Spintronics:
Physics and applications (I)

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IPM, 15 TiR 1387

وزارت علوم، تحقیقات و فناوری
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The Nobel Prize in Physics 2007

"for the discovery of Giant Magnetoresistance"

Albert Fert

1/2 of the prize

France

Université Paris-Sud;
Unité Mixte de Physique
CNRS/THALES
Orsay, France

b. 1938

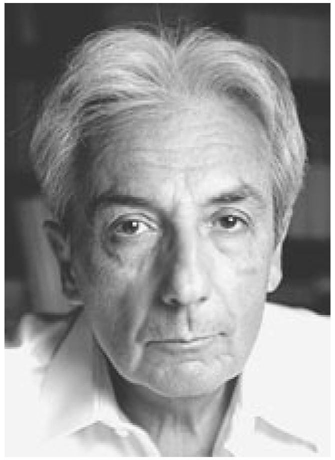


Photo: B. Fert, Invisuphoto

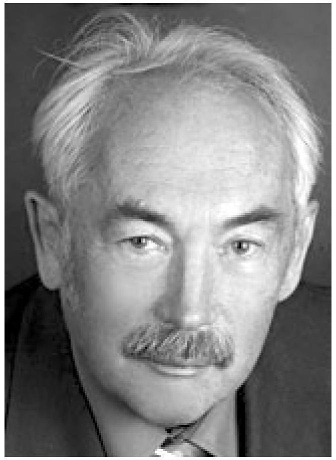


Photo: © Forschungszentrum Jülich

Peter Grünberg

1/2 of the prize

Germany

Forschungszentrum Jülich
Jülich, Germany

b. 1939

- **Very weak magnetic changes give rise to major differences in resistance in a GMR system (.(١٩٨٨**
- **GMR has made possible miniaturizing hard disks so radically in recent years: in ١٩٩٧ the first GMR read-out head was launched.**
- **GMR has led to spintronics: use of spin of electron to transfer or store information**
- **GMR is considered one of the first real applications of nanotechnology.**

Prof . G. Öquist, Secretary General of the Royal Swedish Academy of Sciences, 9 October ٢٠٠٧

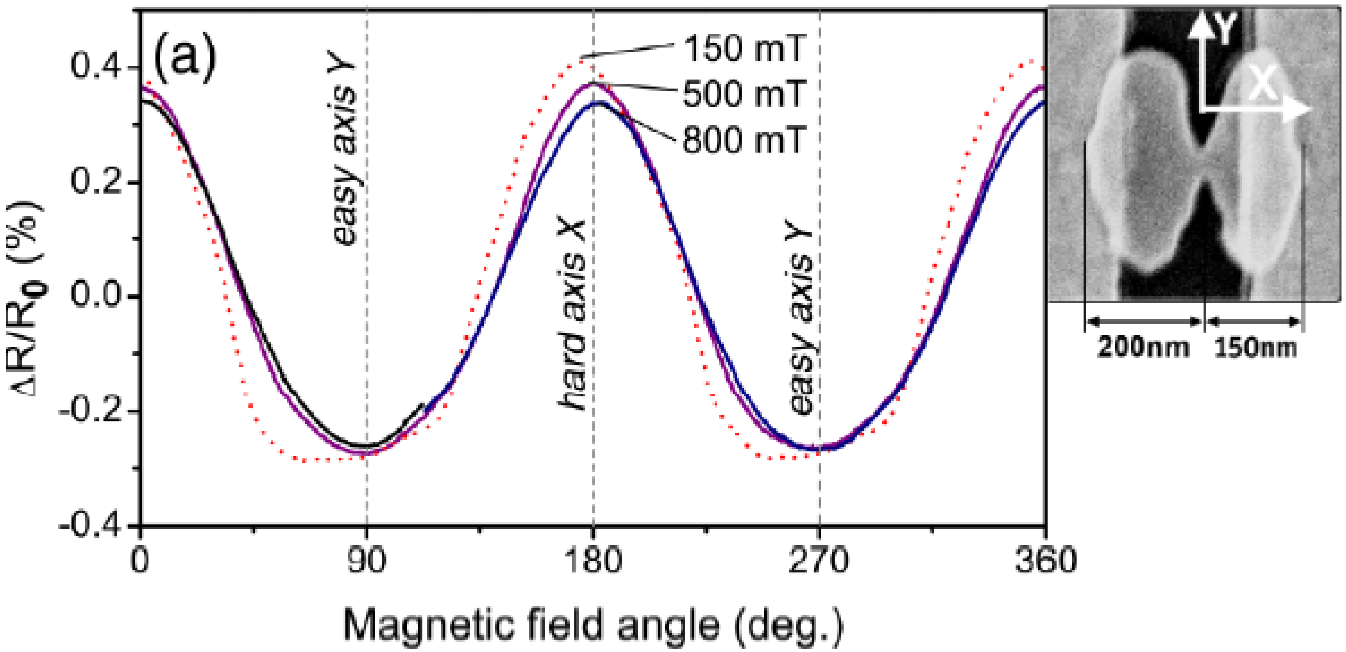
Anisotropic Magnetoresistance

William Thomson (Lord Kelvin) 1856-57:

"I found that iron, when subjected to a magnetic force, acquires an increase of resistance to the conduction of electricity along, and a diminution of resistance to the conduction of electricity across, the lines of magnetization. "

[W. Thomson, Proceeding of the Royal Society of London **8**, 546 (1856-1857)]

Anisotropic Magnetoresistance



interaction of spin of electron with the crystal potential:
spin-orbit coupling

$Fe_{20}Ni_{80}$ (Permalloy): Only few % change in R

[K. I. Bolotin, et al, PRL **97**, 127202 (2006)]

Magnetic multilayers

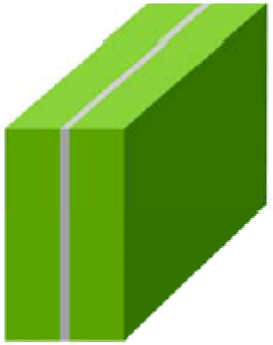
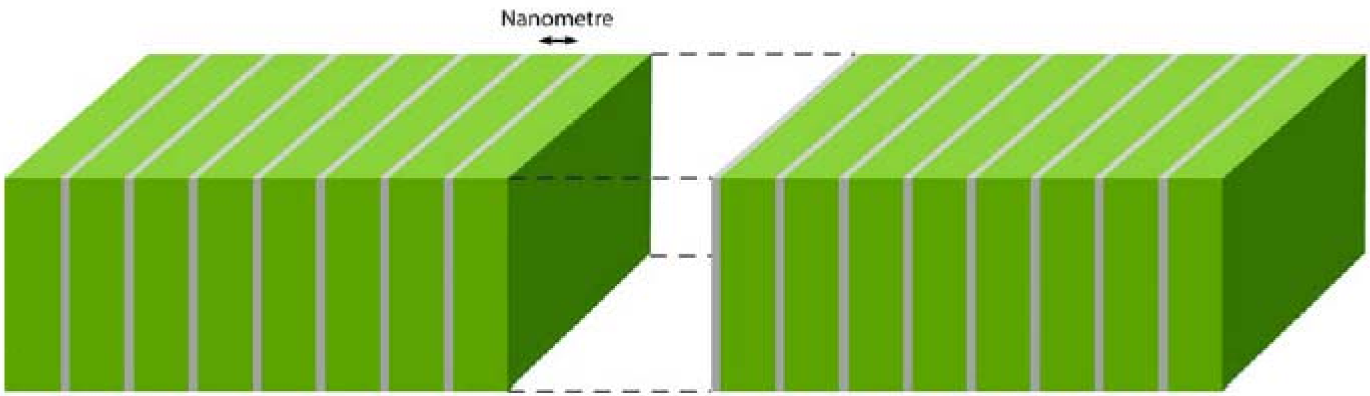
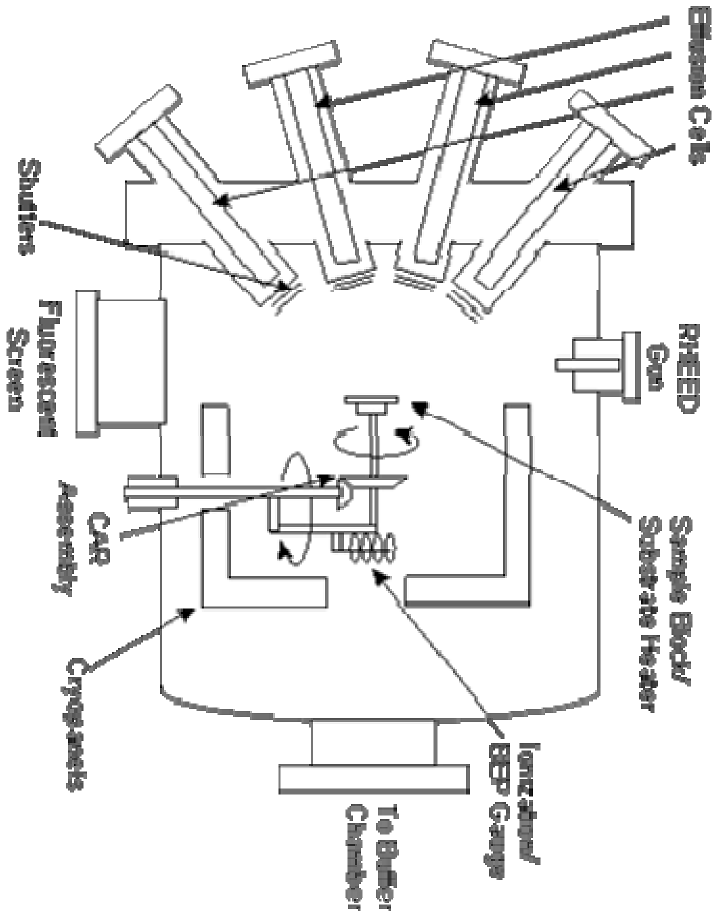


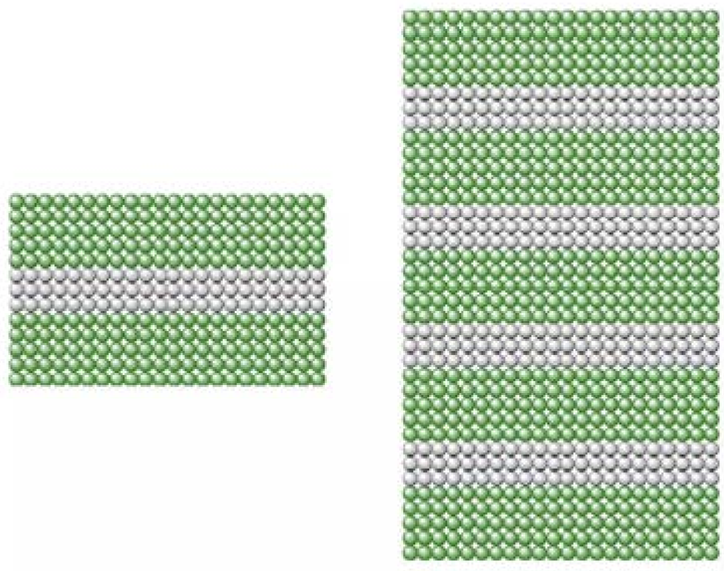
Figure 1. Schematic figure of magnetic multilayers. Nanometre thick layers of iron (green) are separated by nanometre thick spacer layers of a second metal (for example chromium or copper). The top figure illustrates the trilayer Fe/Cr/Fe used by Grünberg´s group (3), and the bottom the multilayer $(Fe/Cr)_n$, with n as high as 60, used by Fert´s group (4).

