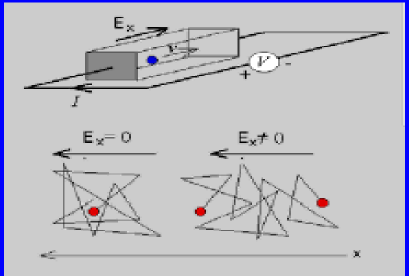
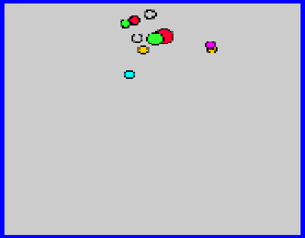
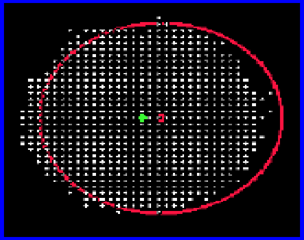
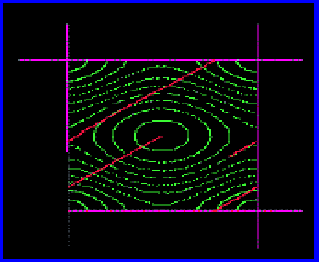
Transport Phenomena in Solids

Motions of electrons and transport phenomena



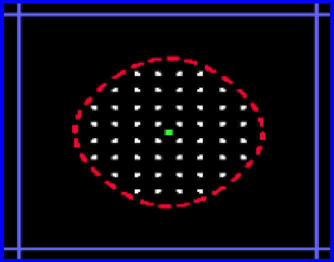


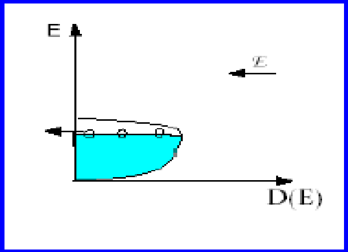


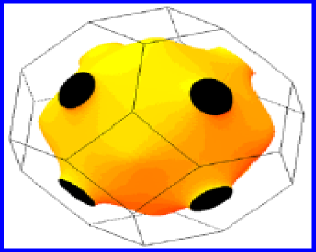


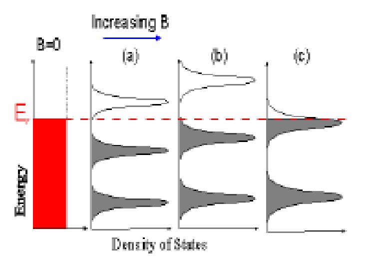
$$\sigma = \frac{ne^2\tau}{m}$$

$$\left(\frac{1}{m^*}\right)_{ij} = \frac{1}{\hbar^2}\sum_j \frac{\partial^2 E(\vec{k})}{\partial k_i \partial k_j}$$









Some pictures are taken from the UvA-VU Master Course: Advanced Solid State Physics by Anne de Visser (University of Amsterdam), from Ashcroft and Mermin and from several sources on the web.

TUNNEL MAGNETORESISTANCE

Recap

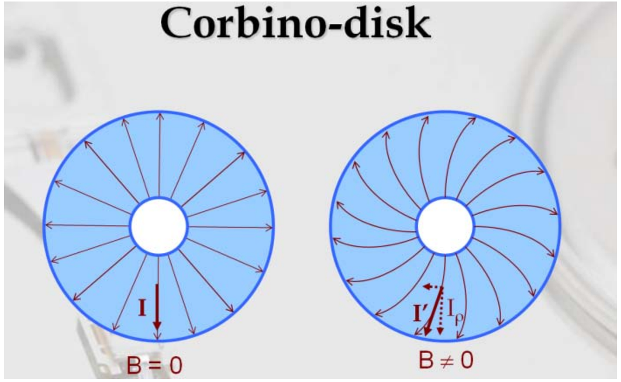
Magnetoresistance is the property of a material to change the value of its electrical resistance when an external magnetic field is applied to it.

$$\boxed{MR = (\rho(H) - \rho(0)) / \rho(0)}$$

The level of magnetoresistance shown by a material is usually expressed in terms of the **percentage change in resistance** from the highest to the lowest resistance and is usually of the order of **a few percent**. The main application for MR sensors is in the read heads of hard disk drives.

Ordinary Magnetoresistance

Lorentz force acting on trajectory of electron; longitudinal magnetoresistance (MR).



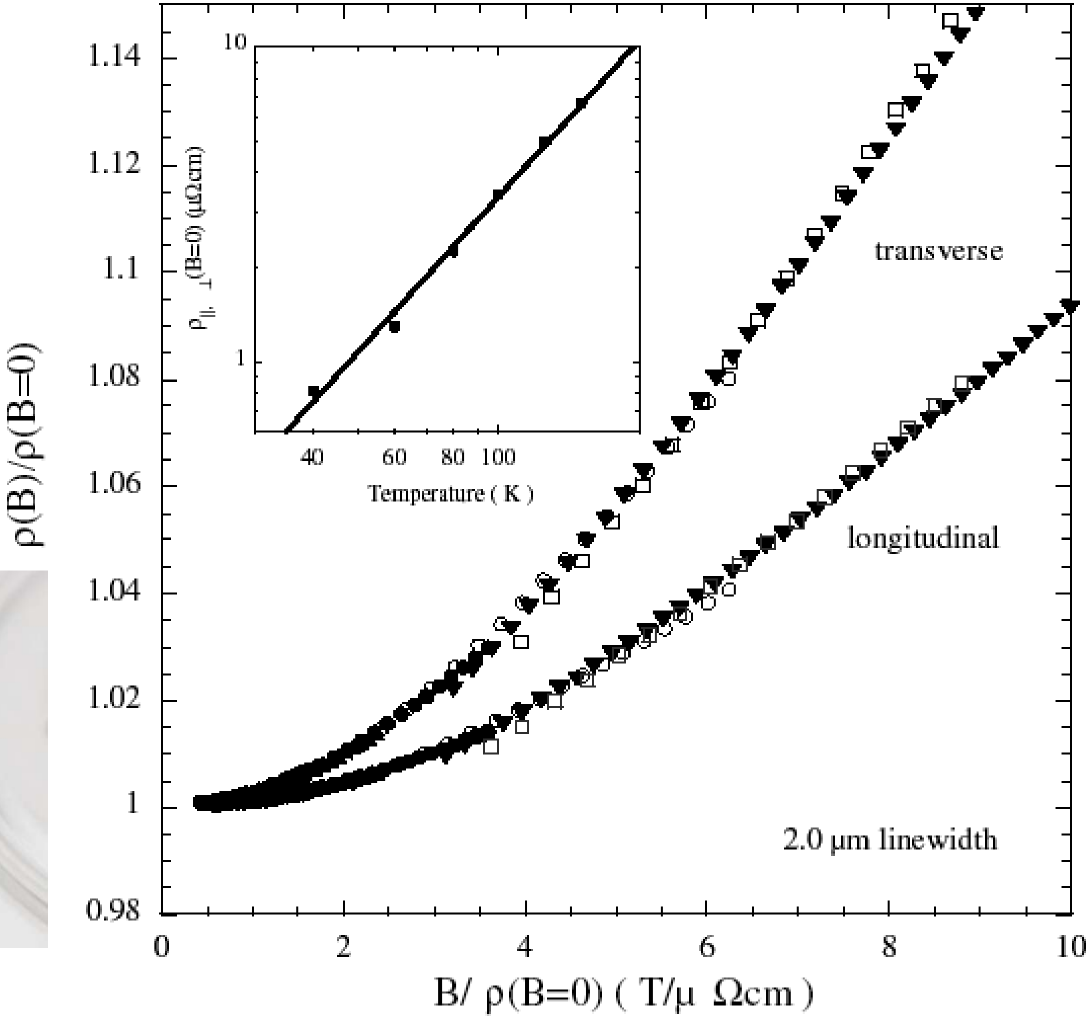


Figure 10. Scaling plot of transverse and longitudinal MR above magnetic saturation for a 2 μm wire in the form $\rho(B)/\rho(B=0)$ versus $B/\rho(B=0)$ at temperatures of (open squares) 1.5 K, (open triangles down) 40 K, (open circles) 60 K, (solid circles) 80 K, (solid triangles up) 100 K, (solid diamonds) 125 K, and (open diamonds) 150 K. The inset shows the scaling parameters $\rho_{\parallel}(B=0)$ and $\rho_{\perp}(B=0)$ as a function of temperature on a log-log plot, and overlap on the scale shown in the plot.

A.D. Kent *et al*
J. Phys. Cond. Mat. ***13***, R461 (2001)

Anisotropic MR

a dependence of electrical resistance on the angle between the direction of electric current and orientation of magnetic field

