J Barnaś*, A Fuss, R E Camley†, U Walz, P Grünberg and W Zinn, *Kernforschungsanlage, IFF, Postfach 1913, 5170-Jülich, FRG*





Spin Valve

Co/Au/Co/CoO

RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 43, NUMBER 1 1 JANUARY 1991

Giant magnetoresistance in soft ferromagnetic multilayers

B. Dieny,* V. S. Speriosu, S. S. P. Parkin, B. A. Gurney, D. R. Wilhoit, and D. Mauri†
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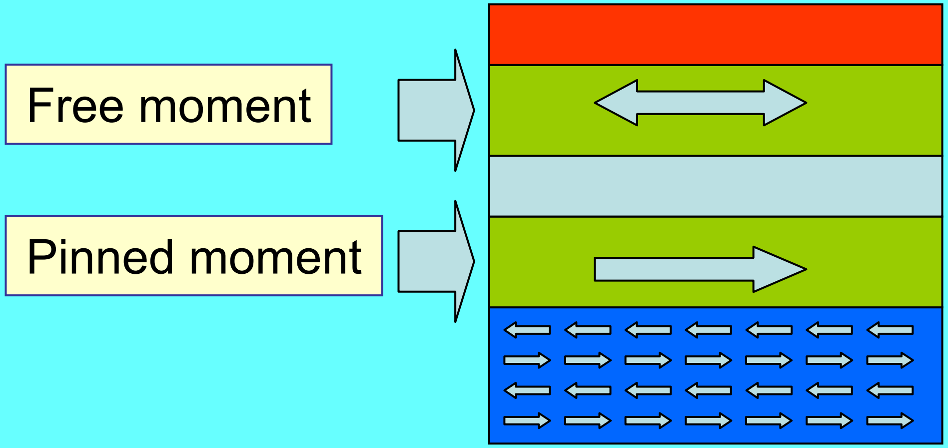
(Received 25 July 1990; revised manuscript received 21 September 1990)



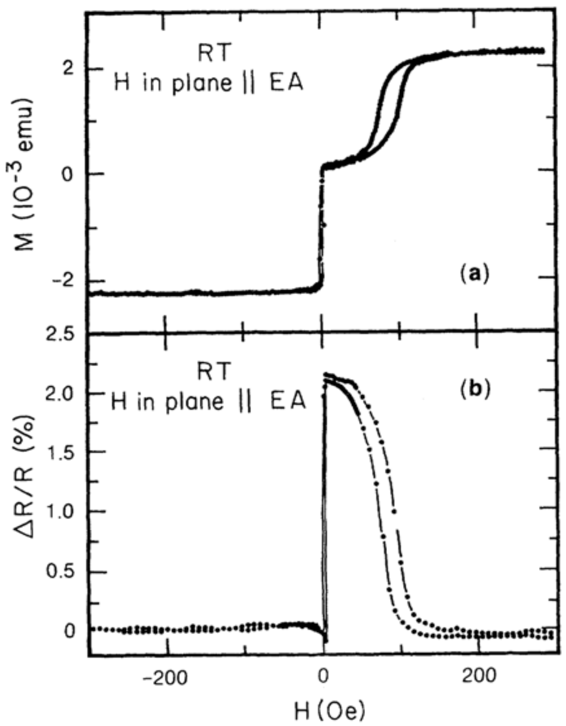
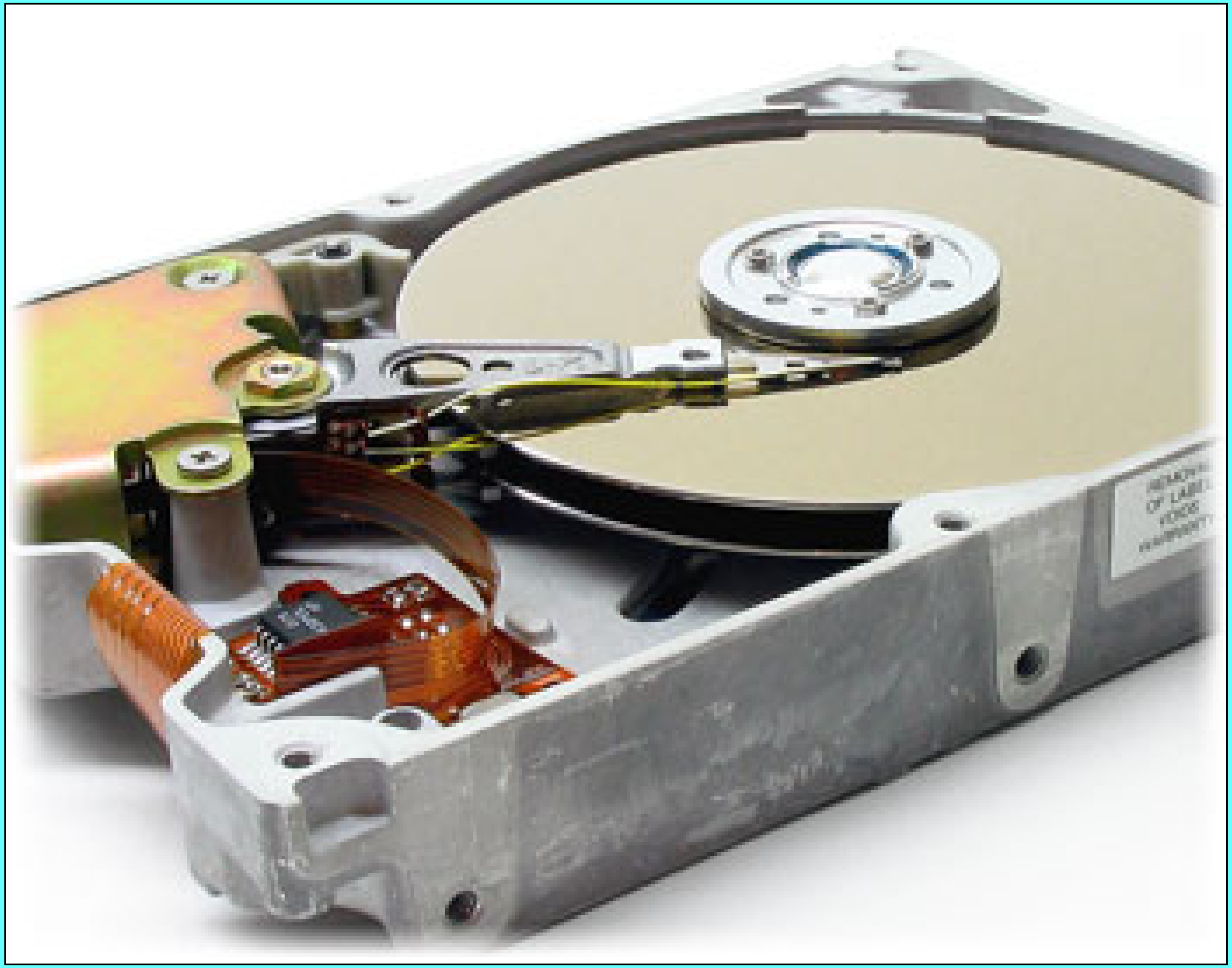


FIG. 1. Magnetization curve (a) and relative change in resistance (b) for Si/(150-Å NiFe)/(26-Å Cu)/(150-Å NiFe)/(100-Å FeMn)/(20-Å Ag). The field is applied parallel to the exchange anisotropy field created by FeMn (EA). The current is flowing perpendicular to this direction.