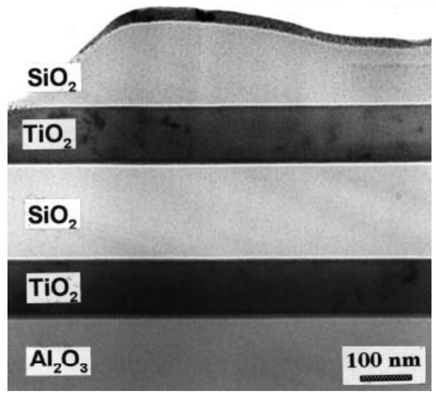


Molecular Beam Epitaxy: MBE during 1970s

MBE: Growth of Superlattices







Layer deposition with high purity and atomic thickness precision:Ultra high vacuum 10^{-11} torr
(Compare with atmosphere 10^{3} torr)

RAPID COMMUNICATIONS

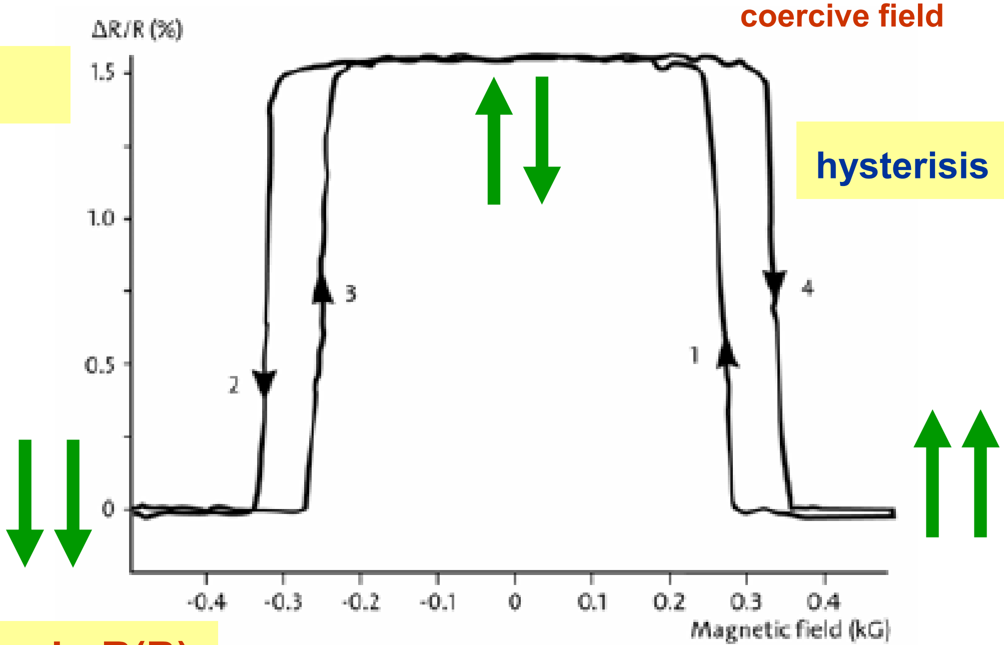
PHYSICAL REVIEW B VOLUME 39, NUMBER 7 1 MARCH 1989

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.

Fe-Cr-Fe trilayer at room temperature



10% decrease in R(B)

VOLUME 61, NUMBER 21 PHYSICAL REVIEW LETTERS 21 NOVEMBER 1988

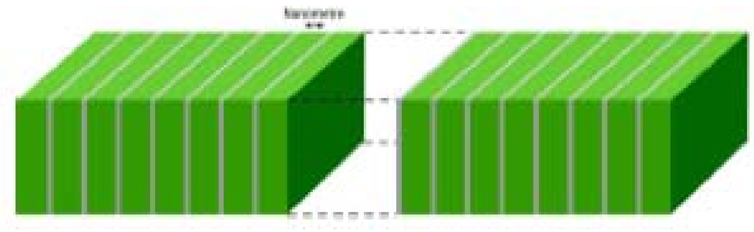
Giant Magnetoresistance of (001) Fe/(001) Cr Magnetic Superlattices

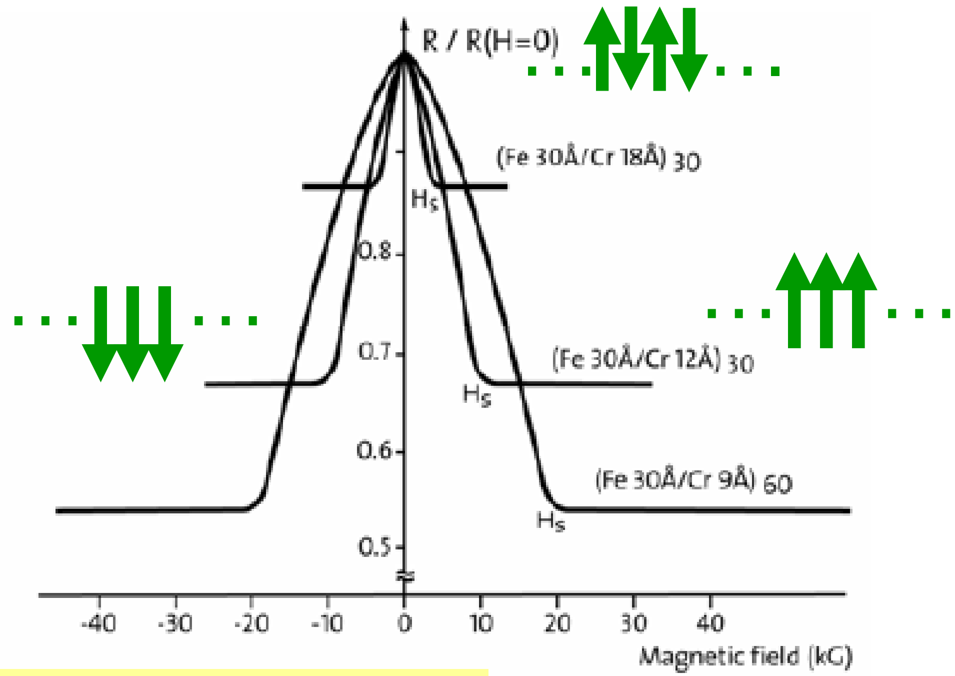
M. N. Baibich,[a] J. M. Broto, A. Fert, F. Nguyen Van Dau, and F. Petroff
Laboratoire de Physique des Solides, Université Paris-Sud, F-91405 Orsay, France

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.

$(FeCr)_{30,60}$ multilayer at T=4.2K



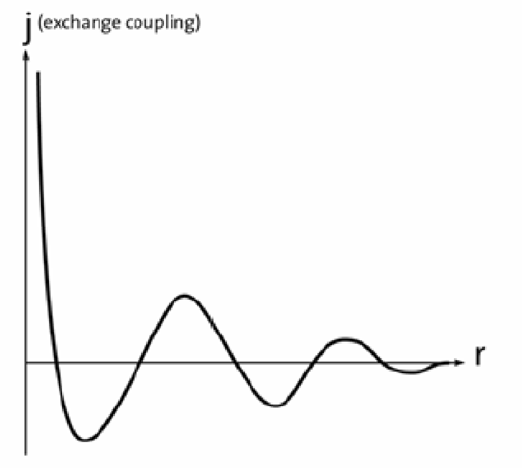


50% decrease in R(B): Giant MR

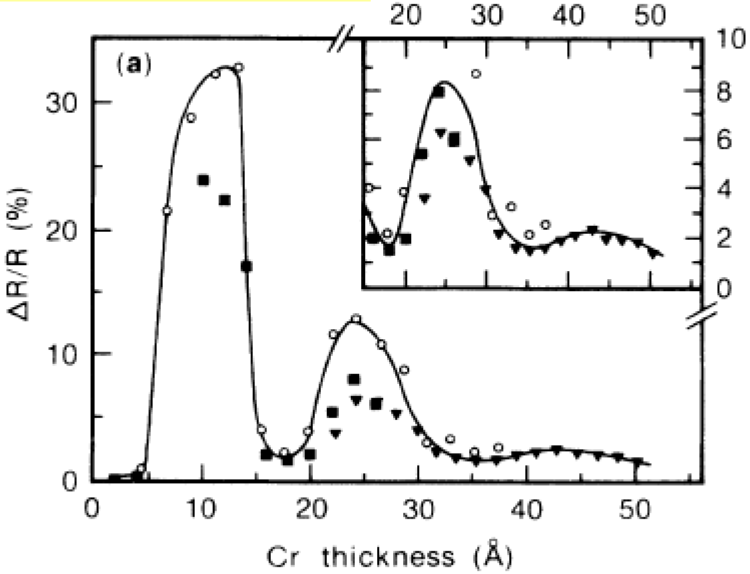
Interlayer Exchange Coupling

Spin Friedel Oscillations between two magnetic impurities

Similar coupling in F-multilayers: by magnetization measurements in equilibrium



$(FeCr)_{20}$ multilayer at T=4.5K



[S. S. P. Parkin et al, PRL **64**, 2304 (1990)]

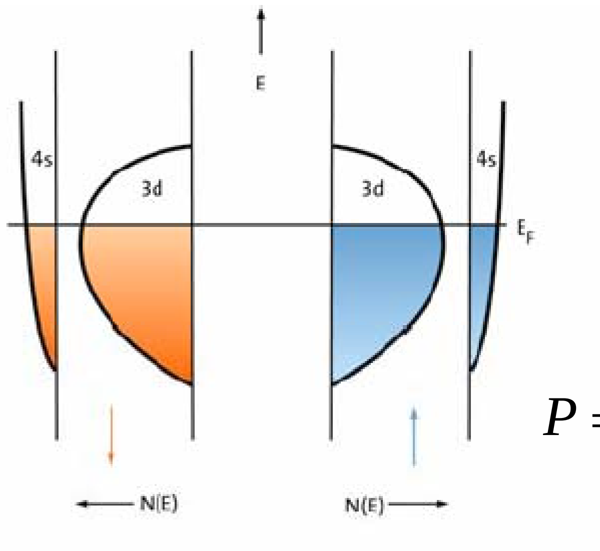
Spin physics in ferromagnets

Ferromagnetic metals

Energy bands in 3d transition metals: s-band is wider than d band

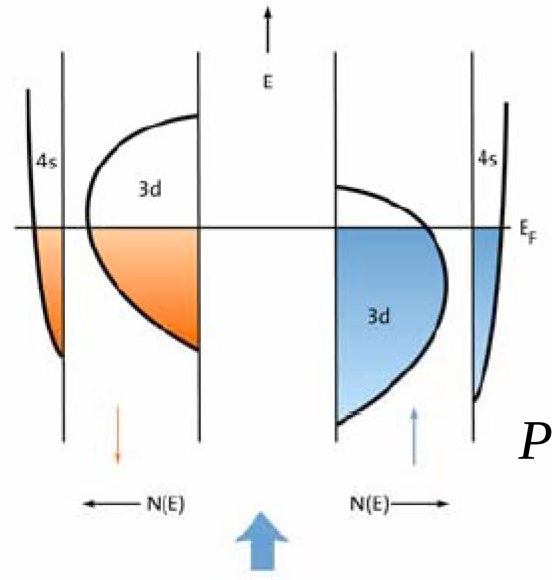
paramagnet

$P = 0$



$$P = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}}$$

ferromagnet



$P \neq 0$

Stoner criteria $E_{exh} N(E_F) > 1$

Imbalance in number of up and down e spins: band kinetic energy vs exchange energy E_{exh}
→ *Net magnetization*

high DOS, $N(E_F)$ of heavier 3d metals: Fe, Co, Ni

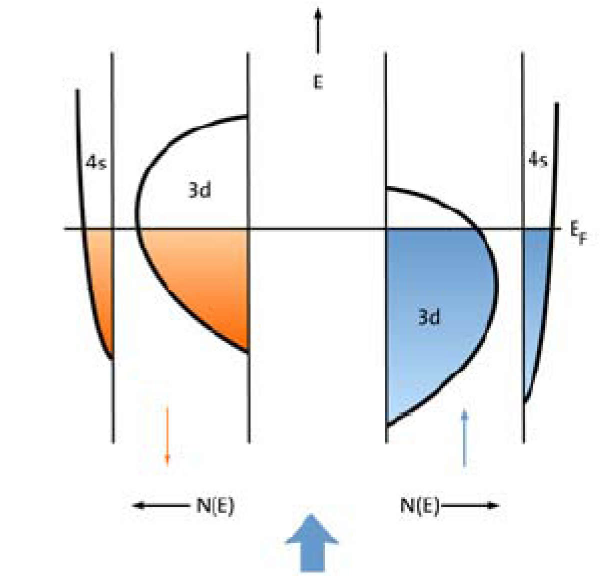
Curie temperature can be neglected at room temperature