Spin-orbit coupling leads to spin dependent scattering of conduction electrons

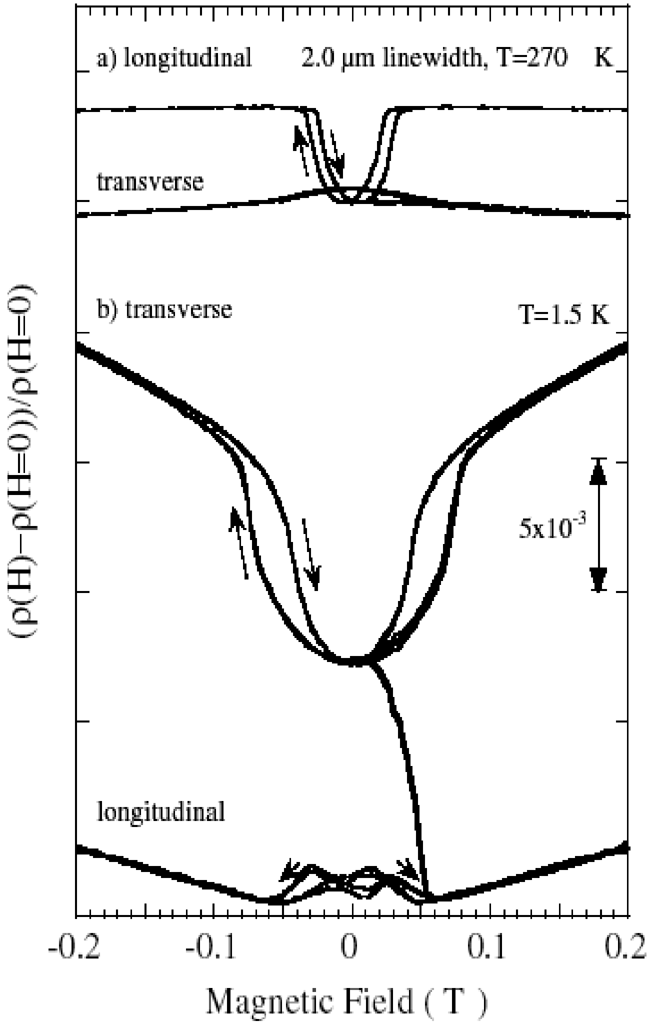


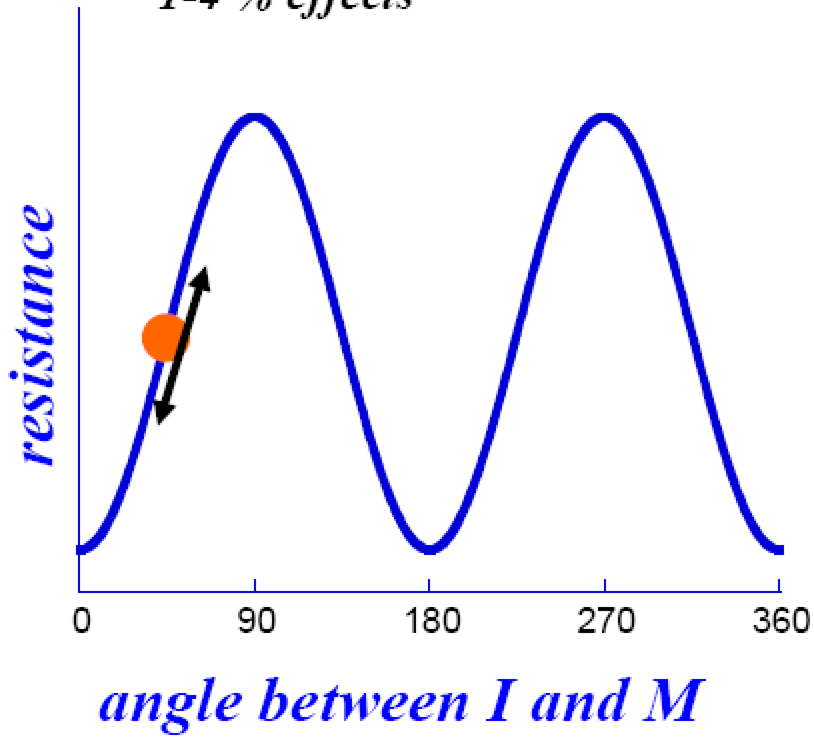
Figure 9. (a) MR data at 270 K of a 2 μm wire in the transverse and longitudinal field geometries ($\rho_\perp(H = 0, 270\text{ K}) = 14.7\ \mu\Omega$cm). (b) MR at 1.5 K again in the transverse and longitudinal field geometries ($\rho_\perp(H = 0, 1.5\text{ K}) = 0.74\ \mu\Omega$cm).

A.D. Kent *et al*
J. Phys. Cond.
Mat. ***13***, R461
(2001)

Anisotropic Magneto-resistance (AMR)

high resistance

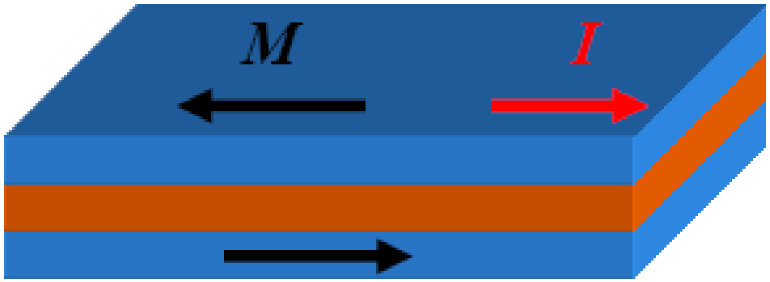
low resistance



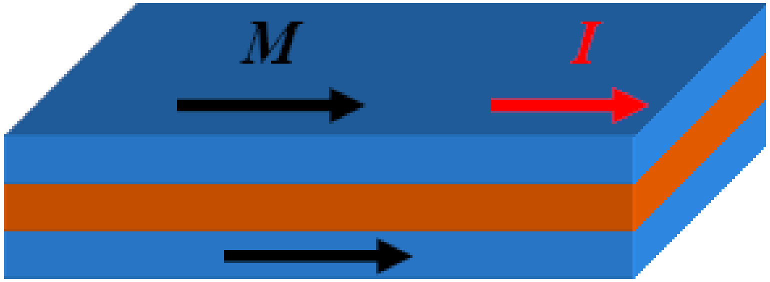
1-4 % effects

Bulk property of magnetic materials

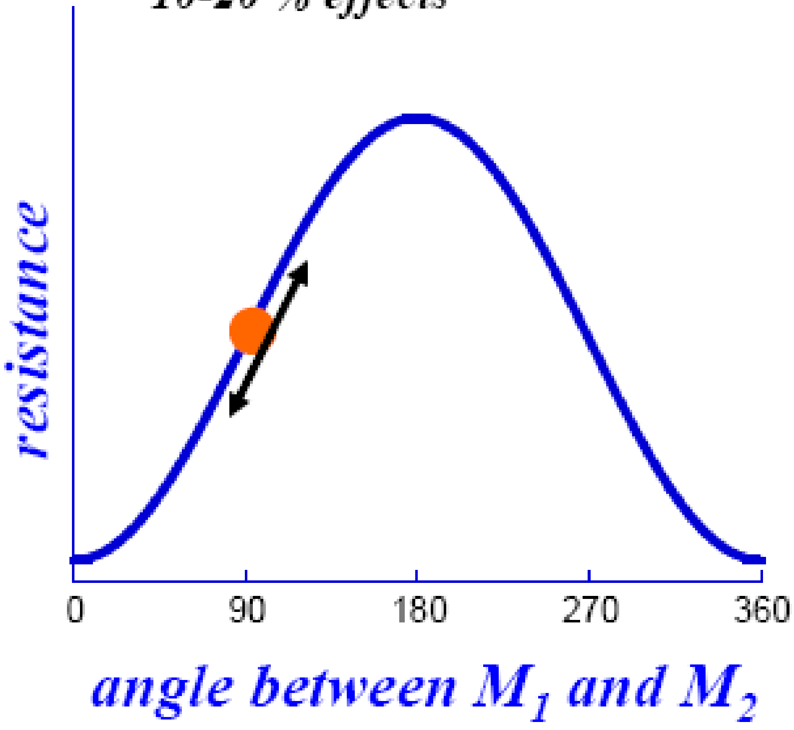
Giant Magneto-resistance (GMR)



high resistance



low resistance



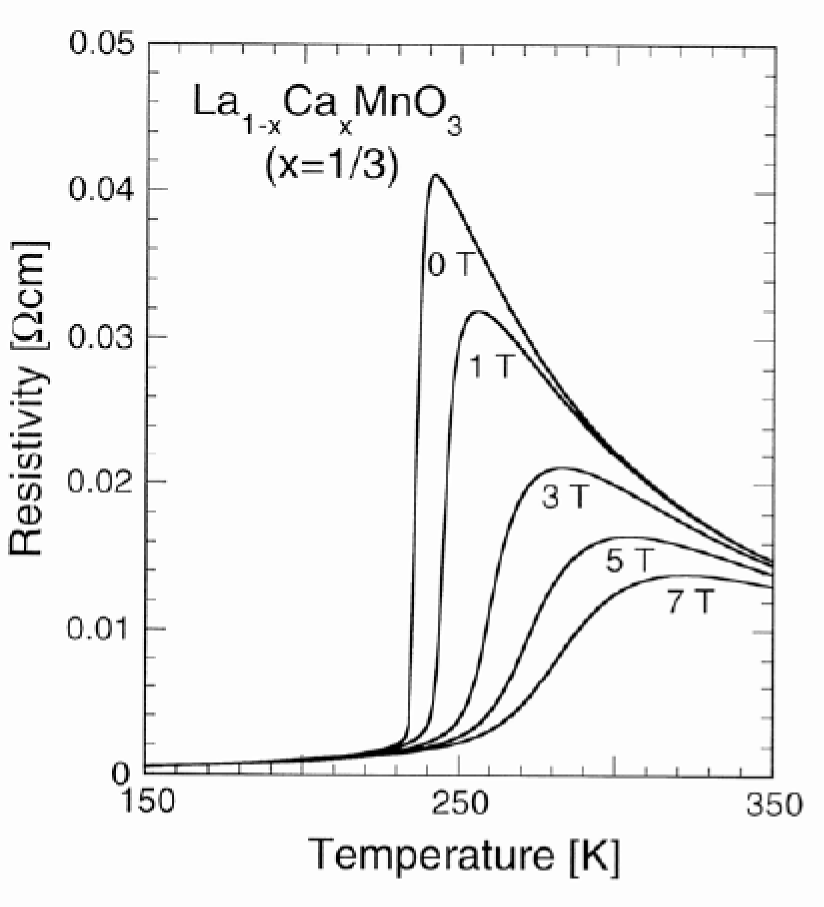
10-20 % effects

Interface property of magnetic materials

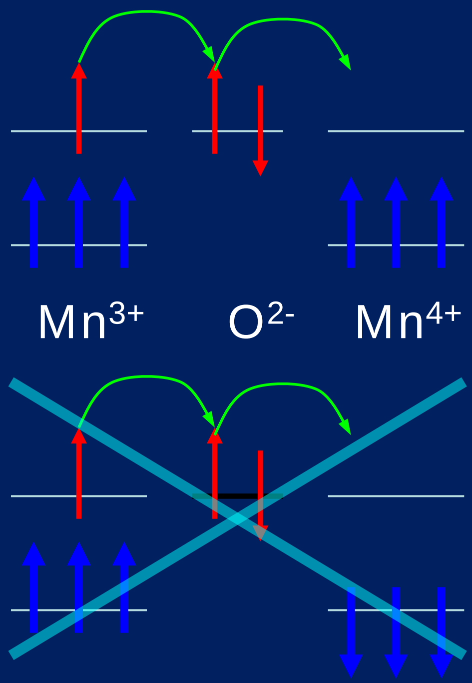
Baibich et al. Phys. Rev. Lett. ***61*** *2472 (1988)*