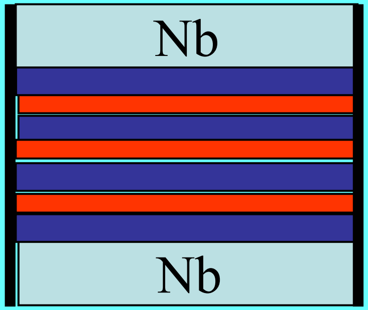
Spin Valve



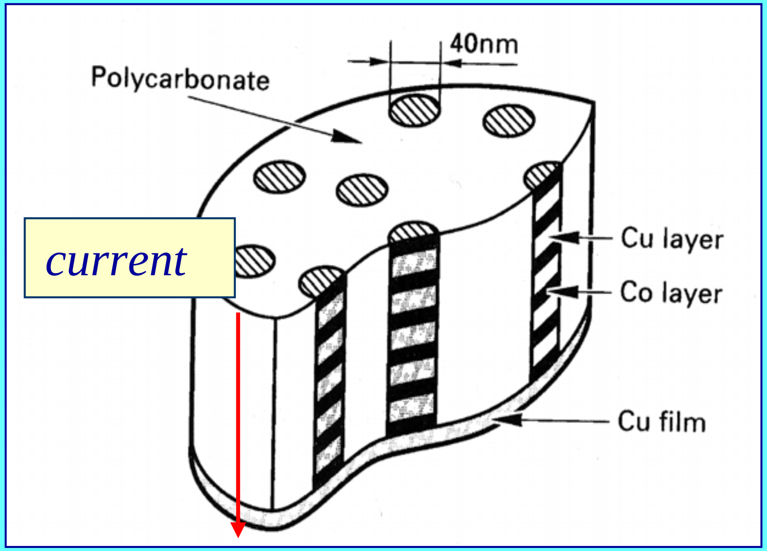
http://motls.blogspot.com/2007/10/physics-nobel-prize-2007.html

Geometria CPP (Current-perpendicular-to-plane)

current

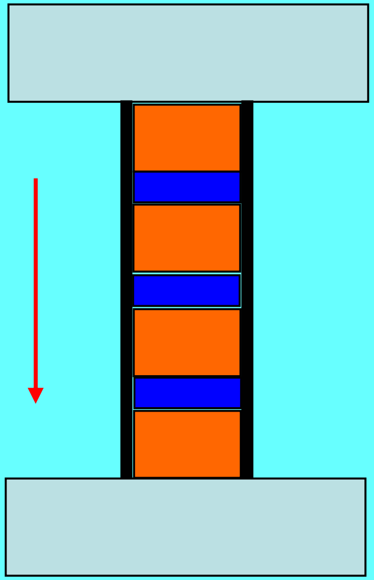


A Superconducting electrodes



L Piraux et al., APL 65, 1994

current



B Pillar structures (nano-columns)

C Electrochemical deposition in nanopores in membranes

- CPP GMR usually larger than CIP
- Characteristic length scale for the nonmagnetic spacer is the spin diffusion length

PHYSICAL REVIEW B VOLUME 48, NUMBER 10 1 SEPTEMBER 1993-II

Theory of the perpendicular magnetoresistance in magnetic multilayers

T. Valet
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A. Fert
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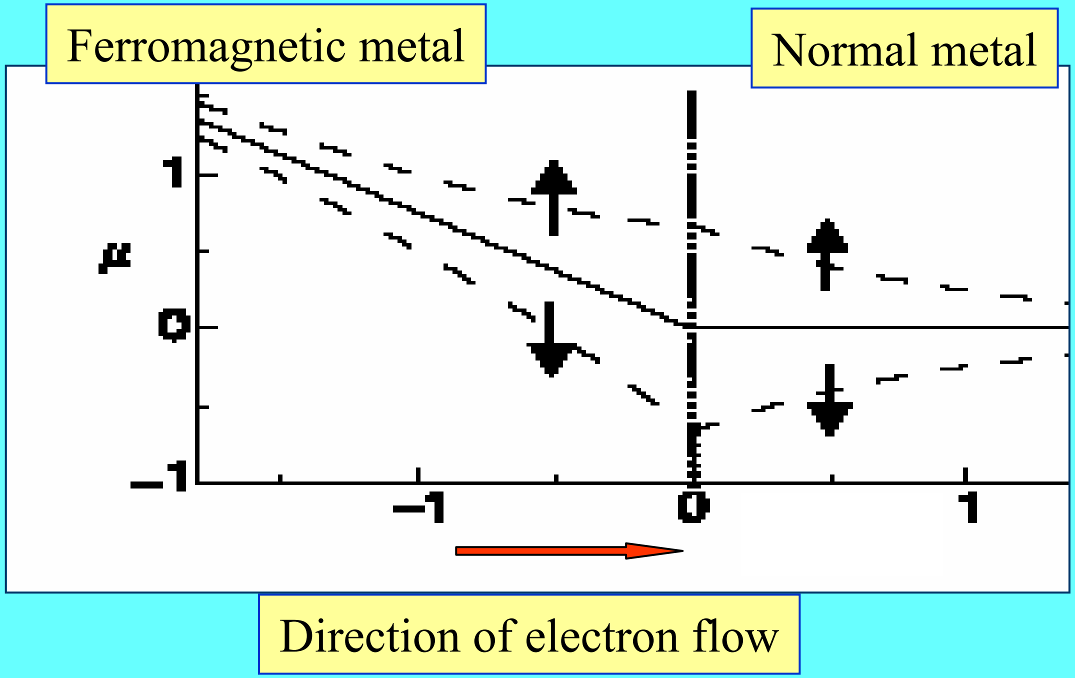

$$\overline{\mu}_\sigma(x) = \mu_\sigma(x) - eV(x)$$

$$\frac{\partial^2 \Delta\mu(x)}{\partial x^2} = \frac{\Delta\mu(x)}{l_{sf}^2},$$

Spin splitting of the electro-chemical potential obeys the diffusion equation

Spin accumulation: a nonequilibrium (current-induced) magnetic moment

Akumulacja spinowa: efekt ‘wąskiego gardła’ spinowego

PHYSICAL REVIEW B VOLUME 49, NUMBER 18 1 MAY 1994-II

Interface resistance for perpendicular transport in layered magnetic structures

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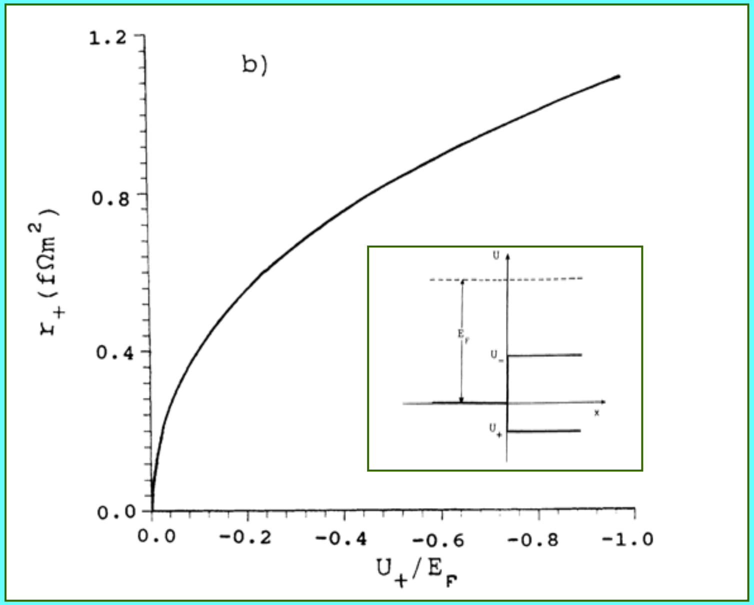
(Received 25 February 1993; revised manuscript received 16 November 1993)