Spin-polarized electrical current

Electrical Resistance= scattering of electrons by deviations from crystal periodic potential: e-imp, e-phonon, …

$$\sigma = \sigma_{\uparrow} + \sigma_{\downarrow}$$

In ferromagnets 2 types of up and down s-bands : different rate of scattering to respective d-bands

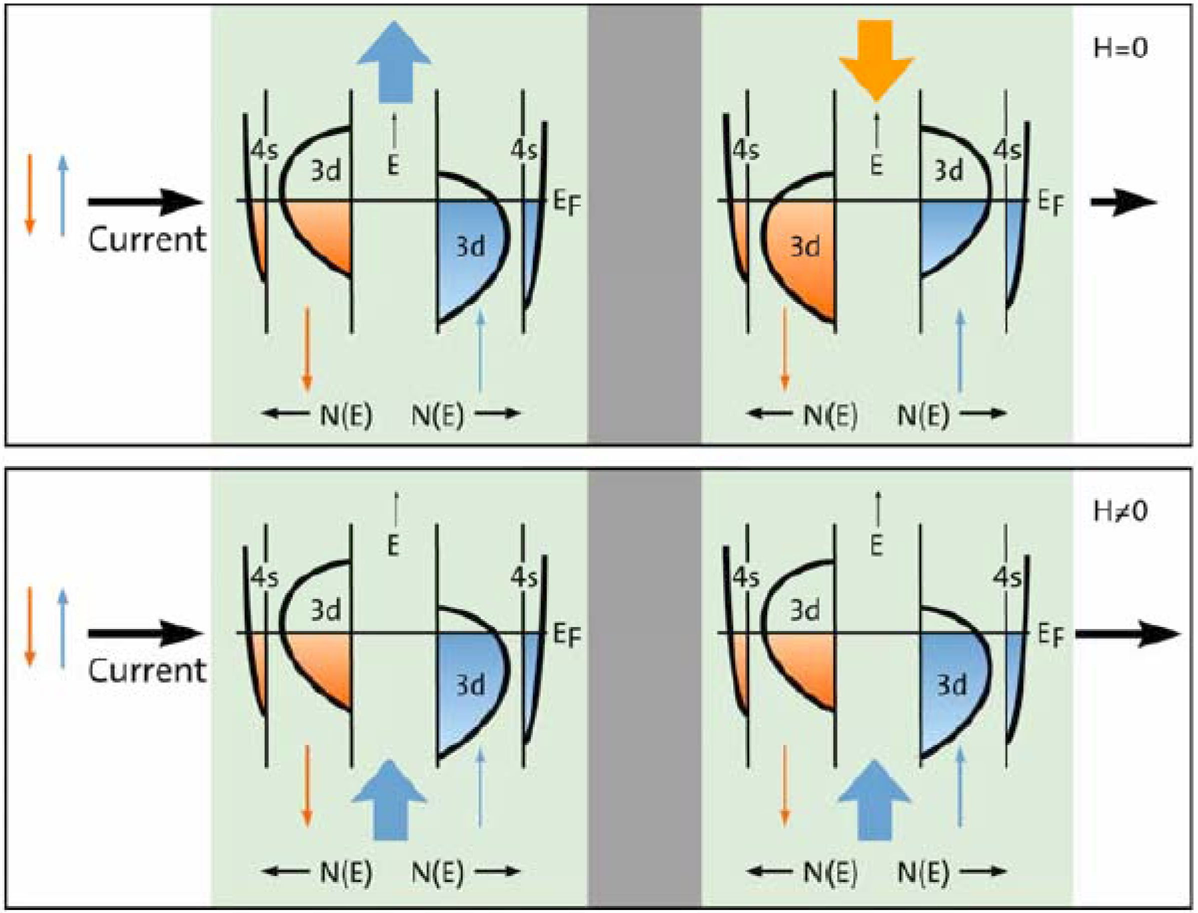


$$P = \frac{N_{\uparrow} - N_{\uparrow}}{N_{\uparrow} + N_{\uparrow}}$$

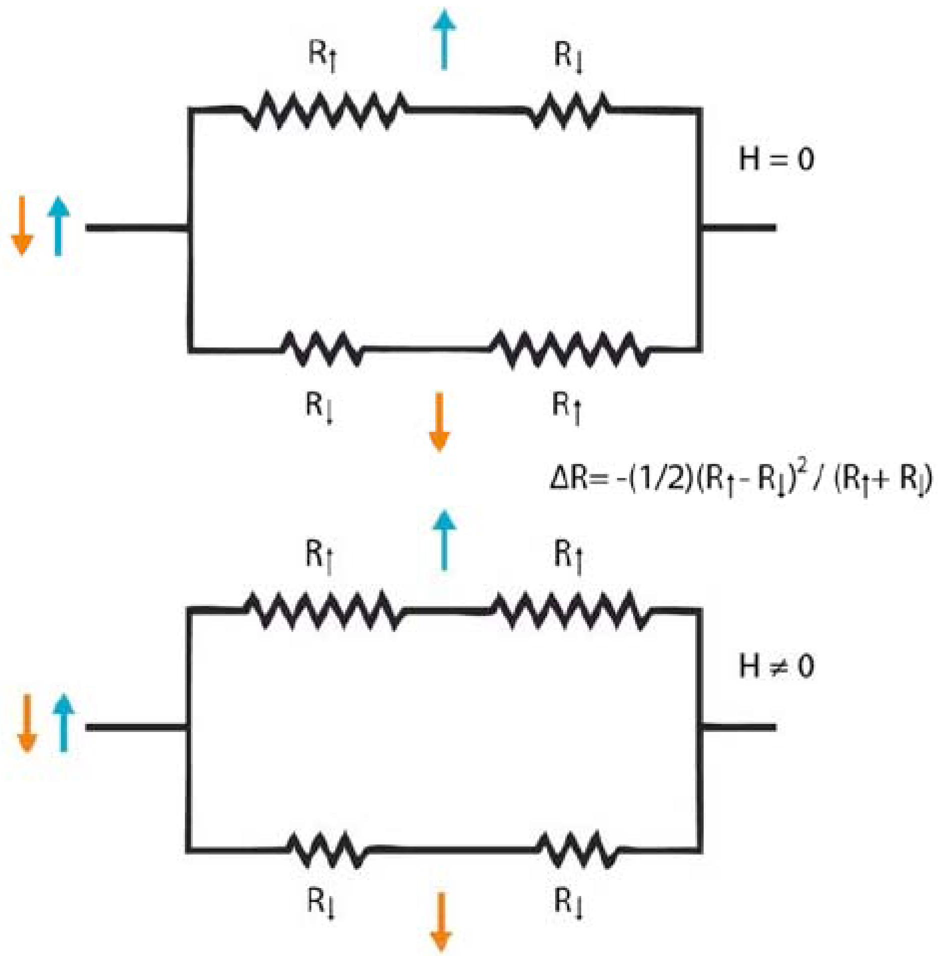
$$\sigma_{\uparrow} \neq \sigma_{\downarrow}$$

[N. Mott, Proc. Roy. Soc. A **153**, 699 (1963)]

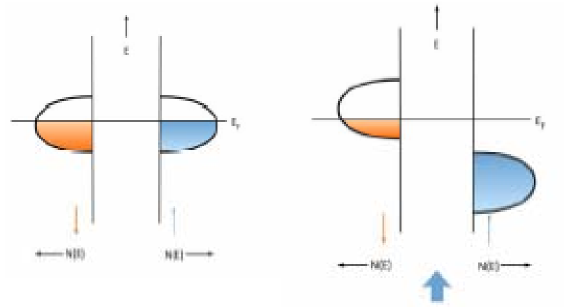
Giant Magnetoresistance

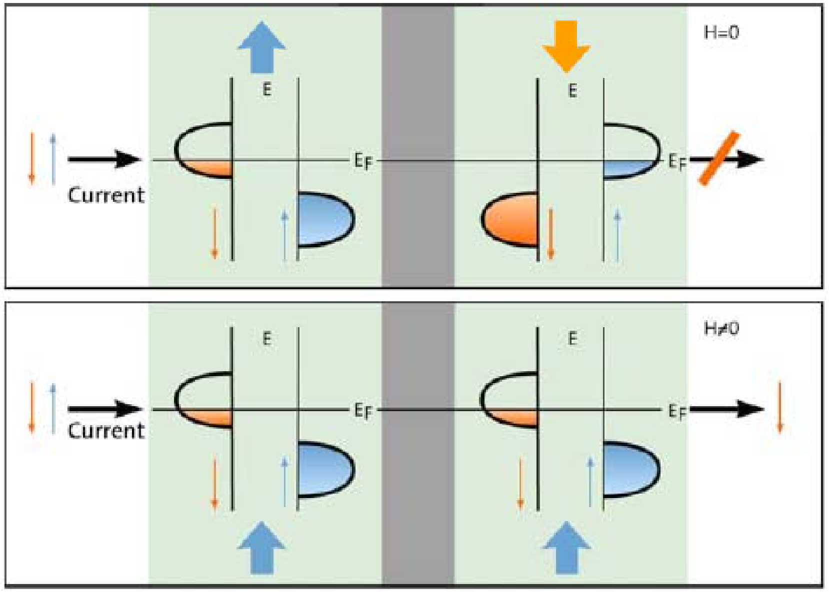


Circuit Model



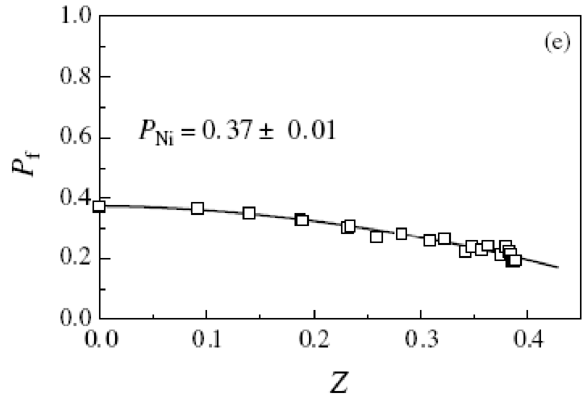
Half-metal GMR systems

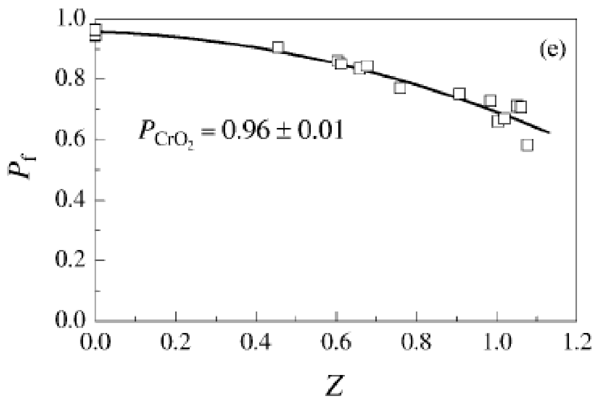




[R. A, deGroot, et al, PRL **50**, 2024 (1983)]

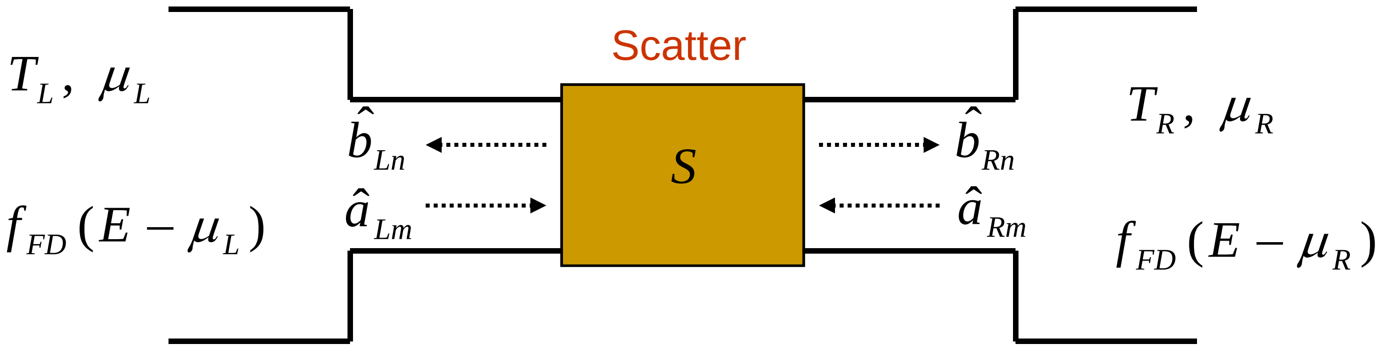
Superconducting point contact spectroscopy: ~100% spin polarization with CrO_2