Binasch et al. Phys. Rev. B 39, 4828 (1989); P. Grunberg, U.S. patent # 4,949,039

Colossal magnetoresistance (CMR)

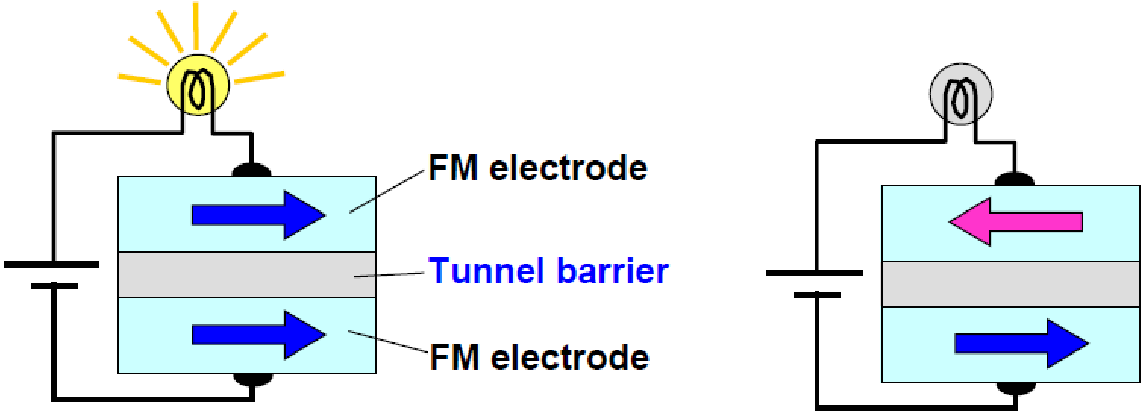


Double exchange



Tokura, Rep. Prog. Phys. **69 (2006) 797–851**

Tunnel magnetoresistance (TMR) effect



Parallel (P) state

Tunnel Resistance R_P : **low**

Antiparallel (AP) state

Tunnel Resistance R_{AP} : **high**

Magnetic tunnel junction (MTJ)

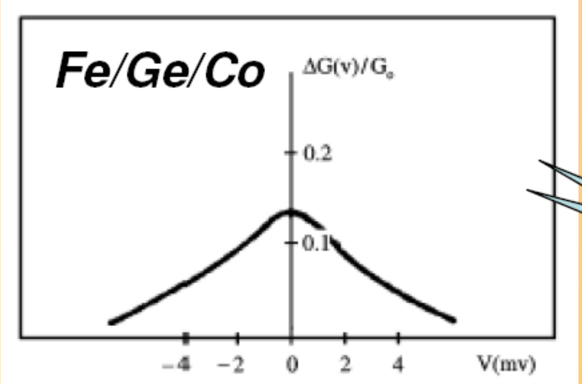
MR ratio ≡ $(R_{AP} - R_P) / R_P$ (performance index)

S. Yuasa et al.

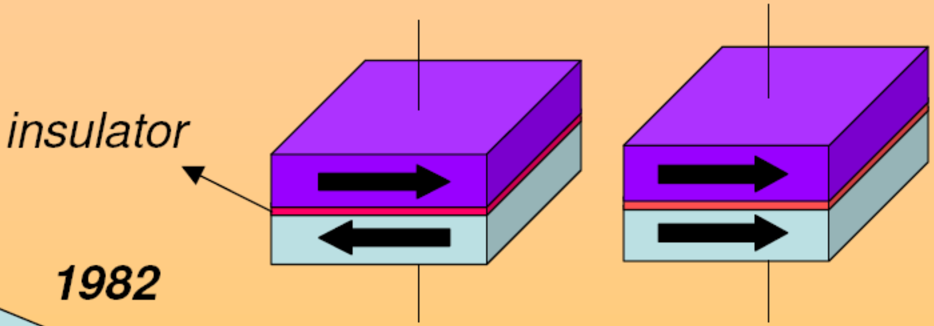
http://www.jst.go.jp/sicp/ws2009_sp1st/presentation/15.pdf

TUNNEL MAGNETORESISTANCE (TMR): how it all started

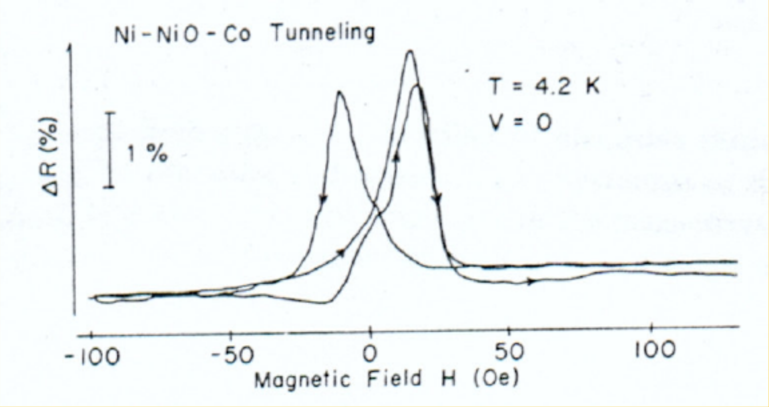
1975



Julliere, Phys. Lett. 54A (1975) 225



1982



Maekawa and Gaefvert, IEEE Transactions on Magnetics 18 (1982) 707

1995

CoFe/Al$_2$O$_3$/Co

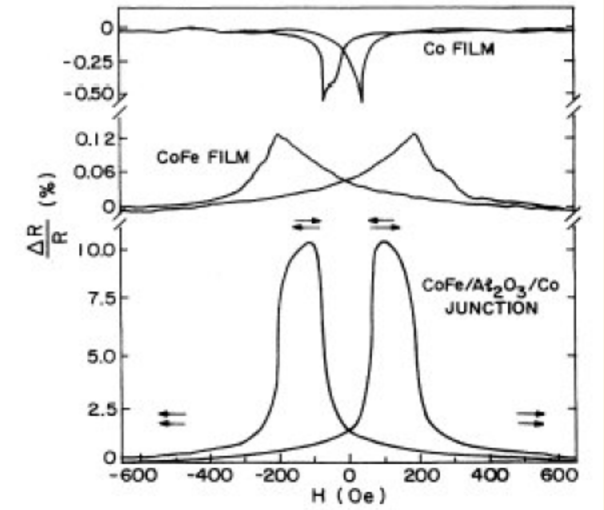


FIG. 2. Resistance of CoFe/Al$_2$O$_3$/Co junction plotted as a function of H in the film plane, at 295 K. Also shown is the variation in the CoFe and Co film resistance. The arrows indicate the direction of M in the two films (see text).

Moodera et al., Phys. Rev. Lett. 74 (1995) 3273

J.M. de Teresa,
Universidad de
Zaragoza,
Spain, ESM
2005 Constanta

http://magnetism.eu/esm/2005-constanta/slides/deteresa-slides.pdf

Tunneling magnetoresistance (TMR) is a dramatic change of the tunneling current in magnetic tunnel junctions when relative magnetizations of the two ferromagnetic layers change their alignment.

TMR is a consequence of spin-dependent tunneling.

See:

M. Coldea, Magnetorezistenta, efecte si aplicatii

J.M deTeresa, New magnetic materials and their functions, 2007, Cluj-Napoca, Romania. Summer School

L. Ranno, Spin dependent tunnel transport and spin polarization, 2003, Brasov.Romania. Summer School

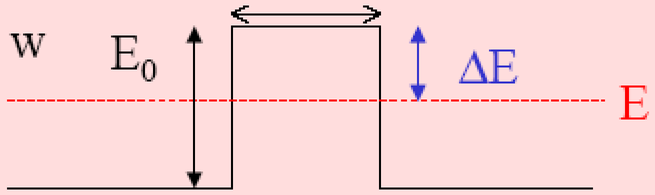
http://esm.neel.cnrs.fr

Introduction to Tunnel Effect

L. Ranno, Spin tunel course, Brasov, 2003, Lab. Louis Néel Grenoble

http://magnetism.eu/esm/2003-brasov/slides/ranno-slides-1.pdf

Tunnel Effect has a Quantum Mechanics Origin



A classical electron with energy $E<E_0$ cannot enter the barrier zone
However a quantum electron obeys the Schrödinger equation !