Wykorzystano formalizm Landauer'a do policzenia oporu kontaktowego wynikającego z niedopasownia struktury elektronowej

$$R=\frac{h}{2e^2}\frac{1+(g^<)^{-1}\sum_i (V_i^<)^{-1}R_i-(g^>)^{-1}\sum_j (v_j^>)^{-1}T_j}{\sum_j T_j},$$



Perpendicular magnetoresistance in magnetic multilayers: Theoretical model and discussion (invited)

Albert Fert
Laboratoire de Physique des Solides,[a] Université Paris-Sud, 91405 Orsay, France

Thierry Valet
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Jozef Barnas
Institute of Physics, A.M. University, 60-769 Poznan, Poland

VOLUME 78, NUMBER 13 PHYSICAL REVIEW LETTERS 31 MARCH 1997

Towards a Unified Picture of Spin Dependent Transport in and Perpendicular Giant Magnetoresistance and Bulk Alloys

S. Y. Hsu,[1] A. Barthélémy,[2] P. Holody,[1] R. Loloee,[1] P. A. Schroeder,[1] and A. Fert[2]

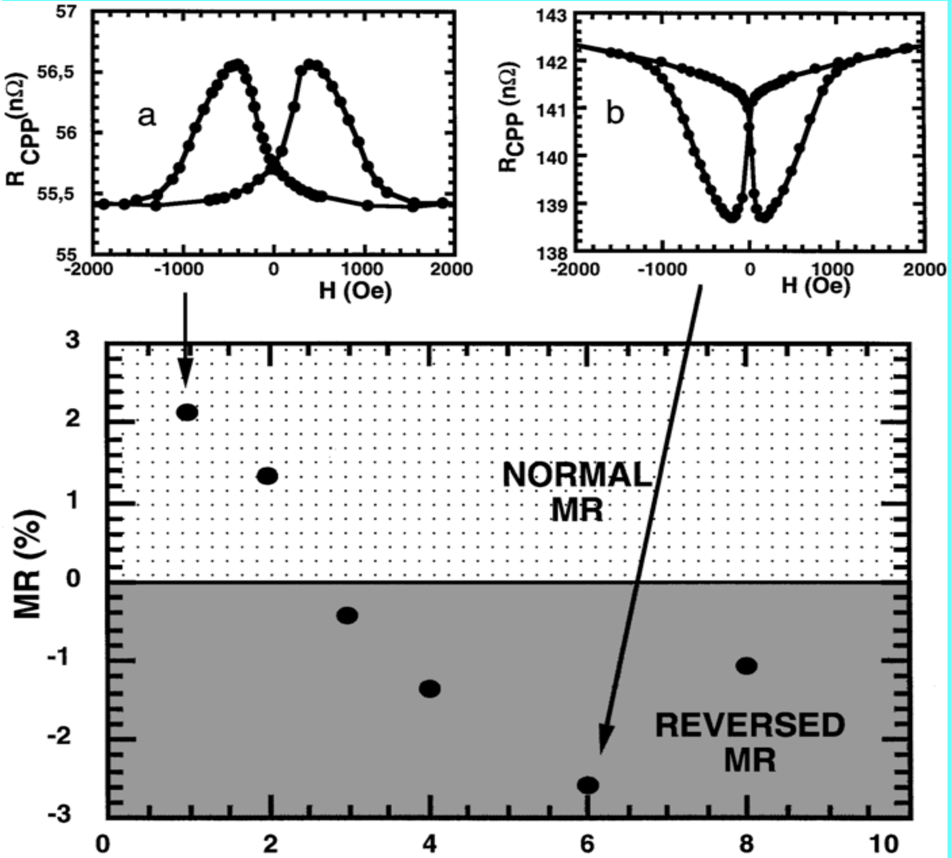

FIG. 2. Variation of the MR ratio at saturation with the thickness of FeV in ($Fe_{72}V_{68}$/Cu 2.3 nm/Co 0.4 nm/Cut_{FeV} 2.3 nm$)_{20}$ samples. We have adopted the positive (negative) sign for normal (inverse) GMR. Inset (a): Normal magnetoresistance curve for 1 nm thick FeV layers. Inset (b): Inverse GMR for 6 nm thick FeV layers.

Odwrotny efekt GMR

$\beta<0,\ \gamma>0$ $\gamma>0,\ \beta>0$

(FeV/Cu/Co/Cu)$_N$

$$\rho_{\pm} = 2\rho^*(1 \mp \beta)$$

$$R_{\pm} = 2R^*(1 \mp \gamma)$$

PHYSICAL REVIEW B VOLUME 54, NUMBER 2 1 JULY 1996-II

Angular dependence of the perpendicular giant magnetoresistance of multilayers

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S. F. Lee and A. Fert
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(Received 15 December 1995; revised manuscript received 21 February 1996)

$$GMR(\varphi) = (R(\varphi) - R_p) / R_p$$

Angular dependence of resistance

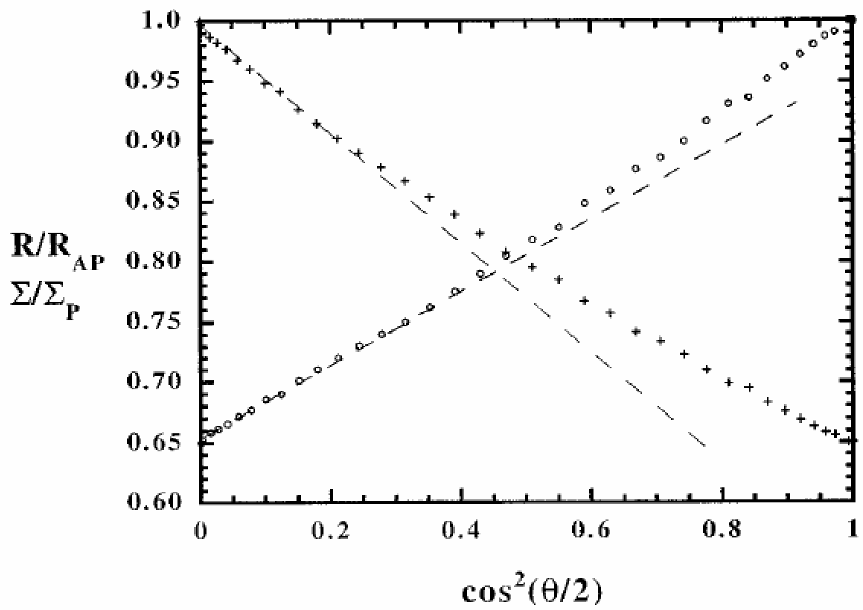

FIG. 4. Angular dependence of the current-perpendicular-to-the-plane conductance (dots) and resistance (crosses) for (Ag 40 Å /Co 4 Å /Ag 40 Å /$Ni_{80}Fe_{20}$ 40 Å$)_{20}$ at 4.2 K.