[Y. Ji, et al, PRL **86**, 005585 (1983)]

Scattering formalism: Landau-Buettiker formula



$$S = \begin{pmatrix} s_{LL} & s_{LR} \\ s_{RL} & s_{RR} \end{pmatrix} \equiv \begin{pmatrix} r & r' \\ t & t' \end{pmatrix}$$

Incoming and out going creation and annihilation operators

$$\hat{a}^{\div}_{\alpha m} \qquad \hat{a}_{\alpha m}$$

$$\hat{b}^{\div}_{\alpha m} \qquad \hat{b}_{\alpha m}$$

$$\left\{\hat{a}^{\div}_{\alpha m}(E), \hat{a}_{\beta n}(E')\right\} = \delta_{\alpha\beta}\delta_{mn}\delta(E-E')$$

$$\left\{\hat{a}^{\div}_{\alpha m}(E), \hat{a}^{\div}_{\beta n}(E')\right\} = 0$$

$$\left\{\hat{a}_{\alpha m}(E), \hat{a}_{\beta n}(E')\right\} = 0 \qquad \alpha, \beta \equiv L, R$$

Scattering formalism: Landauer-Buttiker formula

$$\begin{pmatrix} \hat{b}_{L1} \\ \vdots \\ \hat{b}_{LN_L} \\ \hat{b}_{R1} \\ \vdots \\ \hat{b}_{RN_R} \end{pmatrix} = S \begin{pmatrix} \hat{a}_{L1} \\ \vdots \\ \hat{a}_{LN_L} \\ \hat{a}_{R1} \\ \vdots \\ \hat{a}_{RN_R} \end{pmatrix}$$

$$\hat{b}_{\alpha m}(E) = \sum_n s_{\beta\alpha;mn}(E)\hat{a}_{\beta n}(E)$$

$$S = \begin{pmatrix} s_{LL} & s_{LR} \\ s_{RL} & s_{RR} \end{pmatrix} \equiv \begin{pmatrix} r & r' \\ t & t' \end{pmatrix}$$

$$G = \frac{2e^2}{h}\sum_{nm}|t_{nm}|^2 = \frac{2e^2}{h}\sum_n T_n \ ,$$

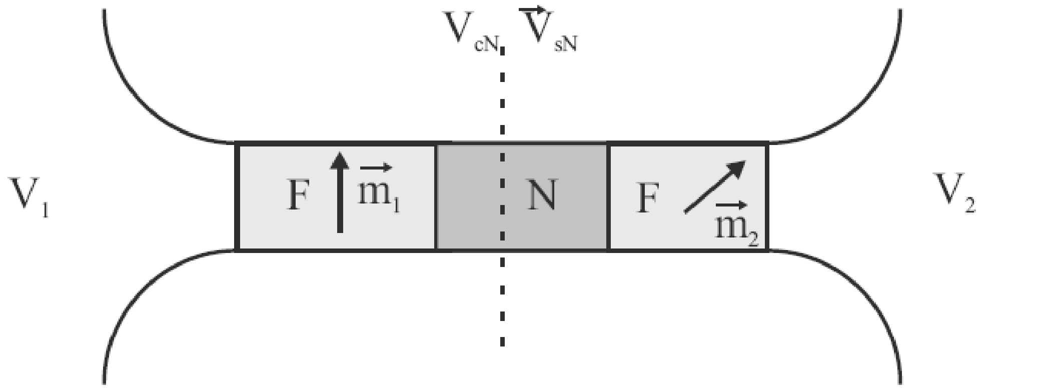
$$G = \frac{e^2}{h}\sum_{n\sigma m\sigma'}|t_{n\sigma m\sigma'}|^2 \ .$$

Conductance matrix

Collinear (diagonal) vs non-collinear (mixing conductance)

$$\hat{g} = \begin{pmatrix} g^{\uparrow} & g^{\uparrow\downarrow} \\ g^{\downarrow\uparrow} & g^{\downarrow} \end{pmatrix} = \sum_{nm} \begin{pmatrix} \delta_{nm} - |r^{\uparrow}_{nm}|^2 & \delta_{nm} - r^{\uparrow}_{nm}(r^{\downarrow}_{nm})^* \\ \delta_{nm} - r^{\downarrow}_{nm}(r^{\uparrow}_{nm})^* & \delta_{nm} - |r^{\downarrow}_{nm}|^2 \end{pmatrix} \ .$$

Scattering formalism: Landau-Buettiker formula



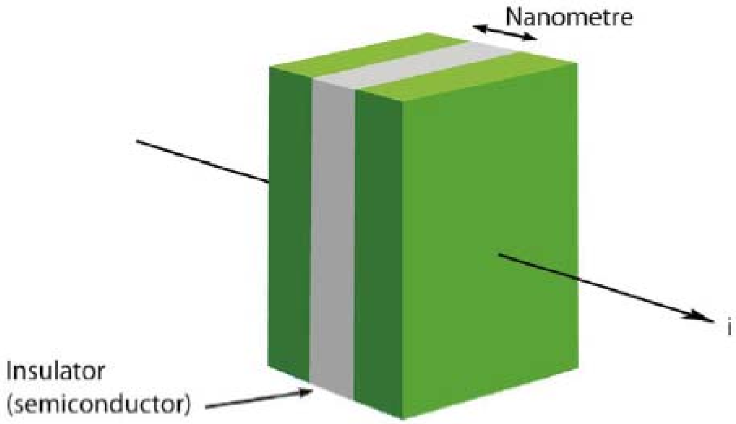
Stoner Hamiltonian

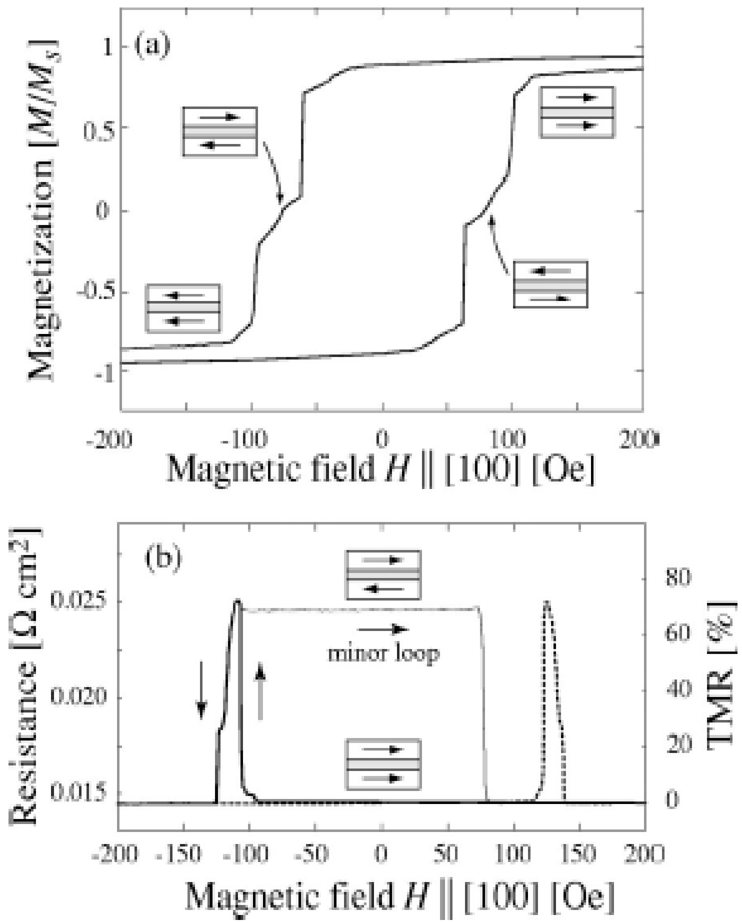
$$\hat{H} = \left[-\frac{1}{2m}\nabla^{2} + V^{C}(\vec{r})\right]\hat{1} + \hat{V}^{S}(\vec{r}),$$

$$\hat{V}^{S}(\vec{r}) = (\vec{\boldsymbol{\sigma}} \cdot \vec{m}(\vec{r}))V^{S}(\vec{r}),$$

Tunnelling Magnetoresistance

[M. Julliere, et al, Phys. Lett. A **54**, 225 (1975)]

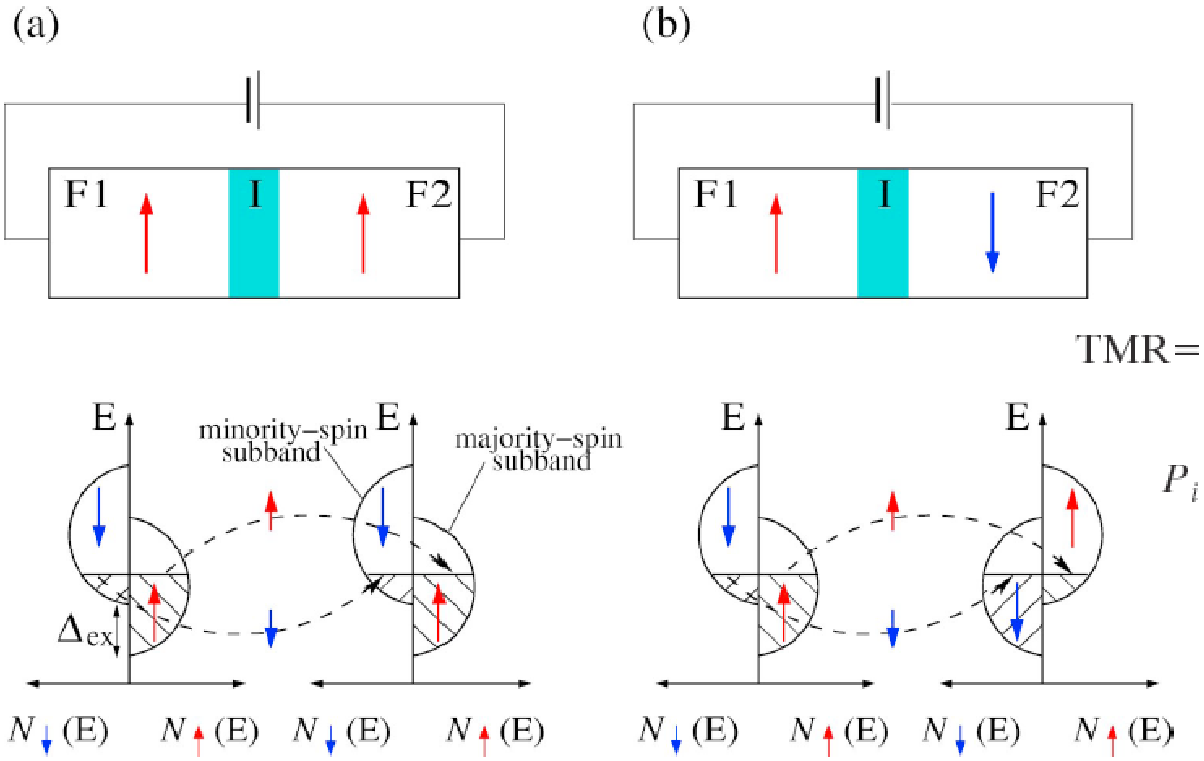




TMR non-volatile MRAMs in market!