(1D model)

$$-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}|\psi\rangle + V(x)|\psi\rangle = E|\psi\rangle$$

Off the barrier $$-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}|\psi\rangle = E|\psi\rangle$$

Plane waves

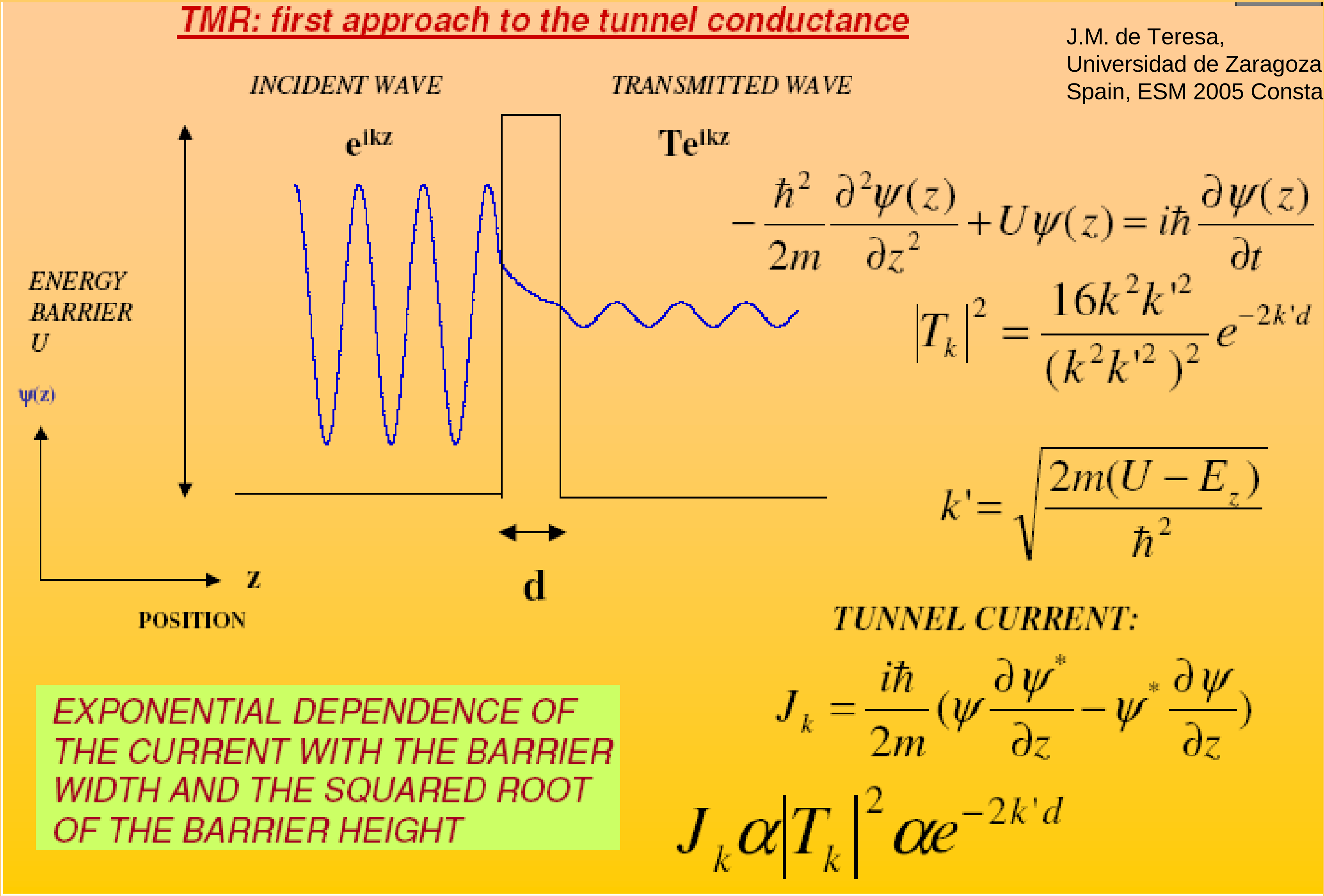
$$|\psi\rangle = e^{i(kr-\omega t)} \quad \text{and} \quad k = \pm\sqrt{\frac{2mE}{\hbar^2}}$$

In the barrier $$-\frac{\hbar^2}{2m}\frac{d}{dx^2}|\psi\rangle = (E-E_0)|\psi\rangle \quad \text{and} \quad E-E_0<0$$

Evanescent waves

$$|\psi\rangle_b = e^{qr-i\omega t} \quad \text{and} \quad q = \pm\sqrt{\frac{2m\Delta E}{\hbar^2}}$$

J.M. de Teresa,
Universidad de Zaragoza,
Spain, ESM 2005 Constanta



TMR: first approach to the tunnel conductance

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi(z)}{\partial z^2}+U\psi(z)=i\hbar\frac{\partial\psi(z)}{\partial t}$$

$$|T_k|^2=\frac{16k^2k'^2}{(k^2k'^2)^2}e^{-2k'd}$$

$$k'=\sqrt{\frac{2m(U-E_z)}{\hbar^2}}$$

TUNNEL CURRENT:

$$J_k=\frac{i\hbar}{2m}\left(\psi\frac{\partial\psi^*}{\partial z}-\psi^*\frac{\partial\psi}{\partial z}\right)$$

$$J_k\,\alpha\,|T_k|^2\,\alpha\, e^{-2k'd}$$

EXPONENTIAL DEPENDENCE OF THE CURRENT WITH THE BARRIER WIDTH AND THE SQUARED ROOT OF THE BARRIER HEIGHT

http://magnetism.eu/esm/2005-constanta/slides/deteresa-slides.pdf

$$q = \pm\sqrt{\frac{2m\Delta E}{\hbar^2}}$$

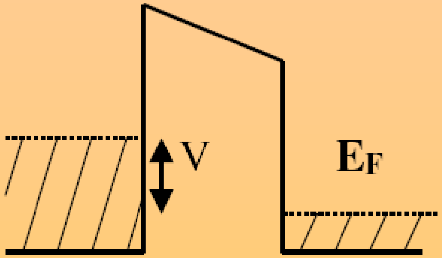
$$\boxed{\begin{array}{l} \Delta E = 1eV \\[2ex] m = \mathit{free} \quad \mathit{electron} \Rightarrow \dfrac{1}{q} = 0.2\,nm \end{array}}$$

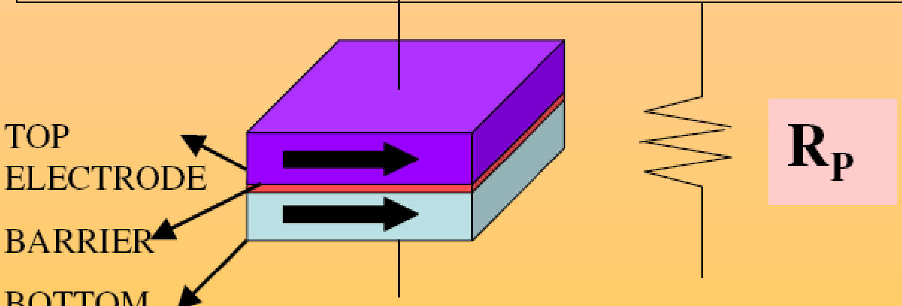
Tunnel barriers must be very thin insulating layers
Width = w < 10 nm

TMR: the basics of magnetic tunnel junctions

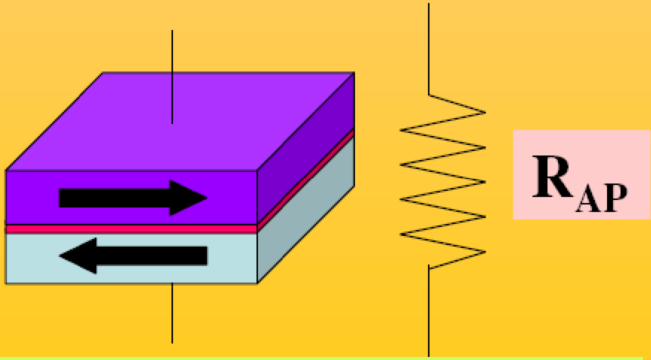
⇒ MAGNETIC TUNNEL JUNCTIONS ARE FORMED BY TWO MAGNETIC MATERIALS (ELECTRODES) SEPARATED BY A NANOMETRIC INSULATING LAYER (BARRIER). CONDUCTION TAKES PLACE THROUGH TUNNELLING.

F1 / I / F2



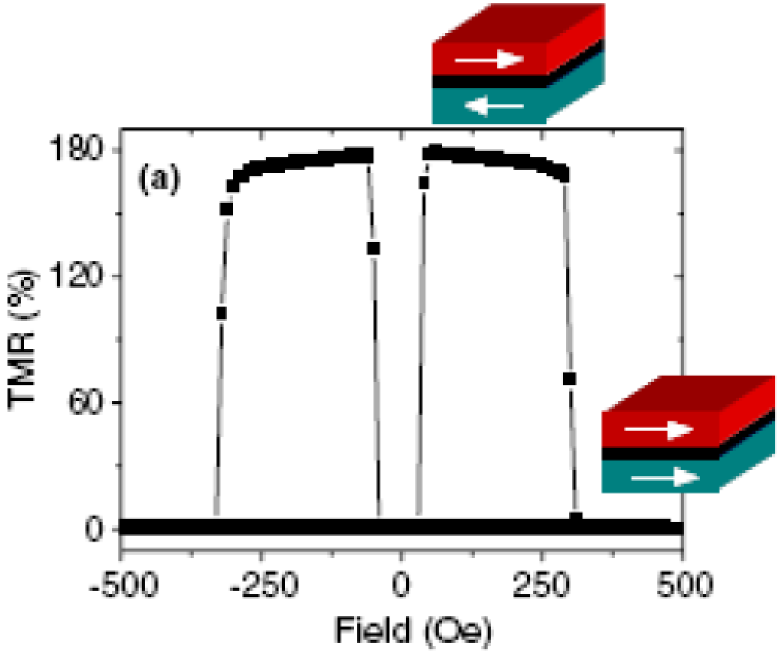


$$TMR\ (\%) = 100 \times (R_{AP}-R_P)/R_{AP}$$



$$TMR = 100 \times 2P_1P_2/(1+P_1P_2)$$

(Julliere's model)