PHYSICAL REVIEW B VOLUME 56, NUMBER 10 1 SEPTEMBER 1997-II

Angular dependence of giant magnetoresistance in magnetic multilayers

J. Barnaś*
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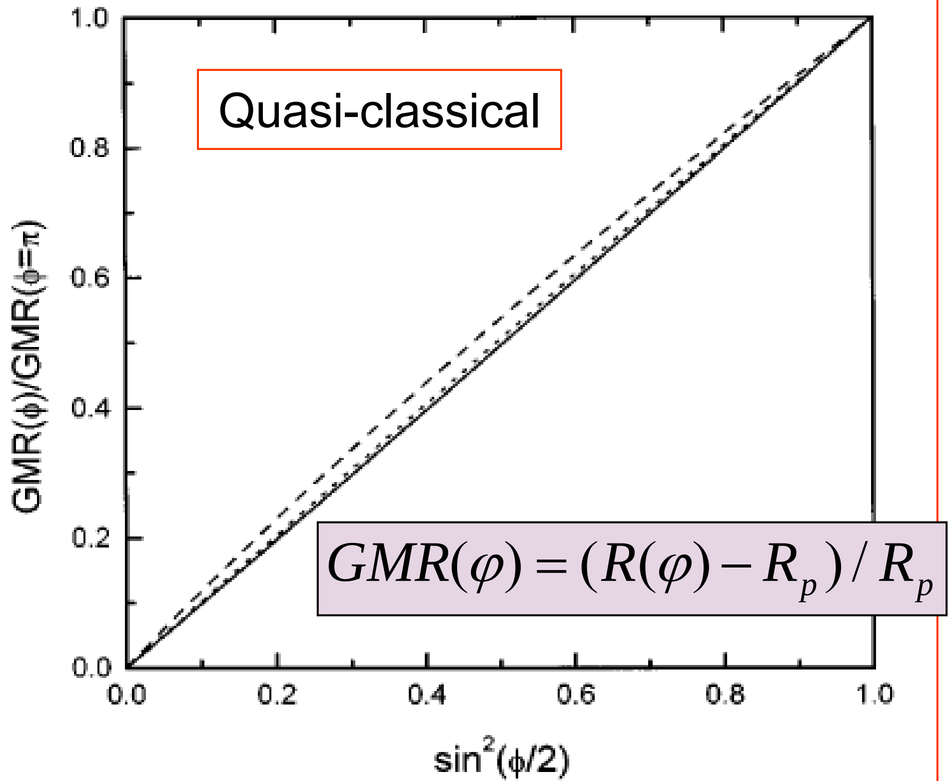
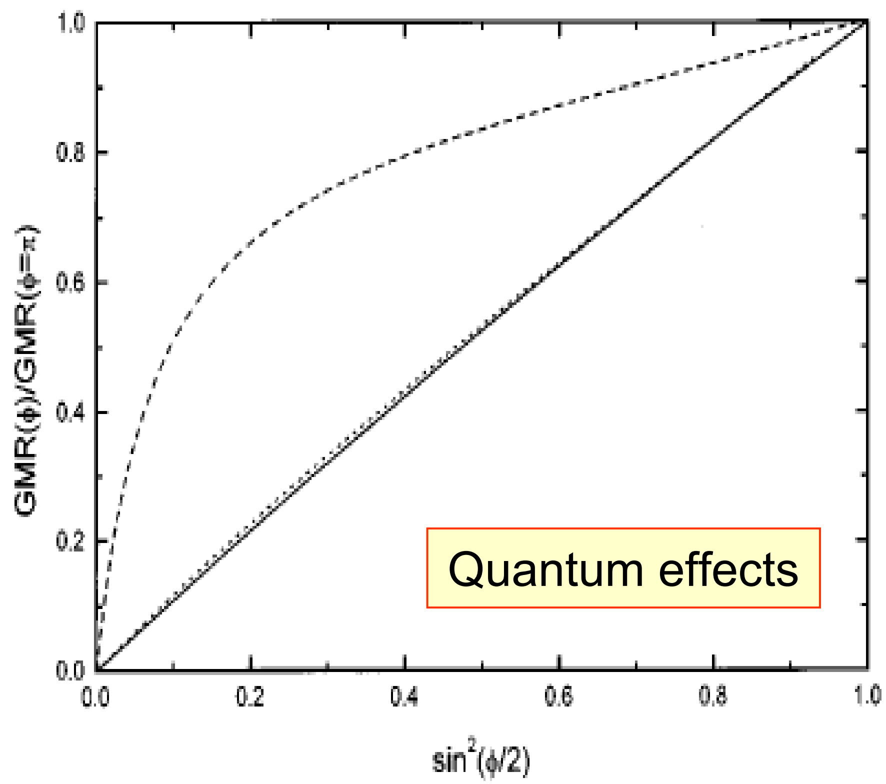


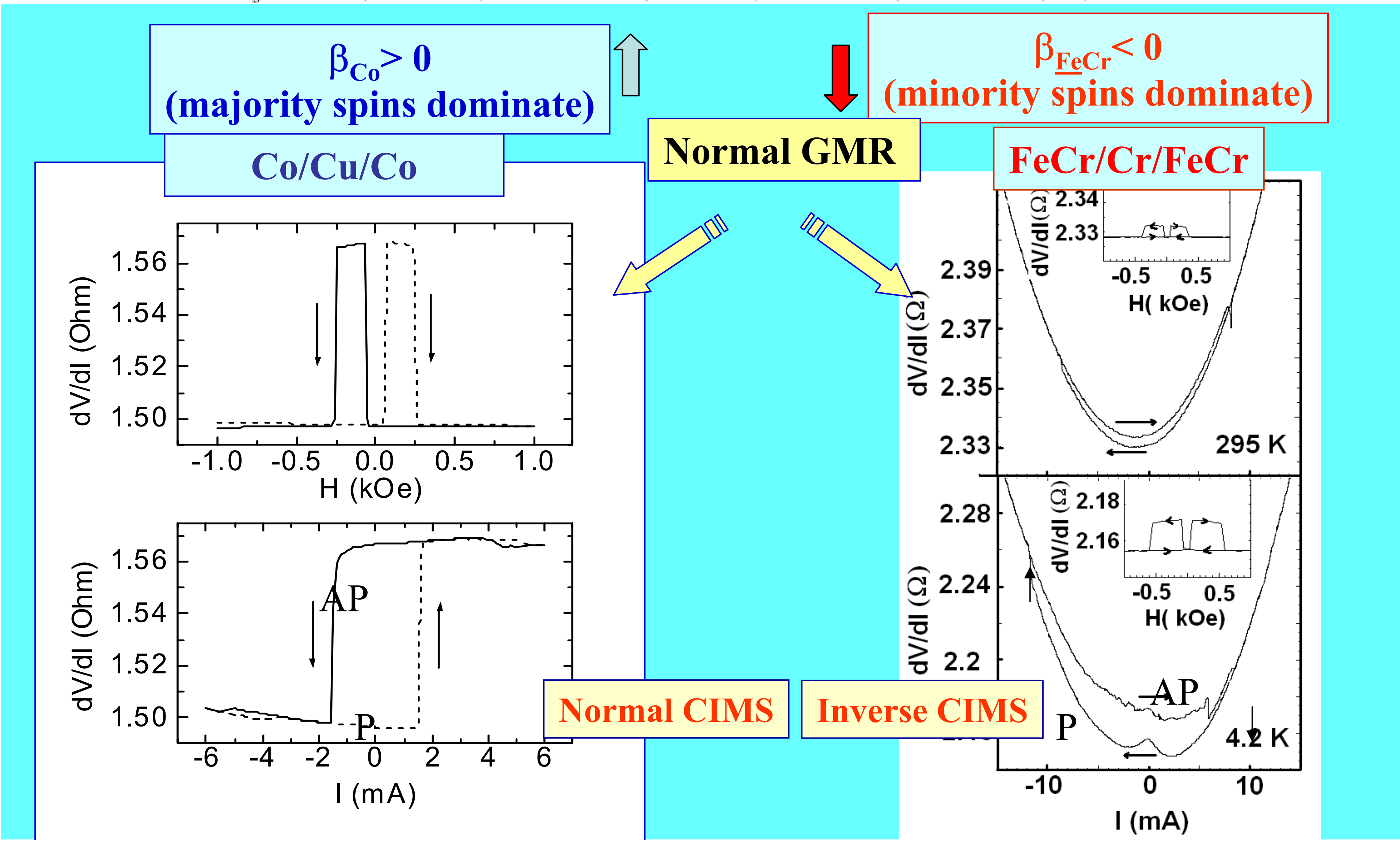
$$GMR(\varphi) = (R(\varphi) - R_p) / R_p$$