[M. Tanaka and Y. Higo, PRL **87**, 026602 (2001)]

Tunnelling Magnetoresistance



$$G_{\uparrow\downarrow} \sim \mathcal{N}_{M1}\mathcal{N}_{m2} + \mathcal{N}_{m1}\mathcal{N}_{M2}$$

$$G_{\uparrow\uparrow} \sim \mathcal{N}_{M1}\mathcal{N}_{M2} + \mathcal{N}_{m1}\mathcal{N}_{m2}$$

$$\mathrm{TMR} = \frac{\Delta R}{R_{\uparrow\uparrow}} = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}} = \frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\downarrow}},$$

$$P_i = (\mathcal{N}_{Mi} - \mathcal{N}_{mi})/(\mathcal{N}_{Mi} + \mathcal{N}_{mi})$$

$$\mathrm{TMR} = \frac{2P_1P_2}{1 - P_1P_2},$$

[M. Tanaka and Y. Higo, PRL **87**, 026602 (2001)]

Applications

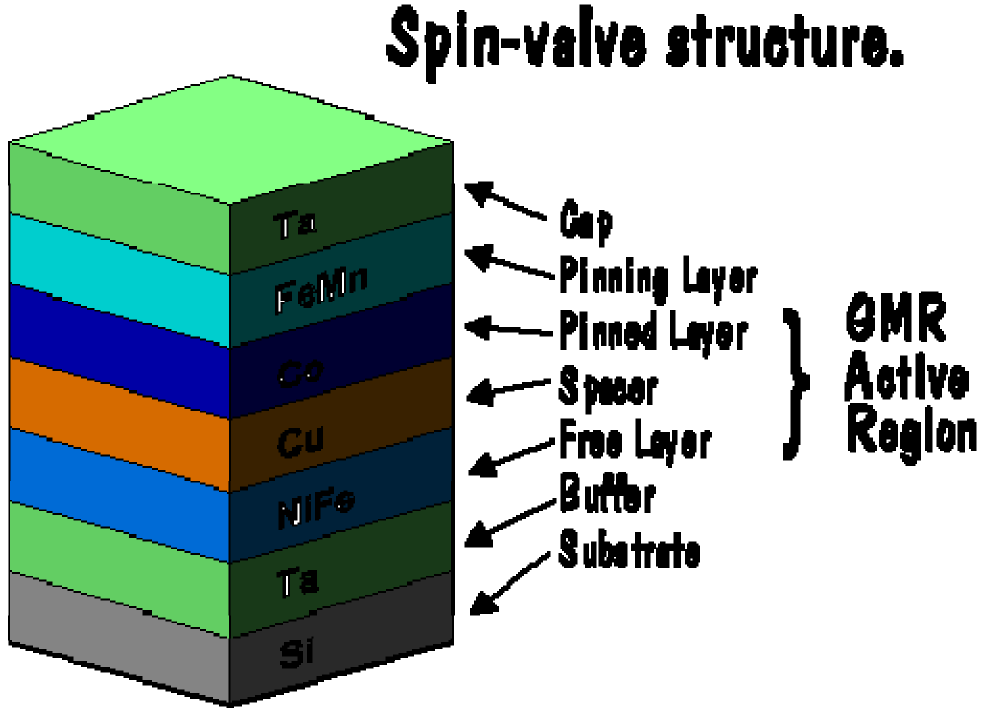
•Magnetic read heads

•Magnetic sensors

•Nonvolatile MRAMs (magnetic random access memory)

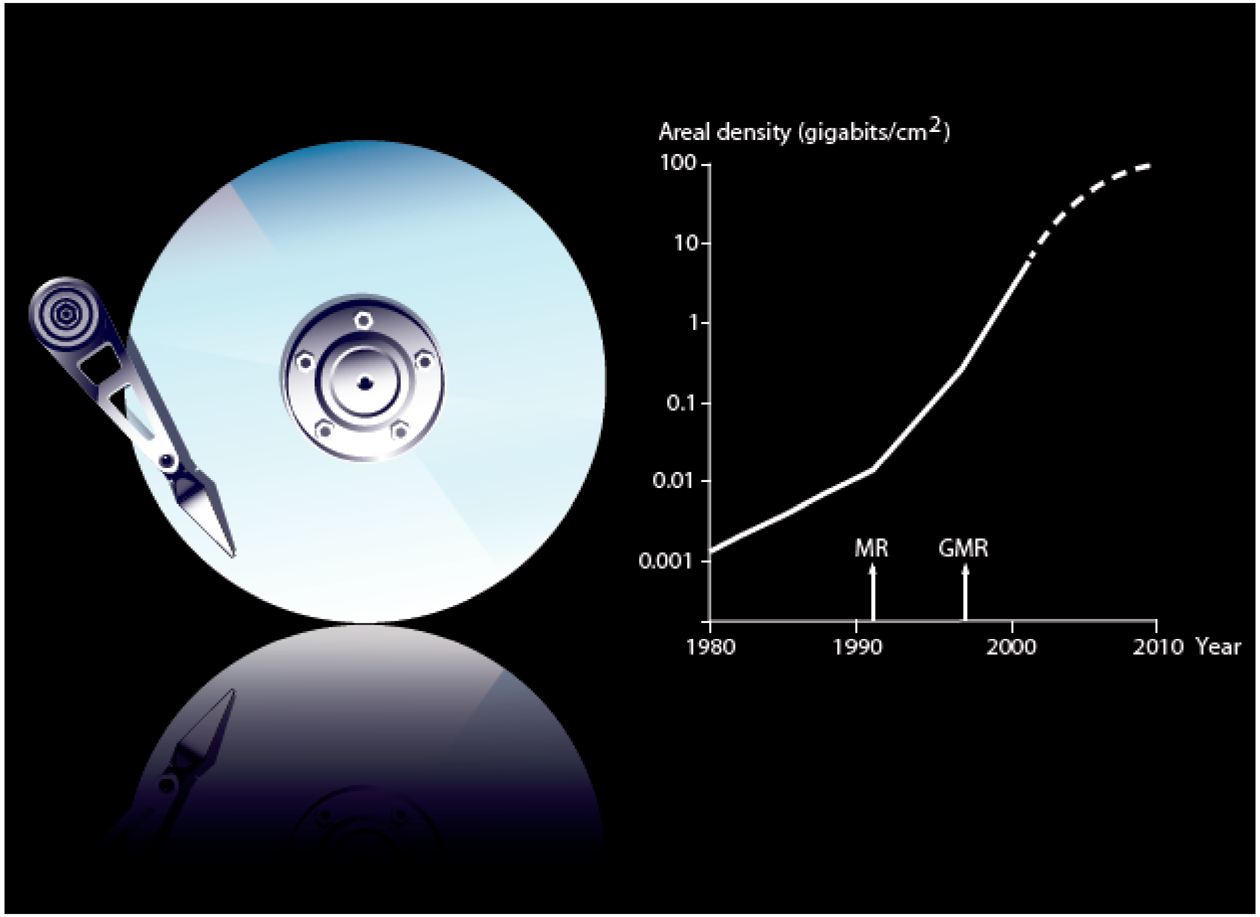
•Quantum computers

•……….



http://www.research.ibm.com/research/demos/gmr/index.html

Read heads for pocket sized compact disks

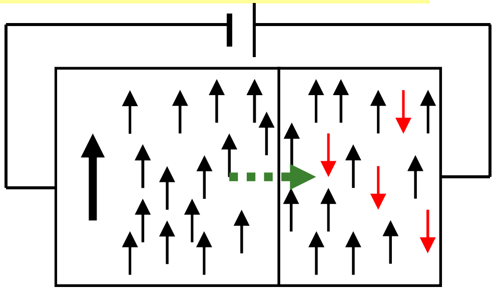


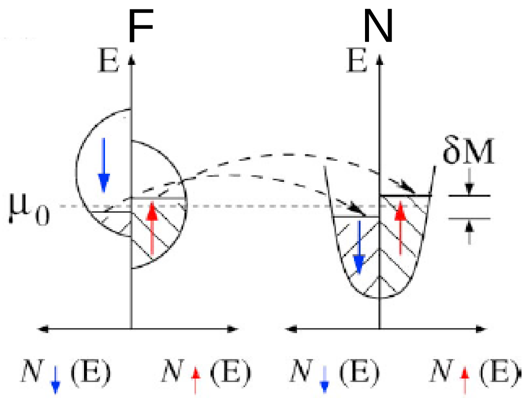
http://www.research.ibm.com/research/demos/gmr/index.html

Spintronics

- **Spin control of the currents and voltages (I-V characteristics)**
- **Currents or voltages control of spin (magnetization)**

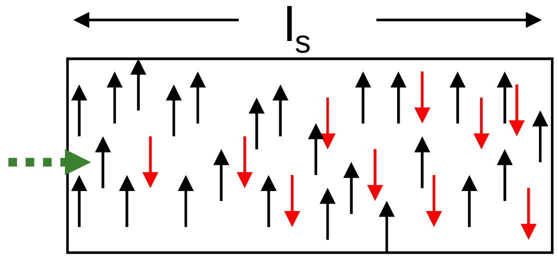
•Effective spin injection





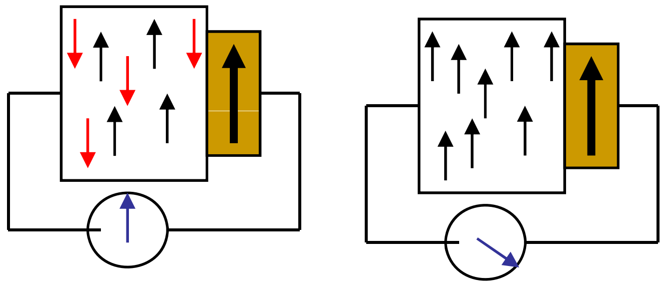
•spin accumulation

•Slow spin relaxation



•spin manipulation

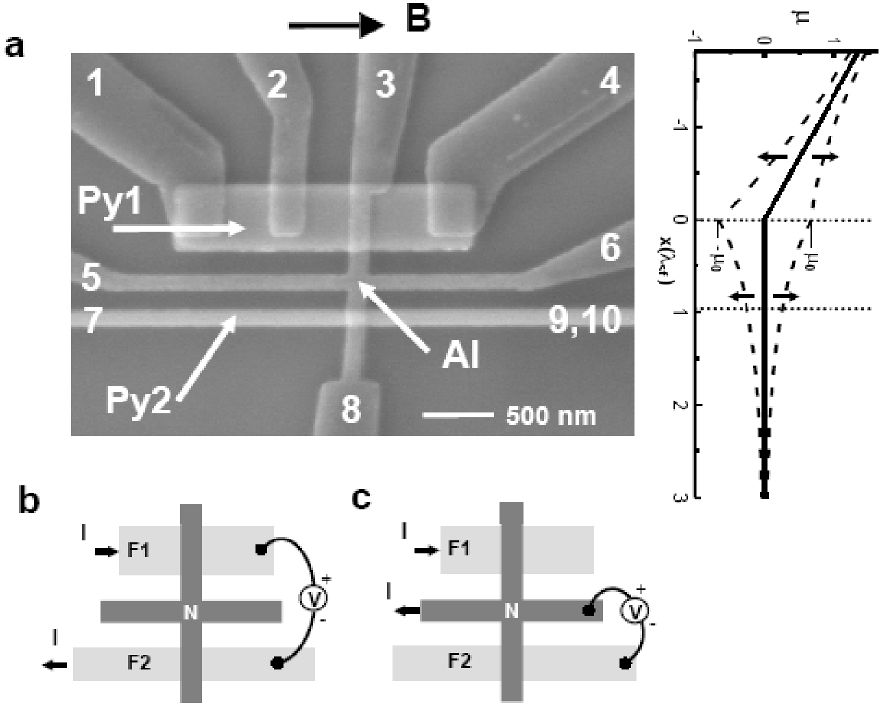
•Reliable spin detection

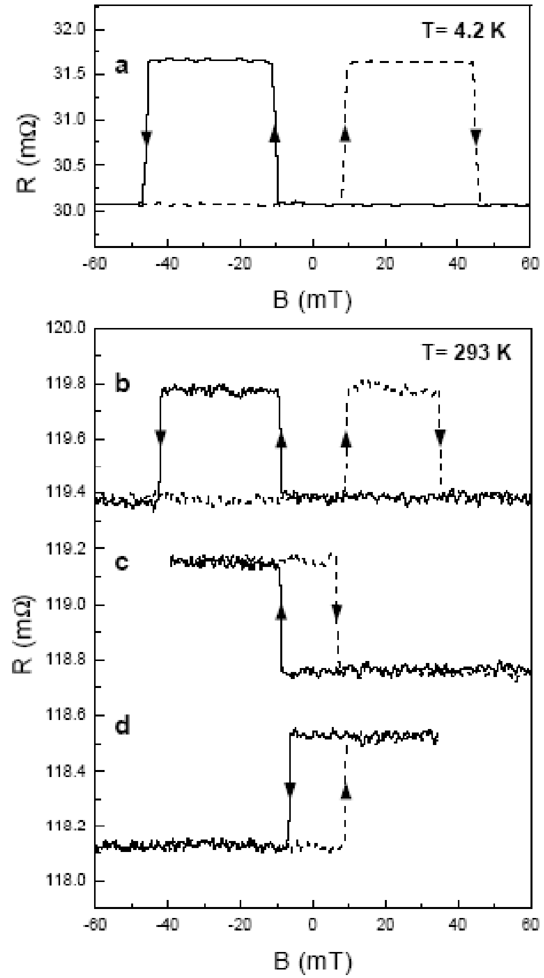


[I. Zutic, et al, Rev. Mod. Phys. **76**, 323 (2004);
Y. Tserkovnyak et al, Rev. Mod. Phys. **77**, 13753 (2005);
A. Brataas et al, Phys. Rep. (2006),….]