http://magnetism.eu/esm/2005-constanta/slides/deteresa-slides.pdf

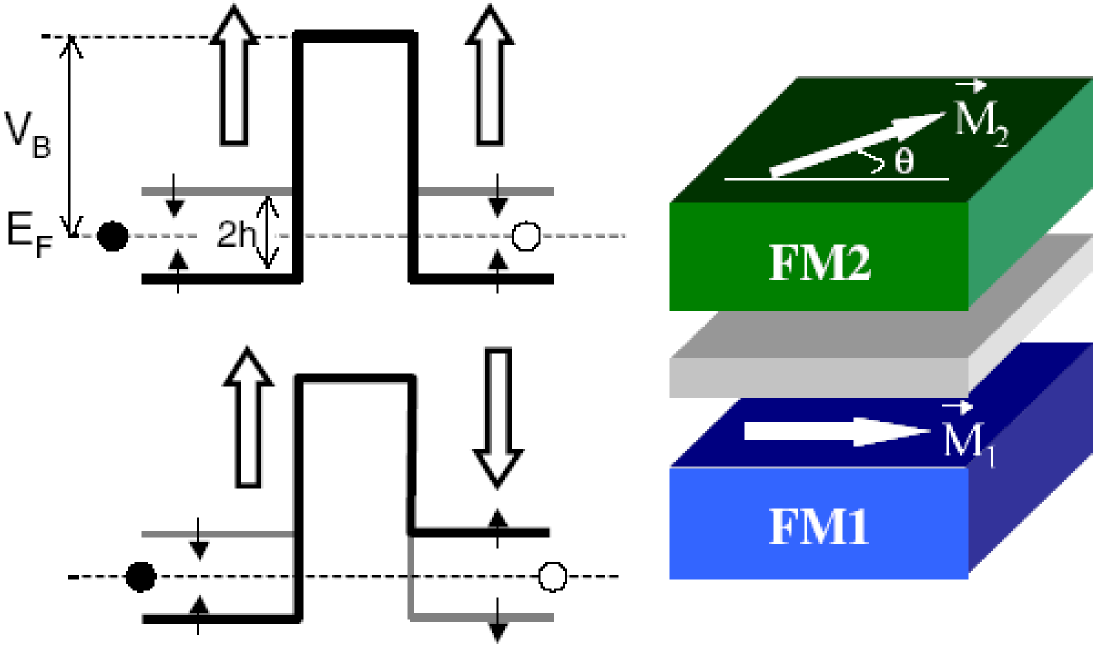
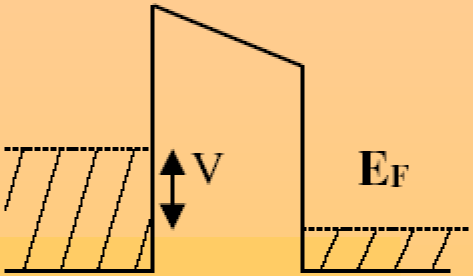


Figure 1. Left panel: potential profile seen by up (thick line) and down spins (thin line) in a magnetic tunnel junction, in the parallel (top) and anti-parallel configurations of magnetization. The exchange splitting in the ferromagnets is $2h$. The rectangular barrier height is V_B, and we denoted the energy of the electrons at the Fermi level by E_F. Right panel: schematic representation of a magnetic tunnel junction composed of two ferromagnetic layers FM1 and FM2 separated by a thin insulating barrier. The magnetization of the two FM layers can be adjusted independently; here we illustrate a configuration where the angle between $\vec{M}_1$ and $\vec{M}_2$ is θ.

TMR: the idea behind Julliere's model

F1 / I / F2



$$I(V,E)\alpha|T(E)|^2 N_1(E-eV)N_2(E)\left[f(E-eV)-f(E)\right]$$

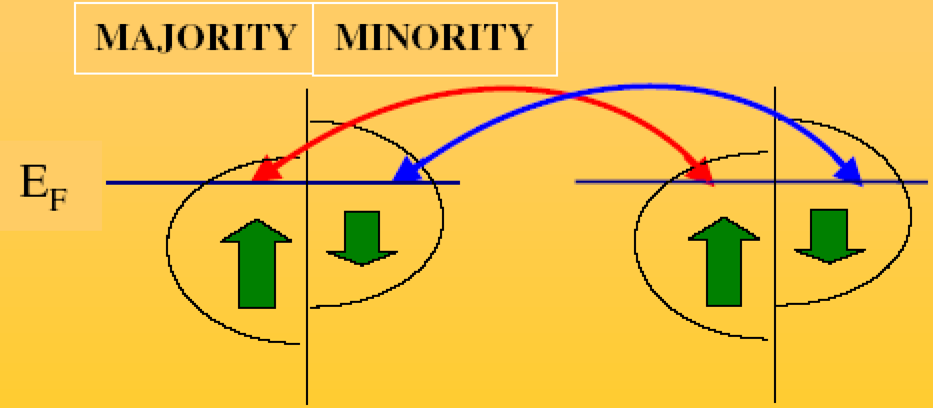
$$\frac{I}{V}\alpha|T(E_F)|^2 N_1(E_F)N_2(E_F) \xrightarrow[\text{APROX.}]{} \frac{I}{V}\alpha N_1(E_F)N_2(E_F)$$

***IF THE SPIN IS CONSERVED*:**

Let $N(E_F)=(1/2)$ * Total number of electrons at E_F

We define an effective spin polarization: $P=[N_\uparrow(E_F)-N_\downarrow(E_F)]/[N_\uparrow(E_F)+N_\downarrow(E_F)]$

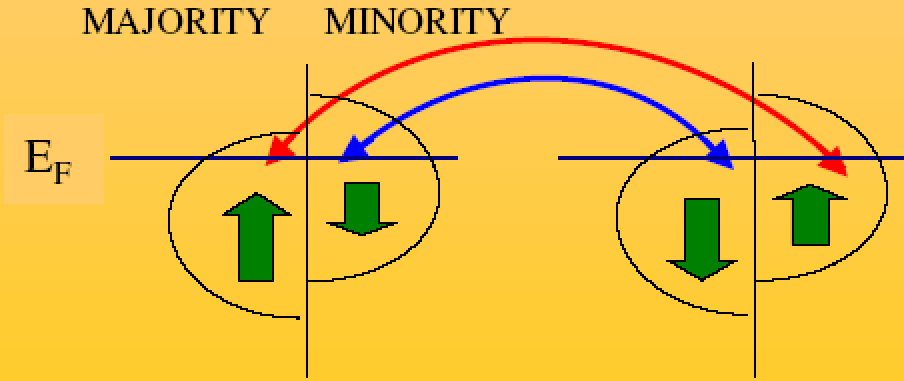
PARALLEL MAGNETIC CONFIGURATION



$I_P\ \alpha\ (1+P_1)(1+P_2) + (1-P_1)(1-P_2)$

$= 2(1+P_1P_2)$

ANTIPARALLEL MAGNETIC CONFIGURATION

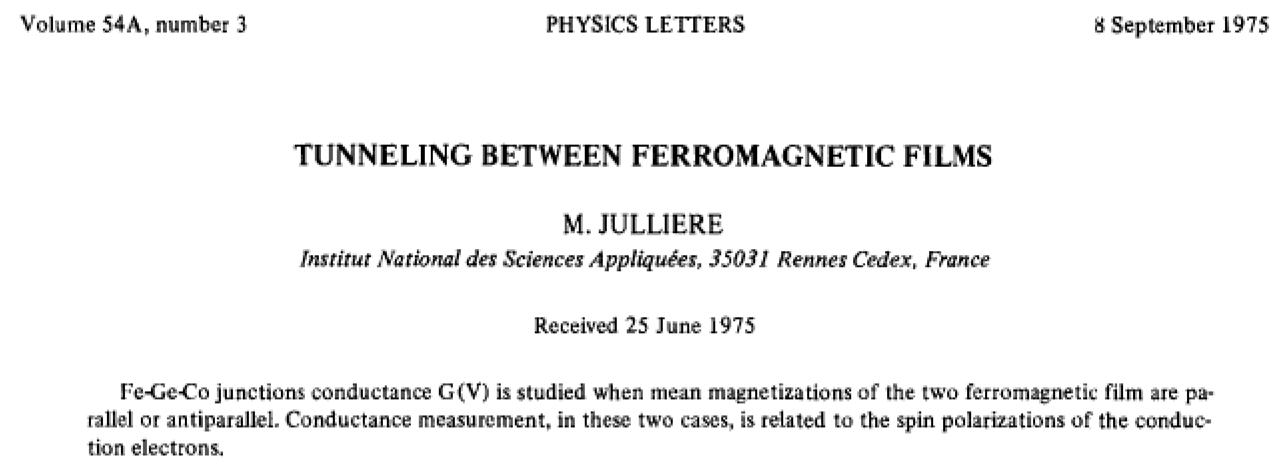


$I_{AP}\ \alpha\ (1+P_1)(1-P_2) + (1-P_1)(1+P_2)$

$= 2(1-P_1P_2)$

$\Rightarrow$ $\boxed{TMR=(R_{AP}-R_P)/R_{AP}=1-(I_{AP}/I_P)=2P_1P_2/(1+P_1P_2)}$

http://magnetism.eu/esm/2005-constanta/slides/deteresa-slides.pdf



Volume 54A, number 3 PHYSICS LETTERS 8 September 1975

TUNNELING BETWEEN FERROMAGNETIC FILMS

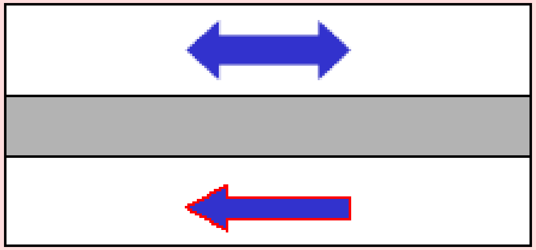
M. JULLIERE
Institut National des Sciences Appliquées, 35031 Rennes Cedex, France

Received 25 June 1975

Fe-Ge-Co junctions conductance G(V) is studied when mean magnetizations of the two ferromagnetic film are parallel or antiparallel. Conductance measurement, in these two cases, is related to the spin polarizations of the conduction electrons.