VOLUME 93, NUMBER 15 PHYSICAL REVIEW LETTERS week ending 8 OCTOBER 2004

Controlled Normal and Inverse Current-Induced Magnetization Switching and Magnetoresistance in Magnetic Nanopillars

M. AlHajDarwish,[1] H. Kurt,[1] S. Urazhdin,[1] A. Fert,[2] R. Loloee,[1] W. P. Pratt, Jr.,[1] and J. Bass[1]

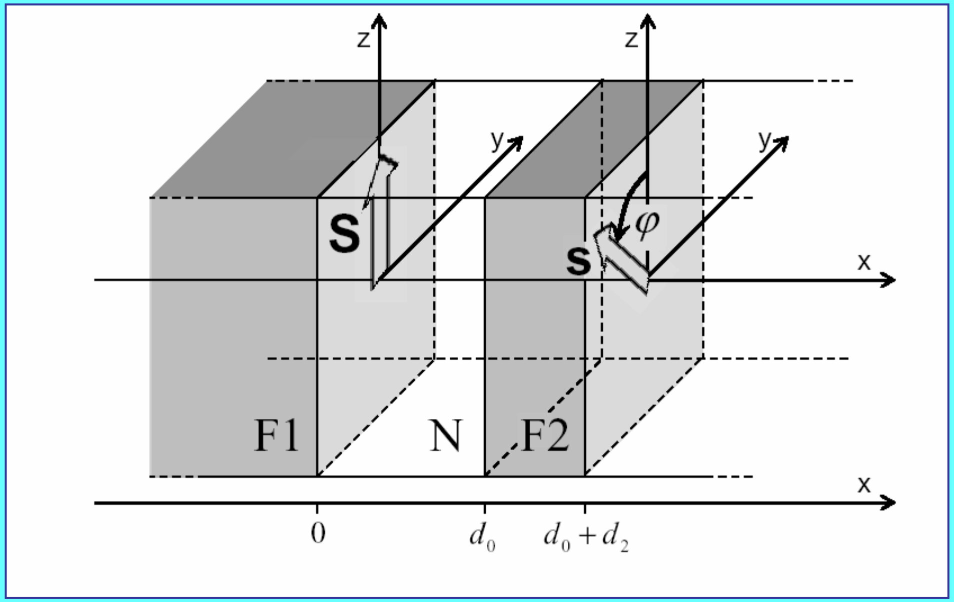


PHYSICAL REVIEW B **72**, 024426 (2005)

From giant magnetoresistance to current-induced switching by spin transfer

J. Barnaś,[1,2] A. Fert,[3] M. Gmitra,[1] I. Weymann,[1] and V. K. Dugaev[4]

$$\boldsymbol{\tau} = \frac{\hbar}{2}(\mathbf{j}^{s}_{\perp L} - \mathbf{j}^{s}_{\perp R})$$



In-plane component

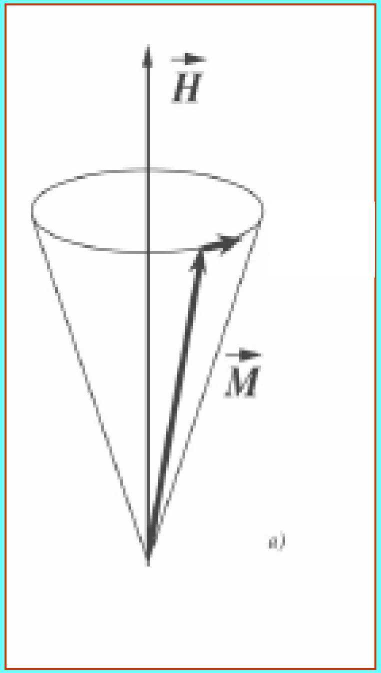
$$\boldsymbol{\tau}_{\parallel} = aI\hat{\mathbf{s}} \times (\hat{\mathbf{s}} \times \hat{\mathbf{S}})$$

Out-of-plane component

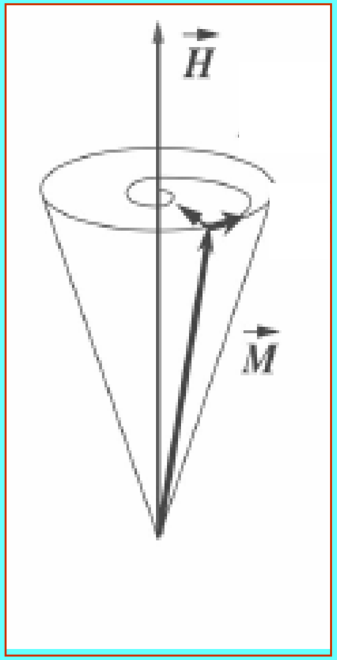
$$\boldsymbol{\tau}_{\perp} = bI\hat{\mathbf{s}} \times \hat{\mathbf{S}}$$

'Spin torque' a magnetyczne przełączanie

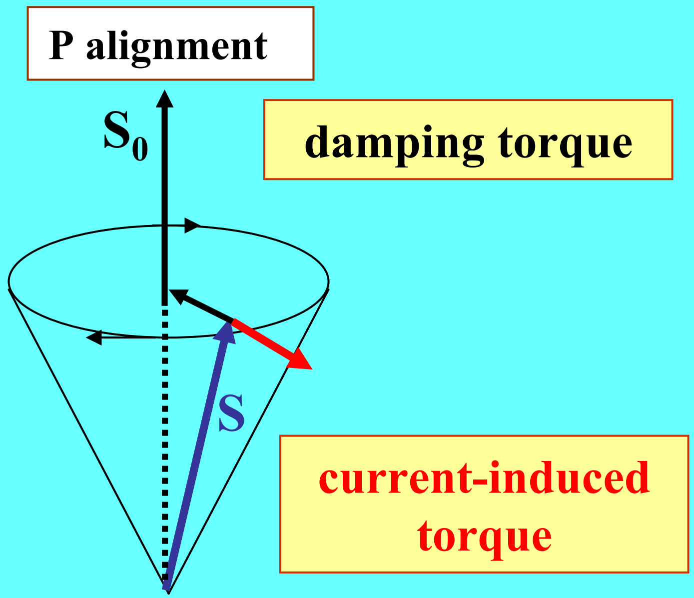
The transverse component of spin current is absorbed in the interfacial region and transferred to the spin momentum of the layer