Spin injection at room temperature

Metallic Spin-Valve



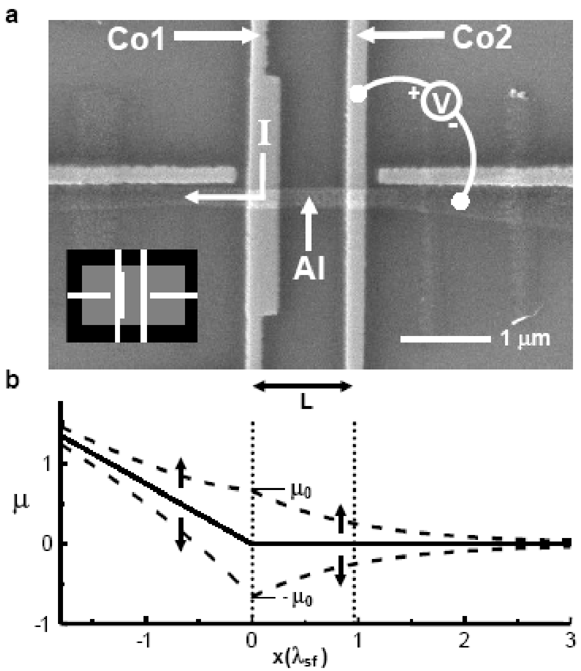


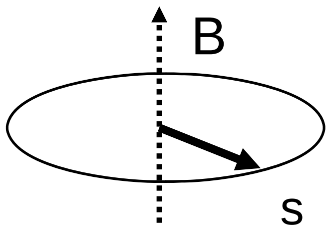
F electrodes permalloy (NiFe); different sizes: different coercive fields;

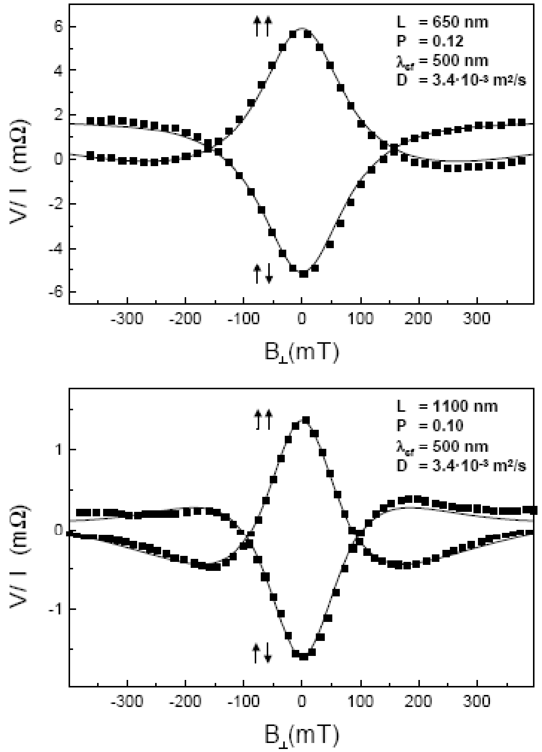
[Jedema et al., Nature **416,** 713(2002)]

Spin precession at room temperature

A perpendicular magnetic field causes precession of spin of electron traveling between F electrodes







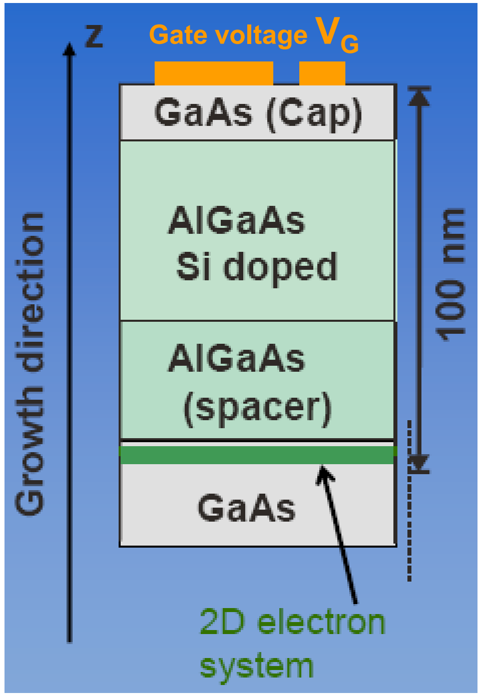
[Jedema et al., Nature **416,** 713(2002)]

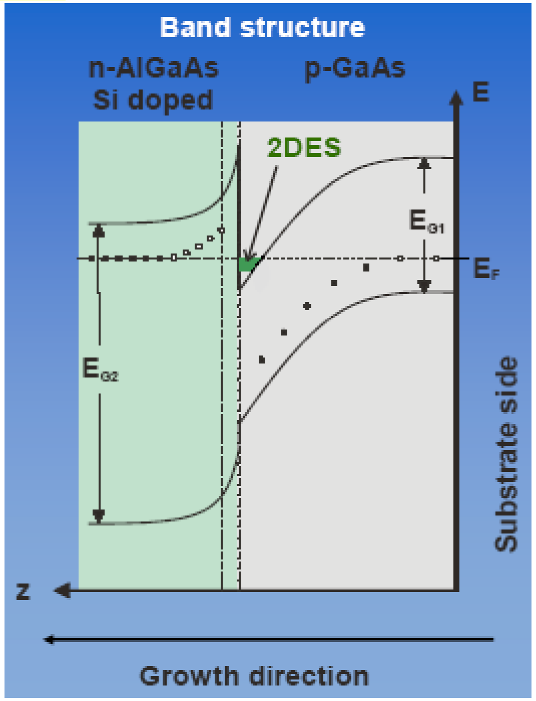
Semiconductor spintronics

Advantages:
- Variable carrier concentration
- Compatibility with current technology
- Long spin flip length

interaction of spin of mobile electron with the structural potential: spin-orbit coupling→
controlled spin dynamic: **an effective magnetic field Ω**
Scattering from Disorders **: spin relaxation**

2DEG in semiconducting hetrostructures



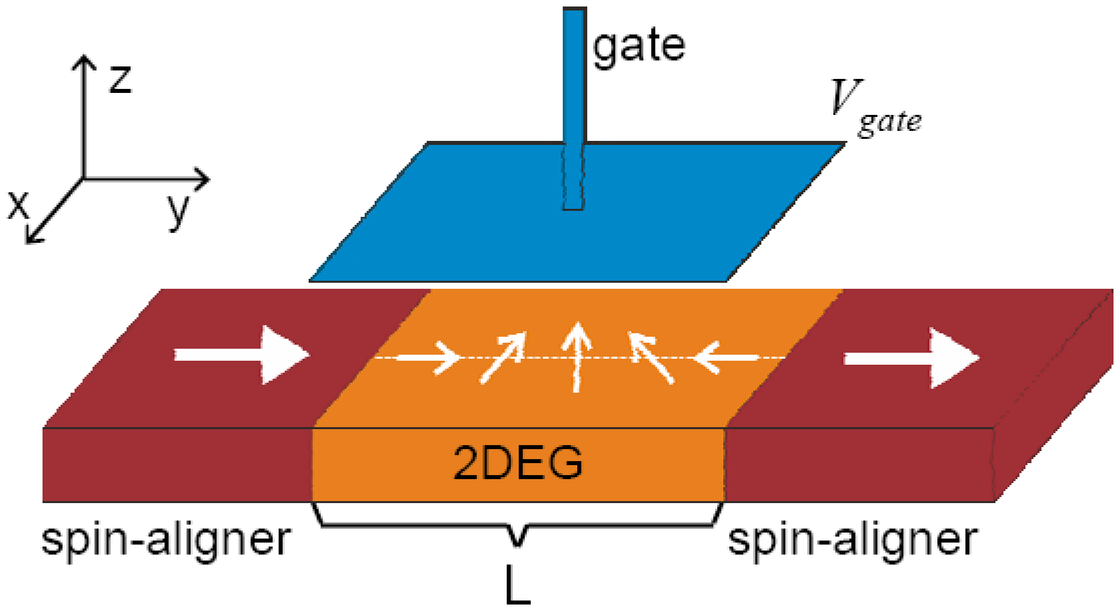


Datta-Das spin field effect transistor

- **normal FET: source, drain, a narrow channel, current controlling gate**

Gate voltage: off or on

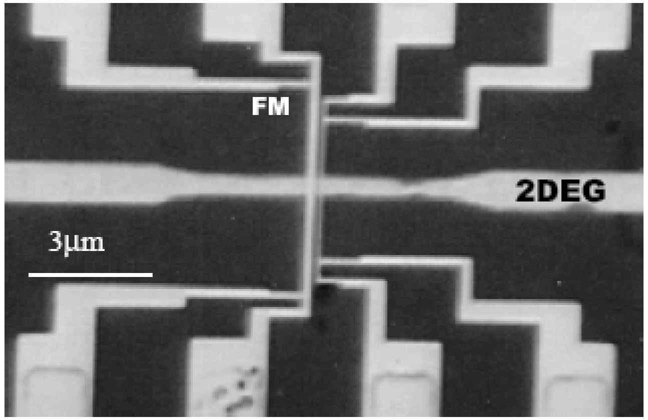
- **SFET: spin injector, detector, a narrow channel, current controlling gate voltage control spin-orbit: effective magnetic field (Ω): off or on**

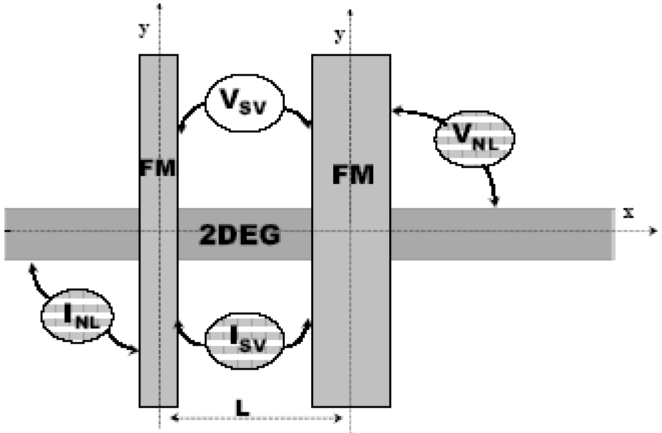


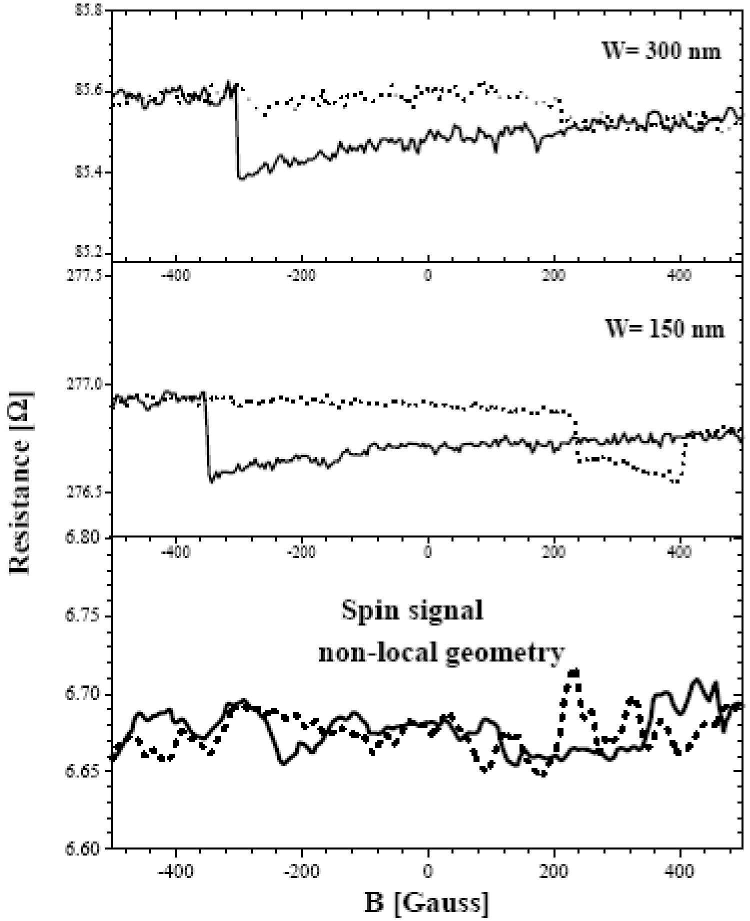
[S. Datta and B. Das, Appl. Phys. Lett. **56,** 665(1990)]

Semiconducting Spin-Valve

Week signals: bad metal-semiconductor contacts, other effects AMR, HE,..?