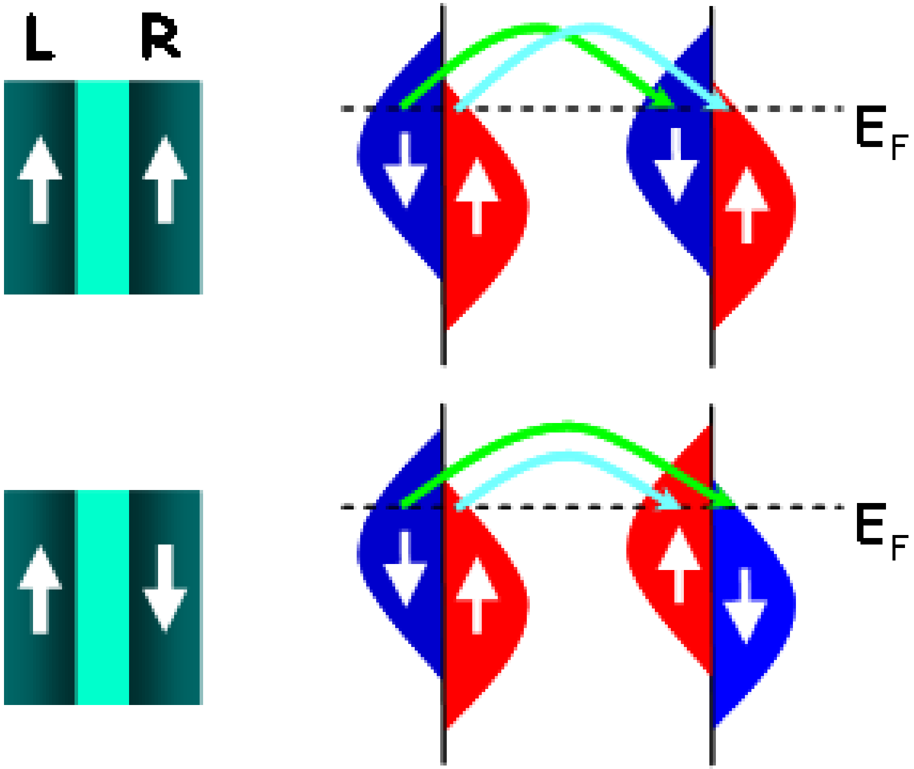
Development of film deposition techniques
Trilayer : better characterisation of electrodes and control of magnetisation

R changes by 14% at low temperature depending on the magnetic configuration



Co
Ge (10-15nm) +dry oxygen
Fe

L. Ranno, Spin dependent tunnel transport and spin polarization, 2003, Brasov.Romania. Summer School


L
R
E_F
E_F

VOLUME 74, NUMBER 16 PHYSICAL REVIEW LETTERS 17 APRIL

1995

Large Magnetoresistance at Room Temperature in Ferromagnetic Thin Film Tunnel Junctions

J. S. Moodera, Lisa R. Kinder, Terrilyn M. Wong, and R. Meservey

Francis Bitter National Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

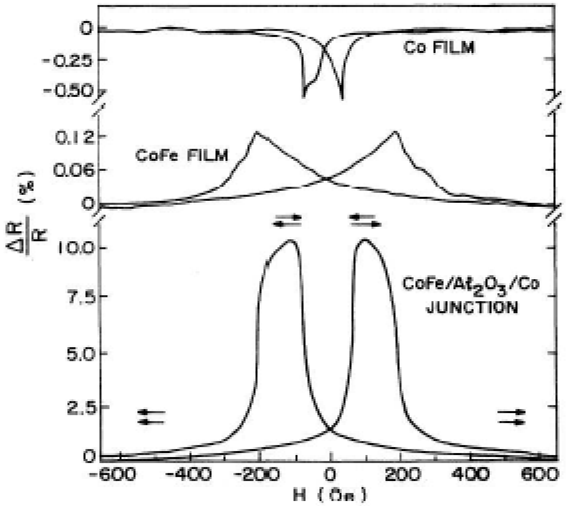
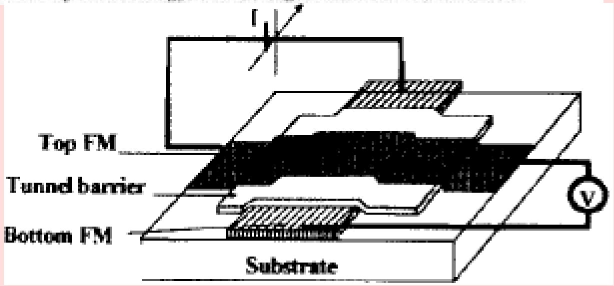


FIG. 2. Resistance of CoFe/Al$_2$O$_3$/Co junction plotted as a function of *H* in the film plane, at 295 K. Also shown is the variation in the CoFe and Co film resistance. The arrows indicate the direction of *M* in the two films (see text).



200μm x 300 μm

11.8% at 300 K
24% at 24 K

ϕ=1.9 eV and t=1.6 nm

$V_{50\%}$=200mV

And also Miyazaki, Tezuka JMMM 139 (1995) L231

Jullière 's model (1975)

Not magnetisation

BUT Polarisation of electrodes is the parameter

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

$$N_{i\uparrow} = \frac{N_i(1+P_i)}{2} \qquad N_{i\downarrow} = \frac{N_i(1-P_i)}{2}$$

Assume : No spin-flip transition across the barrier at low voltage

➡ 2 parallel channels (spin up and spin down)

Conductance is the sum of spin up and down conductances

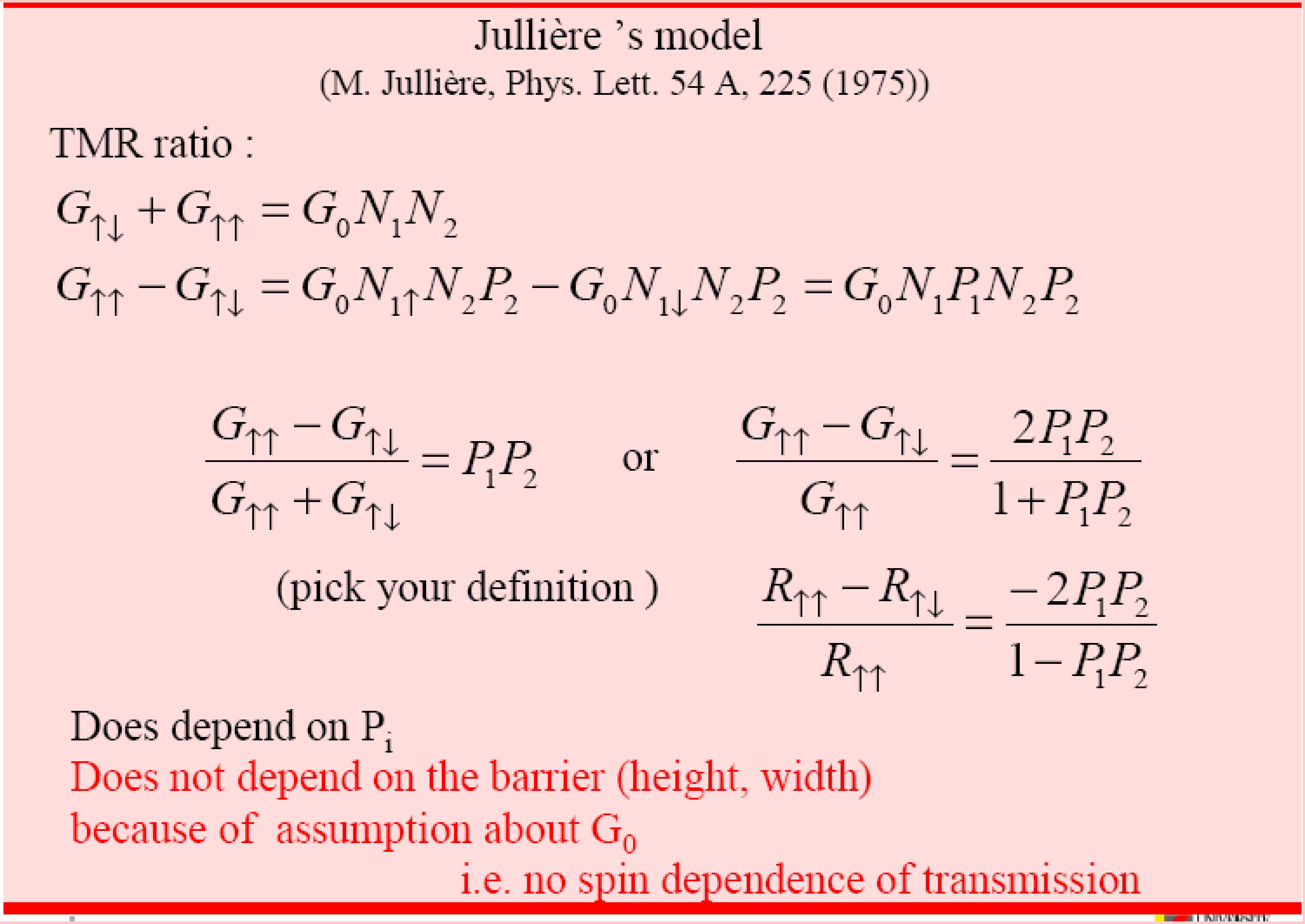
Conductance is proportional to the density of state (d.o.s.) 1 and d.o.s. 2

$$G_{spin\,\mathrm{i}} = G_0 N_{spin\,\mathrm{i\ electrode\ 1}}(E_F) N_{spin\,\mathrm{i\ electrode\ 2}}(E_F)$$

$$G_{\uparrow\uparrow} = G_0 N_{1\uparrow}(E_F) N_{2\uparrow}(E_F) + G_0 N_{1\downarrow}(E_F) N_{2\downarrow}(E_F)$$

$$G_{\uparrow\downarrow} = G_0 N_{1\uparrow}(E_F) N_{2\downarrow}(E_F) + G_0 N_{1\downarrow}(E_F) N_{2\uparrow}(E_F)$$

L. Ranno, Spin dependent tunnel transport and spin polarization, 2003, Brasov.Romania. Summer School



Jullière 's model

(M. Jullière, Phys. Lett. 54 A, 225 (1975))

TMR ratio :

$$G_{\uparrow\downarrow} + G_{\uparrow\uparrow} = G_0 N_1 N_2$$

$$G_{\uparrow\uparrow} - G_{\uparrow\downarrow} = G_0 N_{1\uparrow} N_2 P_2 - G_0 N_{1\downarrow} N_2 P_2 = G_0 N_1 P_1 N_2 P_2$$

$$\frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\uparrow} + G_{\uparrow\downarrow}} = P_1 P_2 \quad \text{or} \quad \frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\uparrow}} = \frac{2P_1P_2}{1+P_1P_2}$$