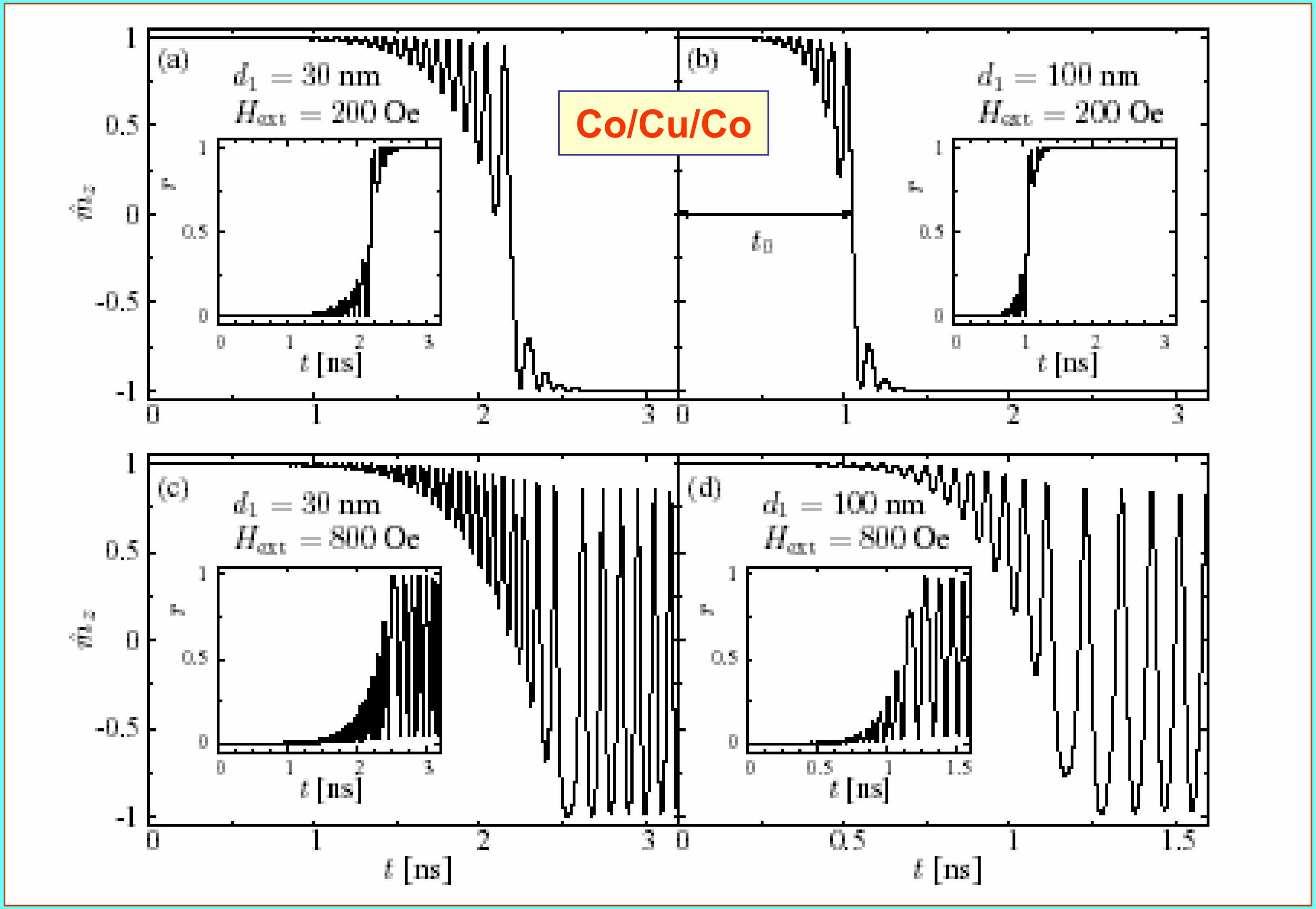
Without damping



With damping

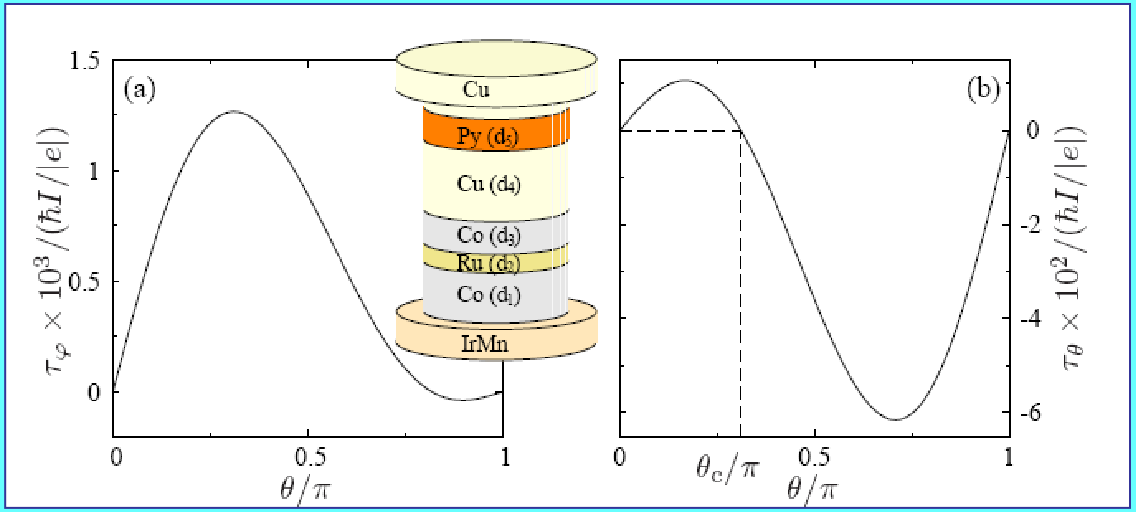


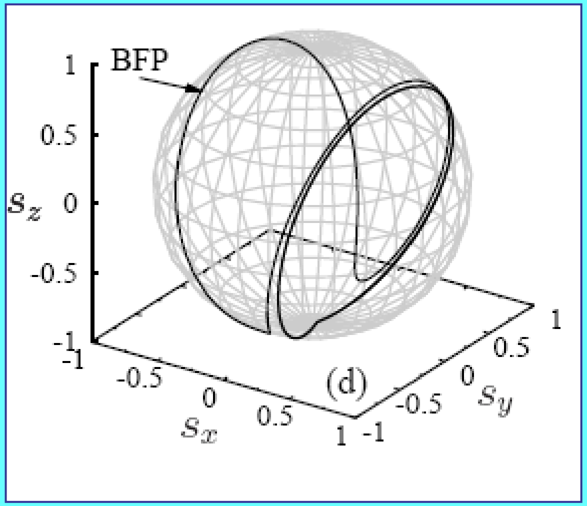
Dynamika magnetycznego przełączania

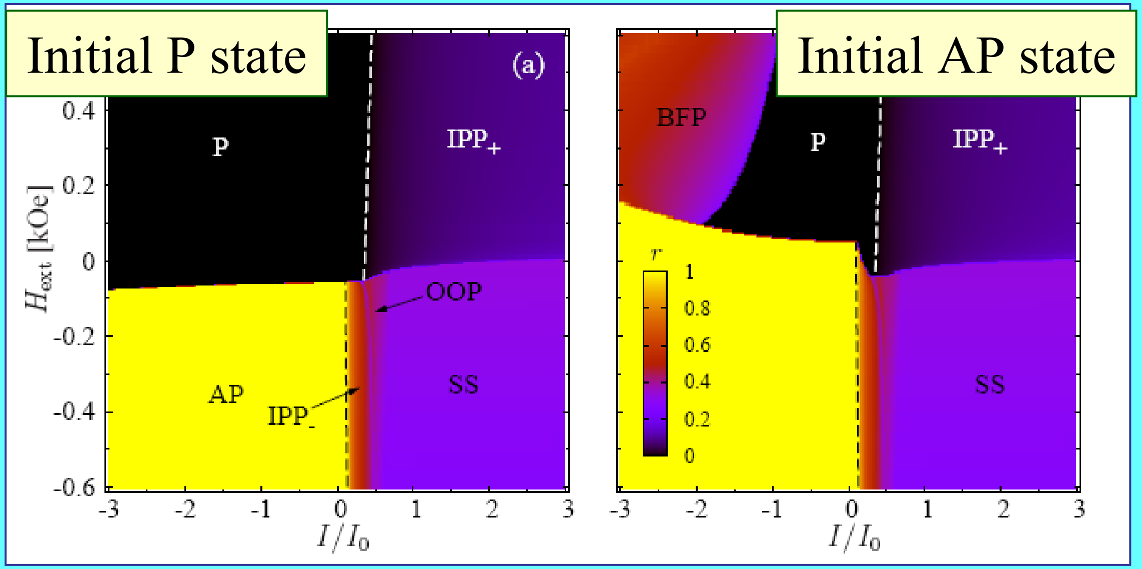


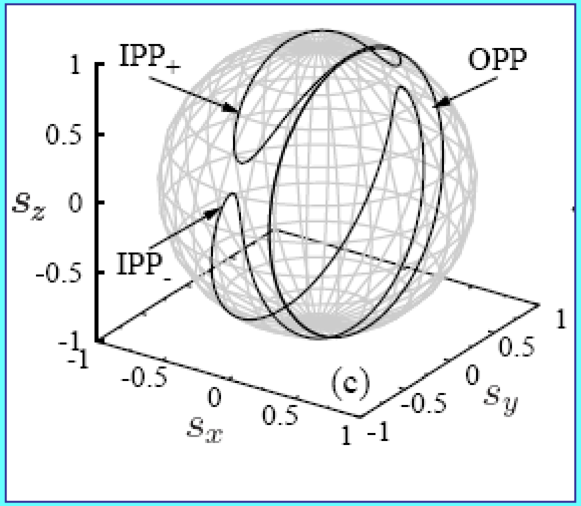