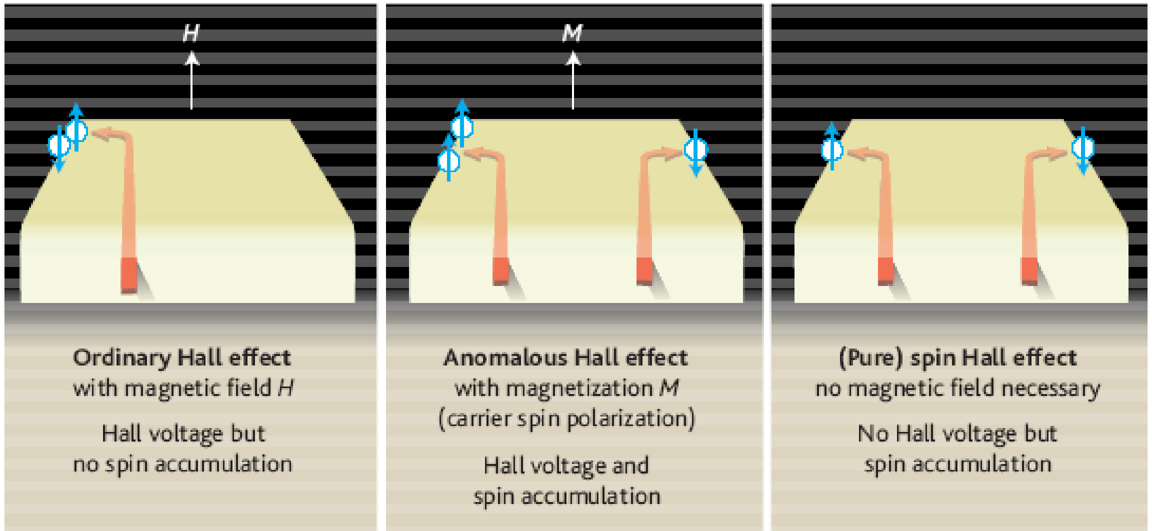






[A. T. Philip et al, PRB **62,** (2000)]

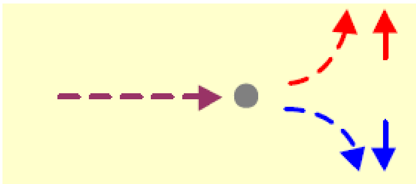
Spin Hall effect



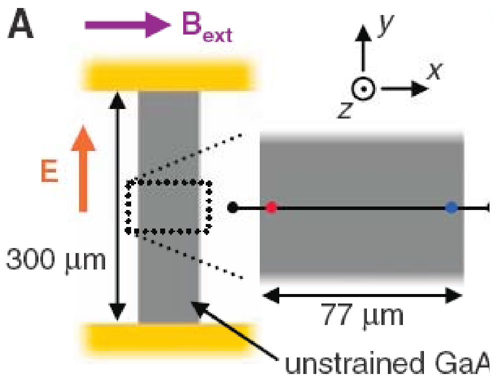
Local Kerr rotation of polarization axis of linearly polarized light at T=30K: direction of spin accumulation

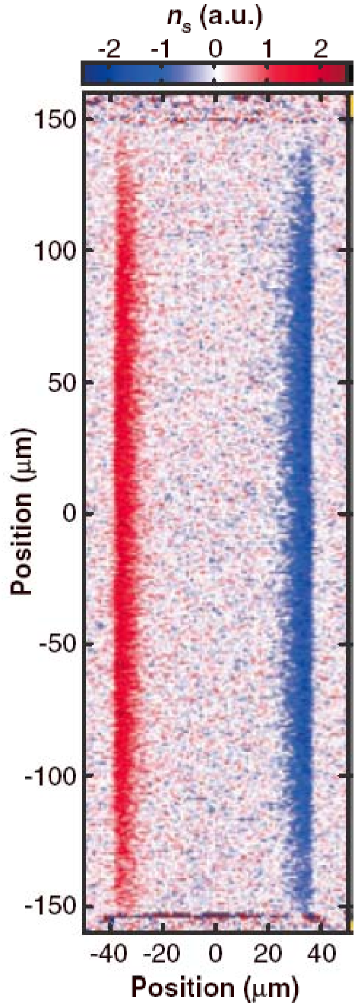
scattering from spinless impurity & SO coupling: skew scattering

[M. I. Dyakonov and V. I. Perel, JETP Lett. **13,** 467(1971)]



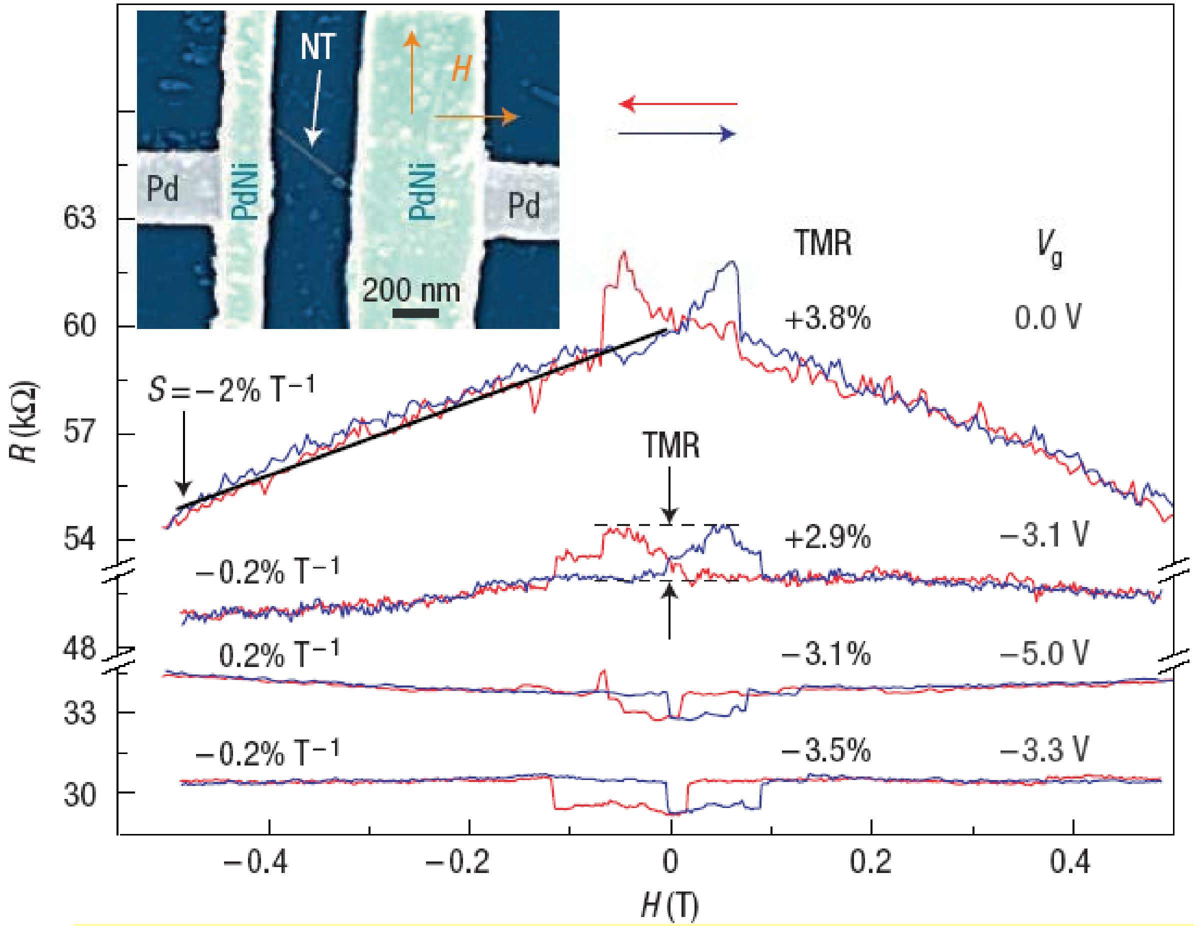
Also may caused by band structure
(intrinsic vs extrinsic)





[Y. K. Kato et al, Science **306,** 1910(2004)]

Nanotube Spin-Valve

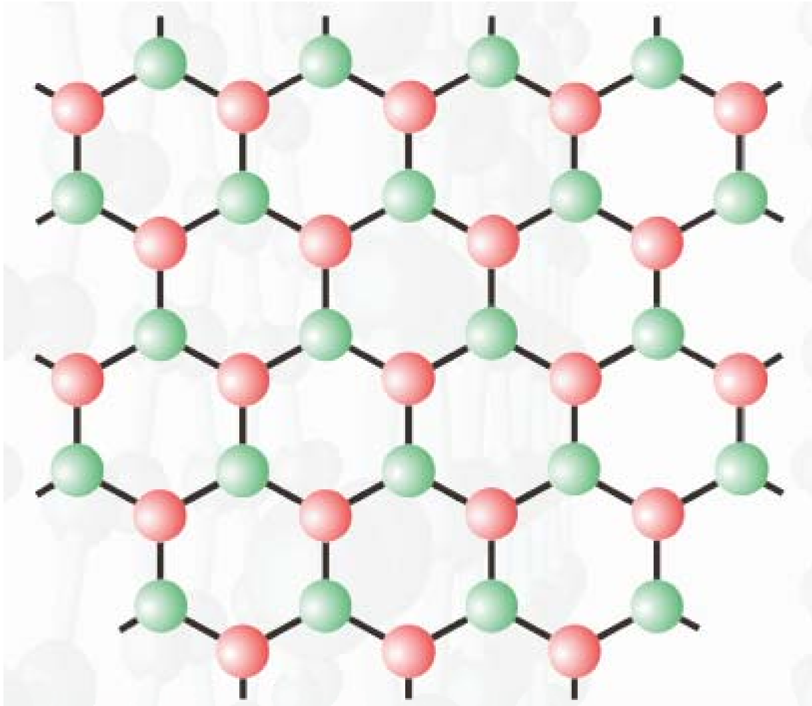


Gate voltage induced GMR change of sign in F-NT-F at T=1.85K

[S. Sahoo et al, Nature Physics **1,** 99 (2005)]

New 2D material: Graphene

Isolated single one atom thick honeycomb lattice of carbon atoms: Two (A and B) sublattices



4-component spinor in two (A,B)sublattices space (pseudospin) and two (-,+)-valley space