(pick your definition)

$$\frac{R_{\uparrow\uparrow} - R_{\uparrow\downarrow}}{R_{\uparrow\uparrow}} = \frac{-2P_1P_2}{1-P_1P_2}$$

Does depend on P_i

Does not depend on the barrier (height, width)

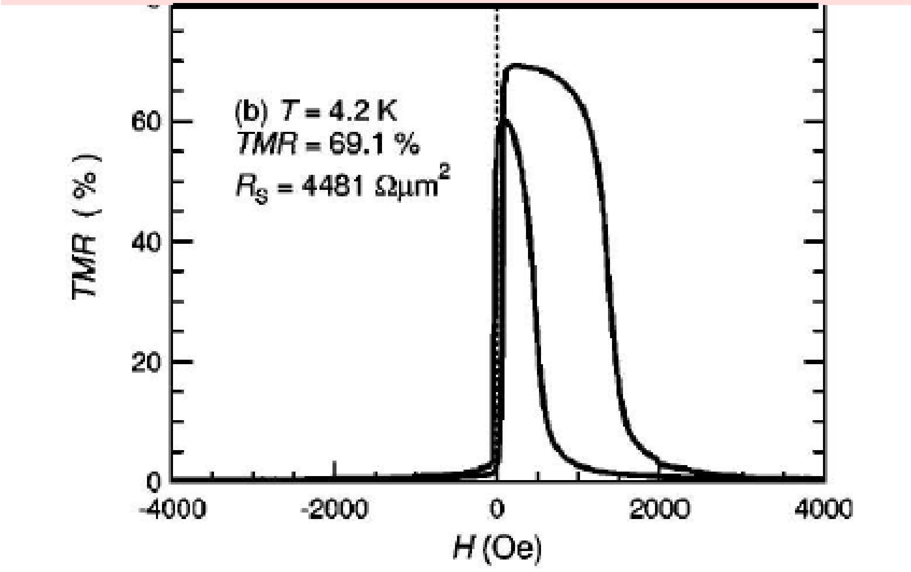
because of assumption about G_0

i.e. no spin dependence of transmission

L. Ranno, Spin dependent tunnel transport and spin polarization, 2003, Brasov.Romania. Summer School

Fe/a-Ge/Co (Jullière)

Exp : TMR=14%
Theor : P_{Co}34% +P_{Fe}44%
TMR 26%



69.1% at 4.2 K

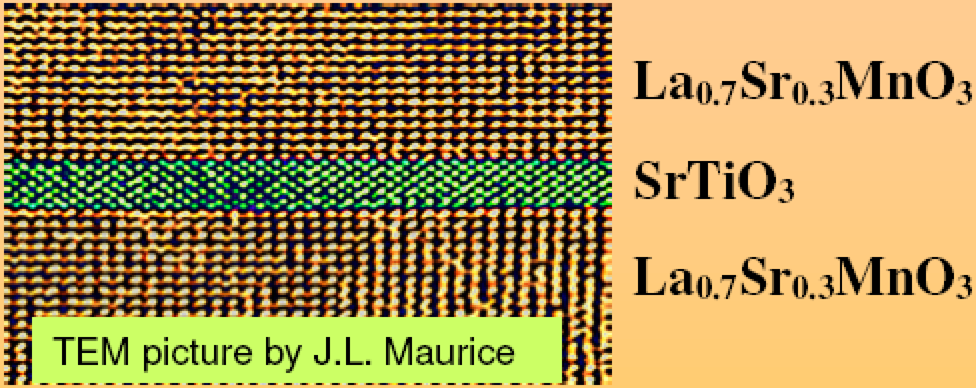
From Jullière 's formula

P_{CoFe}=50.7%
similar to expected

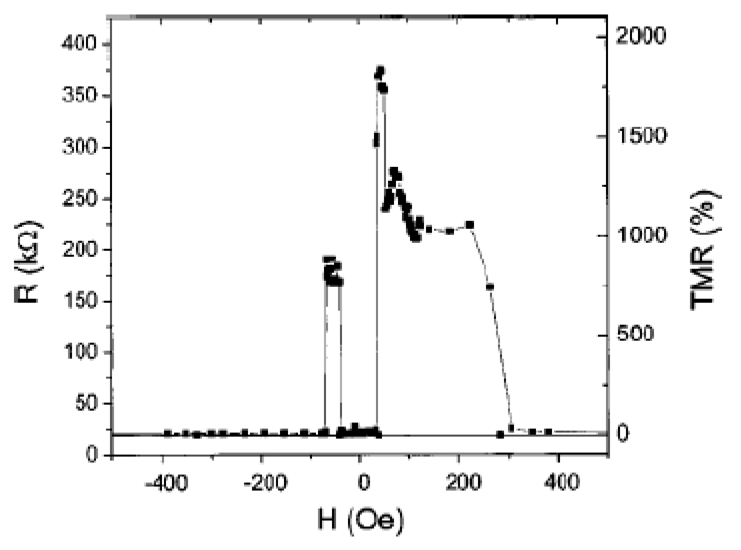
CoFe TMR junction (Tohoku 2000)

L. Ranno, Spin dependent tunnel transport and spin polarization, 2003, Brasov.Romania. Summer School

MANGANITE-based MTJs



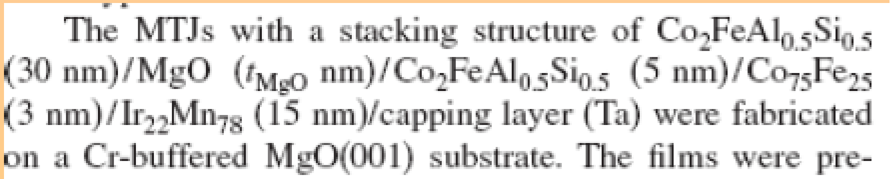
TEM picture by J.L. Maurice

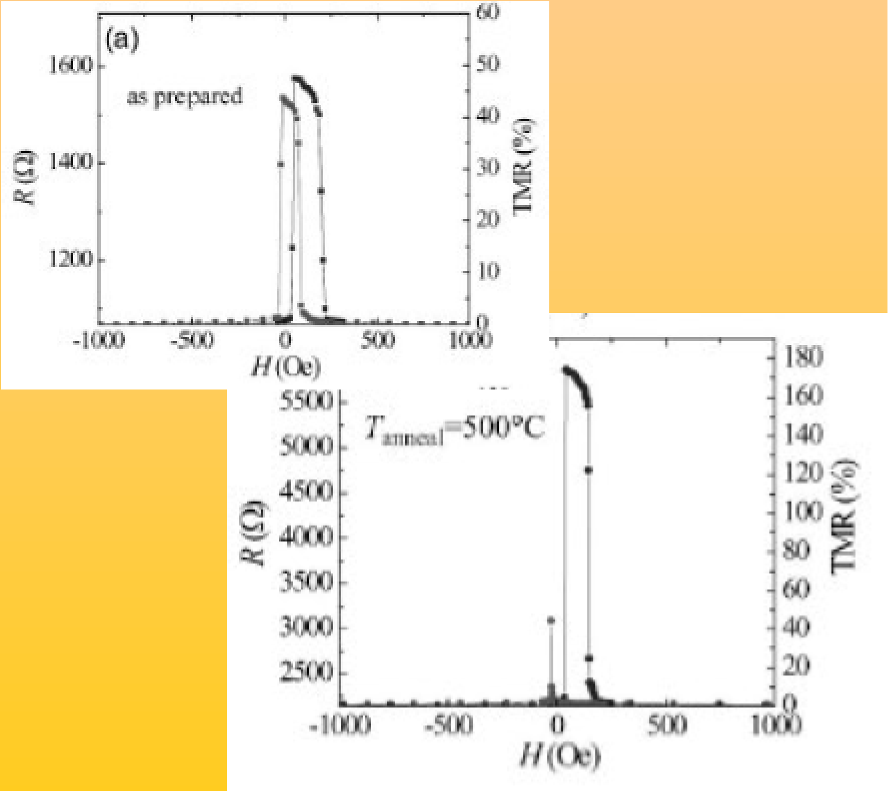


MR>1500% at 5K, which corresponds to P=0.95 (however,the MR vanishes at 300 K)

Bowen et al., Appl. Phys. Lett. 82, 233 (2003)

HEUSLER ALLOYS-based MTJs


The MTJs with a stacking structure of $Co_2FeAl_{0.5}Si_{0.5}$ (30 nm)/MgO (t_{MgO} nm)/$Co_2FeAl_{0.5}Si_{0.5}$ (5 nm)/$Co_{75}Fe_{25}$ (3 nm)/$Ir_{22}Mn_{78}$ (15 nm)/capping layer (Ta) were fabricated on a Cr-buffered MgO(001) substrate. The films were pre-