M.Gmitra, JB, J. Alloys Comp. 06

Diagram fazowy asymetrycznych układów







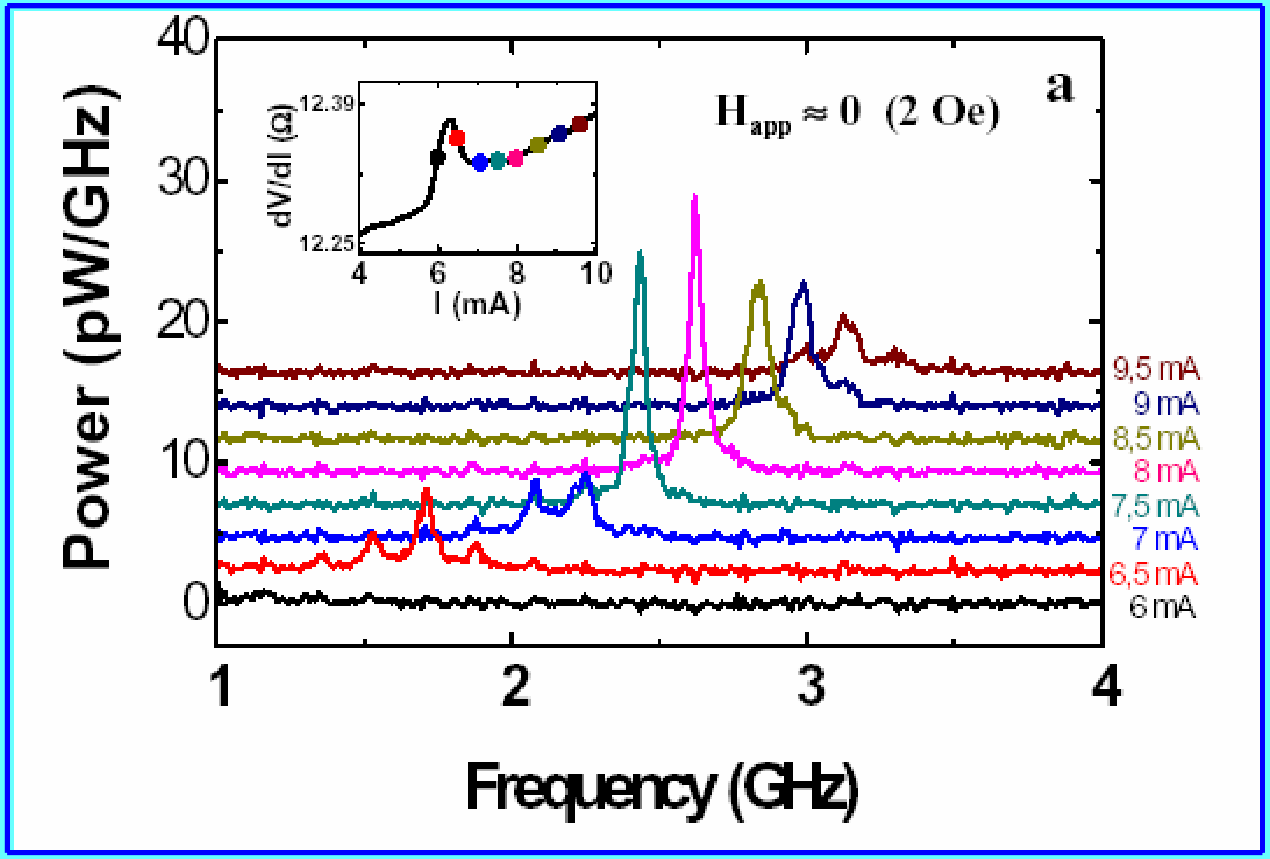


M.Gmitra & Barnaś, PRL 2006;APL 2006;PRL 2007

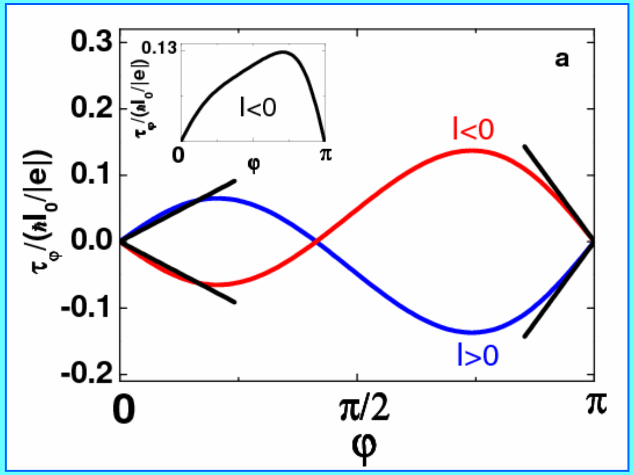
Shaped angular dependence of the spin-transfer torque and microwave generation without magnetic field