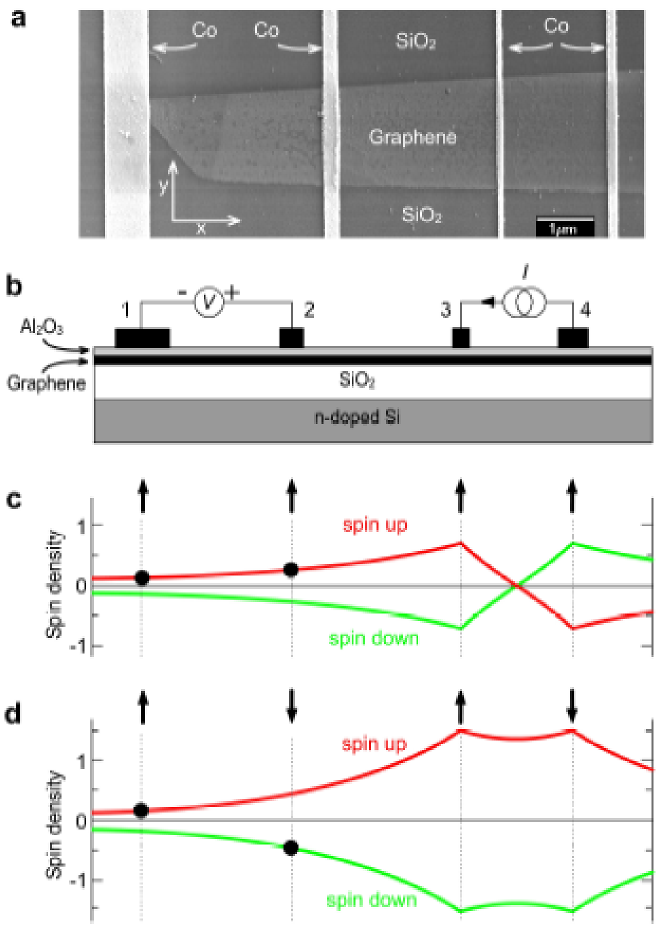
$$\hat{u} = \begin{pmatrix} \psi_A^+ \\ \psi_B^+ \\ \psi_A^- \\ \psi_B^- \end{pmatrix}$$

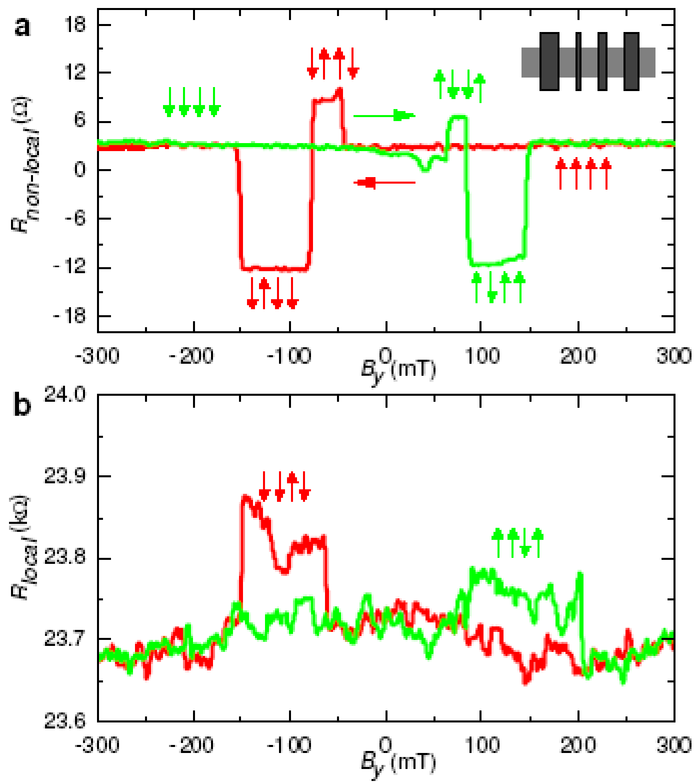
$$\varepsilon(\boldsymbol{k}) = \hbar v |\boldsymbol{k}|$$

electrons behave like massless Dirac fermions: Relativistic condensed matter physics!

[Novesolov et al, Nature **438**, 197 (2005); Zhang et al, Nature **438**, 201 (2005); …]

Graphene Spin-Valve

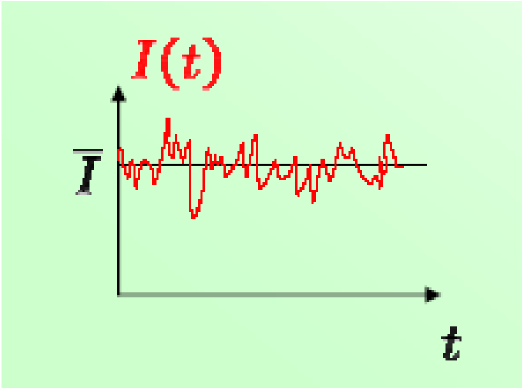




Valley: additional degree of freedom: Valley Valve [A. Rycerz et al, Nature Physics **3**, 172 (2007)]: **valleytronics!**

[N. Tomboros et al, Nature **448,** 571(2007)]

Quantum Shot Noise in Spin-Valves



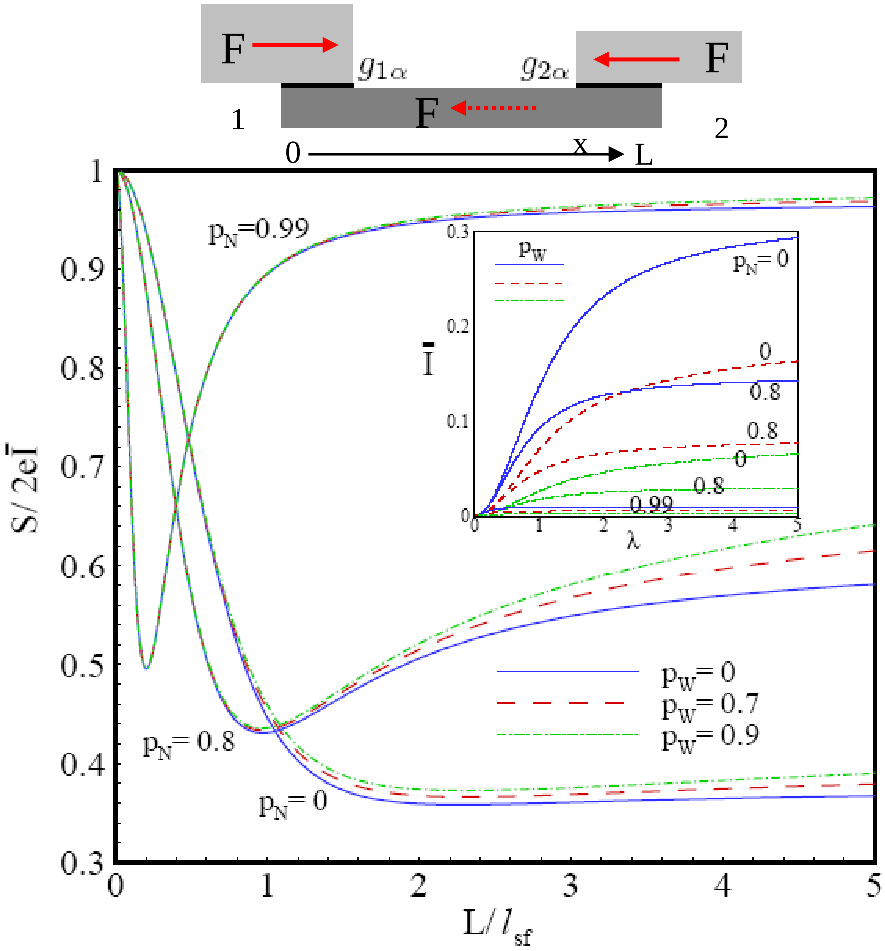
$$\Delta I(t) = I(t) - \langle I(t) \rangle$$

Noise power:

$$S(\omega) = 2\int_{-\infty}^{\infty} dt e^{-\imath\omega t} \langle \Delta I(t) \Delta I(0) \rangle,$$

Shot noise provide unique Information about charge, statistic and the scattering of charge carriers. [Ya. M. Blanter and M. Buettiker, Phys. Rep. 336, 1 (2000)].

100% polarized terminals



RAPID COMMUNICATIONS

PHYSICAL REVIEW B **69**, 140407(R) (2004)

Spin-flip noise in a multiterminal spin valve

W. Belzig[1] and M. Zareyan[2,3]

PHYSICAL REVIEW B **71**, 184403 (2005)

Semiclassical theory of spin-polarized shot noise in mesoscopic diffusive conductors

M. Zareyan[1,2] and W. Belzig[3]

EUROPHYSICS LETTERS 15 June 2005

Europhys. Lett., **70** (6), pp. 817–823 (2005)

DOI: 10.1209/epl/i2005-10036-0

Shot noise of spin current in ferromagnet-normal-metal systems

M. Zareyan[1,2] and W. Belzig[3]

PHYSICAL REVIEW B **73**, 172409 (2006)

Shot noise in diffusive ferromagnetic metals

M. Hatami and M. Zareyan

PHYSICAL REVIEW B **73**, 214442 (2006)

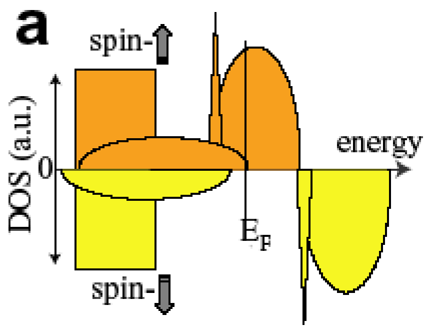
Magneto shot noise in noncollinear diffusive spinvalves

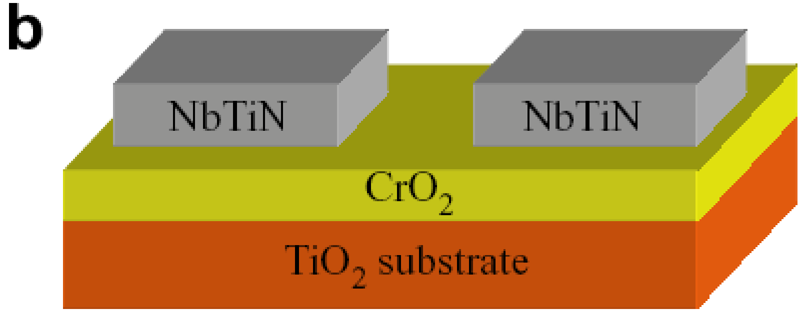
B. Abdollahipour and M. Zareyan

Hetrostructures of ferromagnets and superconductors

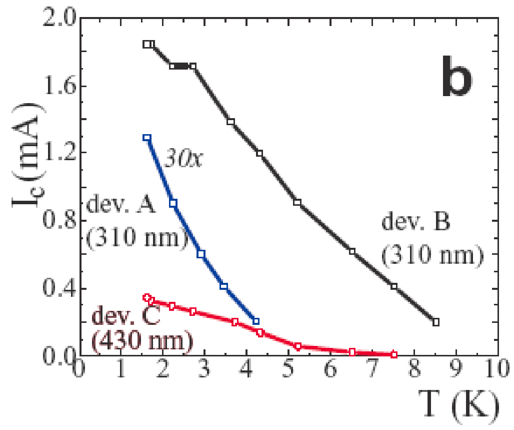
Coexistence of superconductivity and ferromagnetism:

Proximity and Josephson effects: interesting physics And applications





New experimental results [Klapwijk group at Delft, Nature, 439, 825 (2006)]**:**



Projects:

•FS structures with nonhomogeneous and noncollinear magnetizations

•Interlayer exchange coupling: FSN multilayers ; Ferromagnetic superconductors-N systems

•Spin Hall effect: with superconducting hetrostructures?

More recent developements

- Spin torque devices
- Noncollierar magnetoelectronics
- Spin-field effect devices
- Magnetic semiconductor tunnel junction devices
- Spin optoelectronics
- Mesoscopic spintronics
- Spin-polarized semiconductor lasers

- ……

TMR nonvolatile MRAMs