O. BOULLE[1], V. CROS[1]*, J. GROLLIER[1], L. G. PEREIRA[1†], C. DERANLOT[1], F. PETROFF[1], G. FAINI[2], J. BARNAŚ[3] AND A. FERT[1]

Published online: 7 May 2007; doi:10.1038/nphys618



Co/Cu/Py

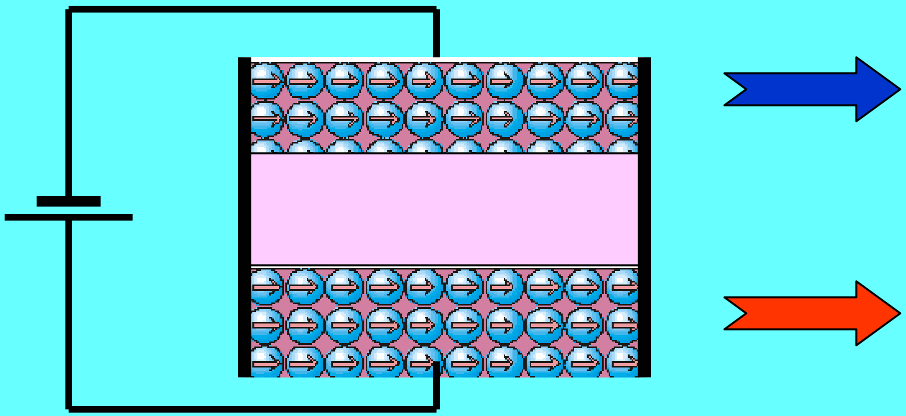


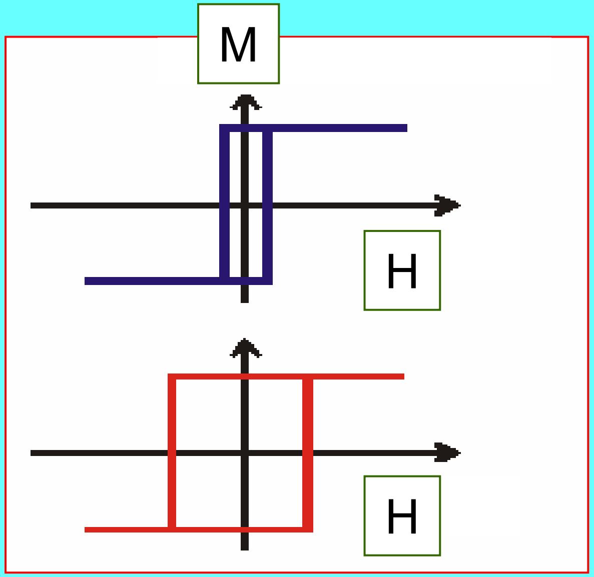
Początek elektroniki spinowej

- Tunelowy magnetoopór
- Efekty magnetyczno-kulombowskie (FM SET)
- Półprzewodnikowa spintronika
- Molekularna spintronika

Tunelowy magnetoopór

- Jullière, Phys Lett A 1975





- Moodera *et al.* 95,
- Nowak & Raułuszkiewicz
- SSP Parkin

RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 56, NUMBER 10 1 SEPTEMBER 1997-II

Spin-dependent tunneling with Coulomb blockade

L. F. Schelp, A. Fert, F. Fettar, P. Holody, S. F. Lee, J. L. Maurice, F. Petroff, and A. Vaurès
Unité Mixte de Physique CNRS-Thomson CSF, 91404, Orsay, France
and Université Paris-Sud, Batiment 510, 91405, Orsay, France

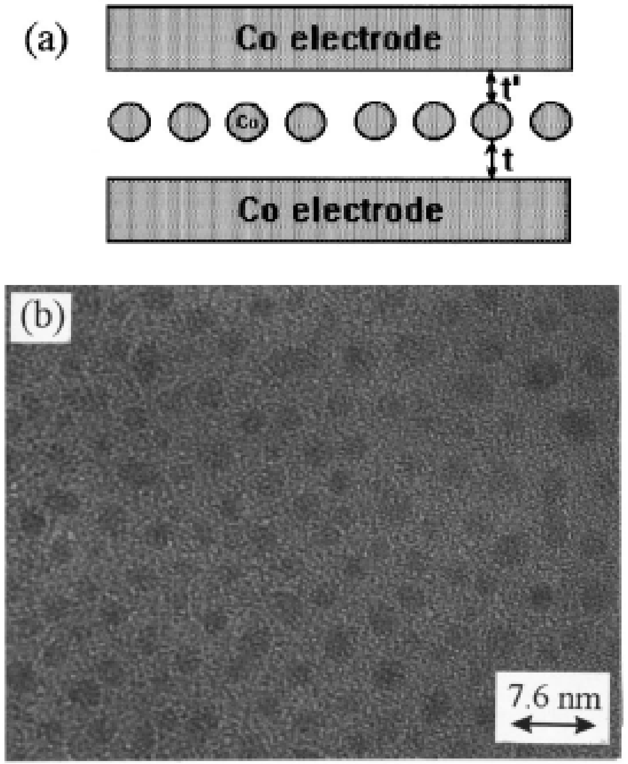


FIG. 1. (a) Schematic of the fabricated junctions (cross section). (b) Transmission electron microscopy (TEM) plane view of a cobalt cluster layer sandwiched between two Al_2O_3 layers deposited on a carbon-coated microscopy grid (the diameter of the clusters range from 3 to 4 nm). (c) TEM cross-section image of the same structure deposited on Si.

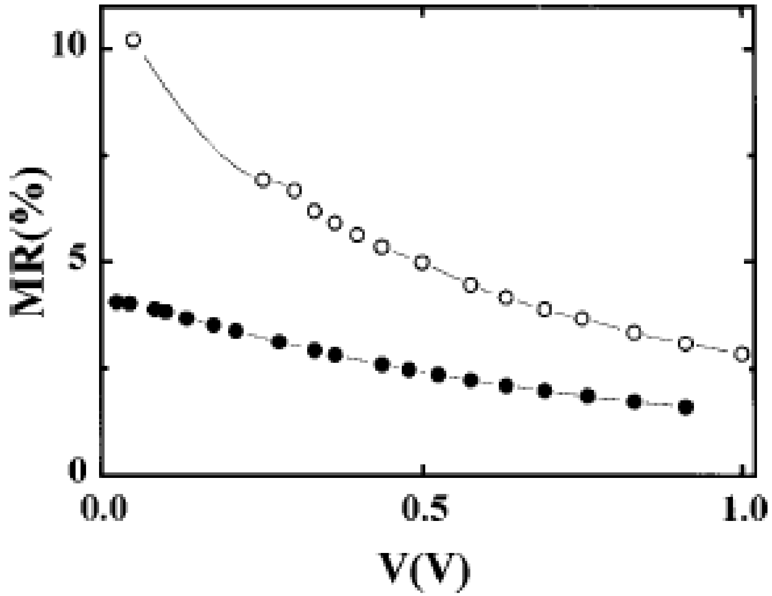


FIG. 4. Magnetoresistance ratio as a function of applied voltage at 4.2 K (open circles) and RT (black dots) for a sample with clusters of 2.5 nm mean diameter, $t=2.7$ nm and $t'=1.4$ nm.

Dziękuję za uwagę