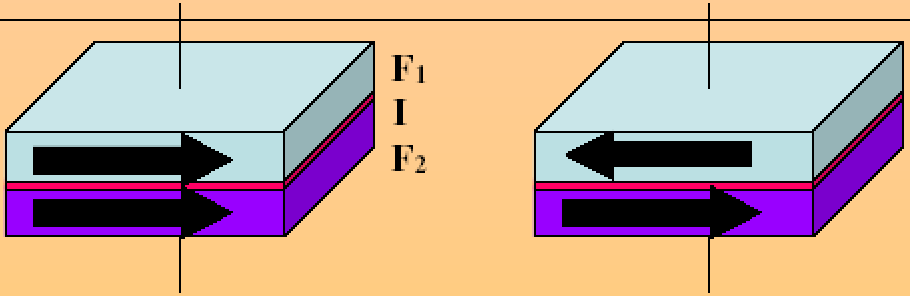


MR=175% at room temperature, which corresponds to P=0.68

Tezuka et al., Appl. Phys. Lett. 89, 252508 (2006)

http://magnetism.eu/esm/2005-constanta/slides/deteresa-slides.pdf

TMR: understanding the TMR effect

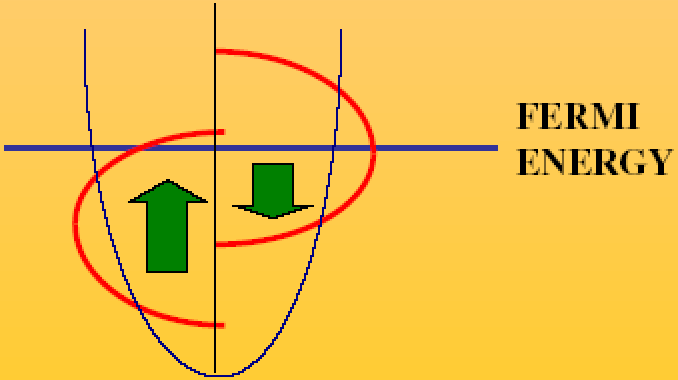


$$TMR\ (\%) = 200\,x\,\frac{P_1P_2}{(1+P_1P_2)}$$

JULLIERE'S MODEL)

MAJORITARY e-"SPIN UP"

MINORITARY e-"SPIN DOWN"



What P value is the right one to be included in Julliere's formula?

$$P = \frac{N(E_F)_\uparrow - N(E_F)_\downarrow}{N(E_F)_\uparrow + N(E_F)_\downarrow}\ ?$$

THE EXAMPLE OF COBALT

-**PHOTOEMISSION: INFORMATION ON**

$$P = \frac{N(E_F)_\uparrow - N(E_F)_\downarrow}{N(E_F)_\uparrow + N(E_F)_\downarrow}$$

P(Co)<0

-**TUNNEL JUNCTIONS F/I/S:**
INFORMATION ON P(Co) IN TUNNELLING

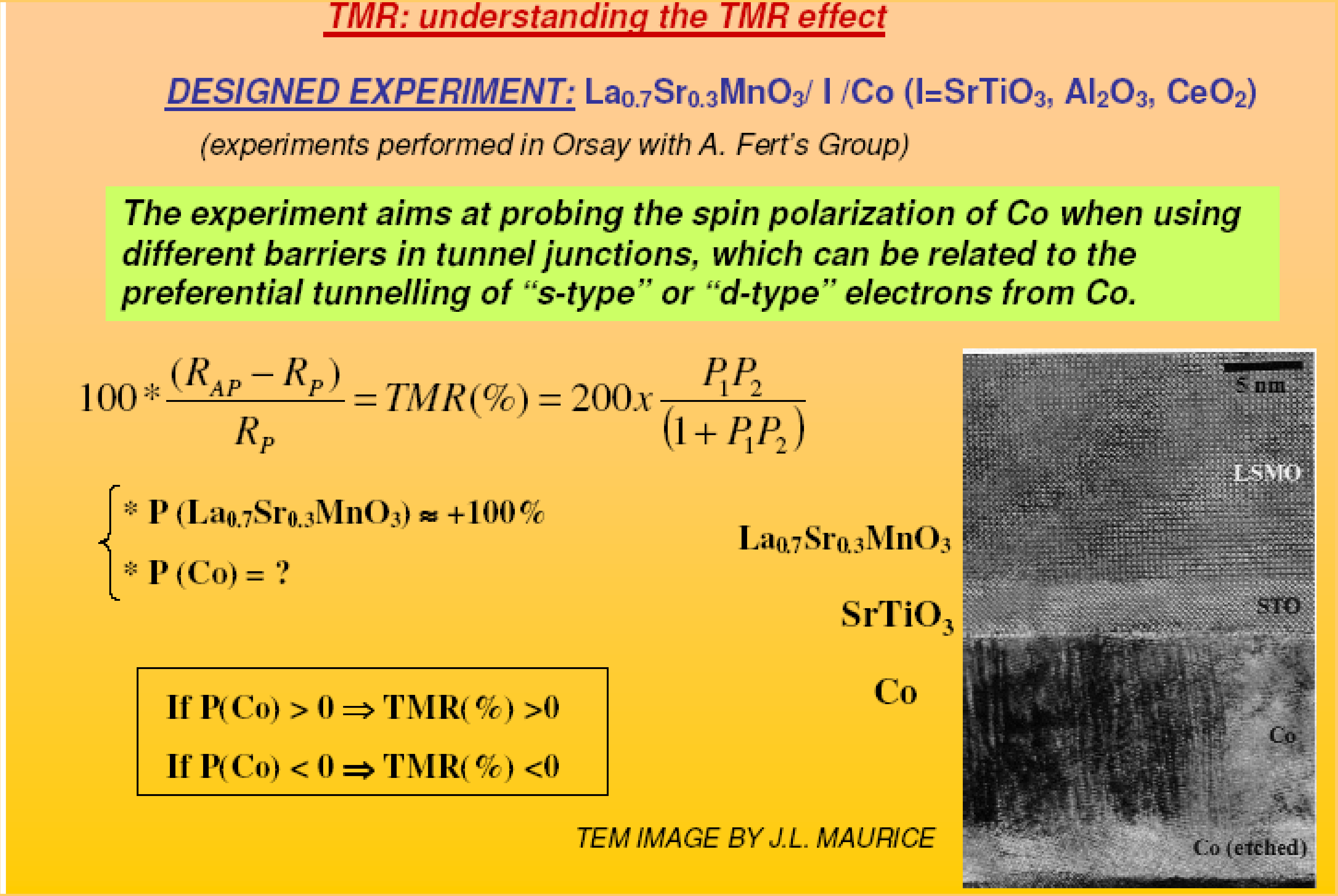
P(Co)>0 WITH Al_2O_3 BARRIER

[experiments carried out by Tedrow and Meservey: see review in Phys. Repts. 238 (1994) 173]

*"s-type" BANDS ⇒ lower density of states, positively polarized, more delocalized electrons

*"d-type" BANDS ⇒ higher density of states, negatively polarized, more localized electrons

http://magnetism.eu/esm/2005-constanta/slides/deteresa-slides.pdf



TMR: understanding the TMR effect

DESIGNED EXPERIMENT: $La_{0.7}Sr_{0.3}MnO_3$/ I /Co (I=$SrTiO_3$, Al_2O_3, CeO_2)

(experiments performed in Orsay with A. Fert's Group)

The experiment aims at probing the spin polarization of Co when using different barriers in tunnel junctions, which can be related to the preferential tunnelling of "s-type" or "d-type" electrons from Co.

$$100 * \frac{(R_{AP}-R_P)}{R_P} = TMR(\%) = 200x \frac{P_1P_2}{(1+P_1P_2)}$$

- * P ($La_{0.7}Sr_{0.3}MnO_3$) ≈ +100%
- * P (Co) = ?

If P(Co) > 0 ⇒ TMR(%) >0

If P(Co) < 0 ⇒ TMR(%) <0

$La_{0.7}Sr_{0.3}MnO_3$

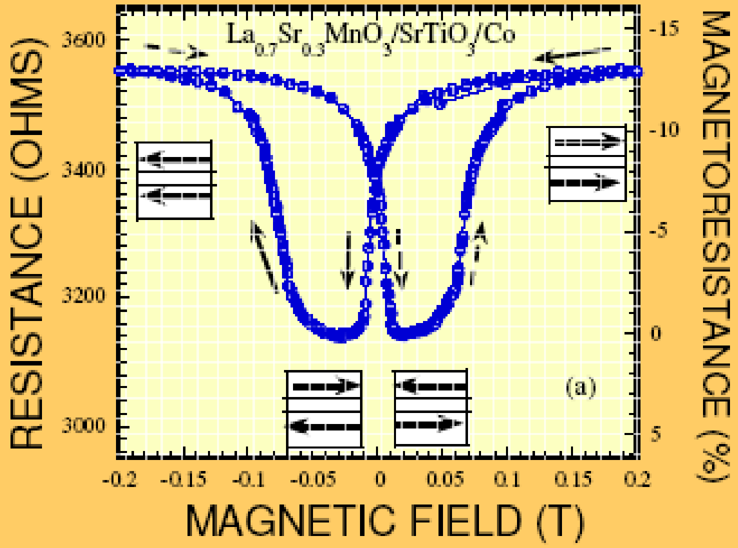
$SrTiO_3$

Co

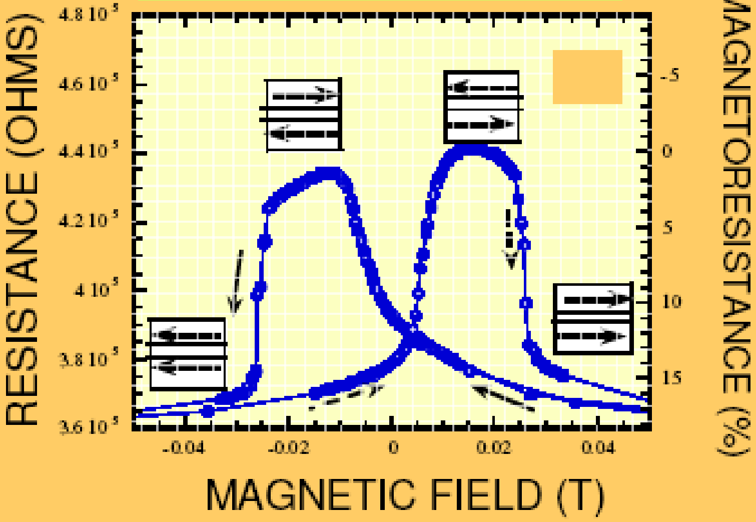
TEM IMAGE BY J.L. MAURICE

http://magnetism.eu/esm/2005-constanta/slides/deteresa-slides.pdf

$La_{0.7}Sr_{0.3}MnO_3/SrTiO_3/Co$



$La_{0.7}Sr_{0.3}MnO_3/Al_2O_3/Co$



INVERSE TMR

$R_{AP} < R_P$

P(Co) IS NEGATIVE

NORMAL TMR

$R_P < R_{AP}$

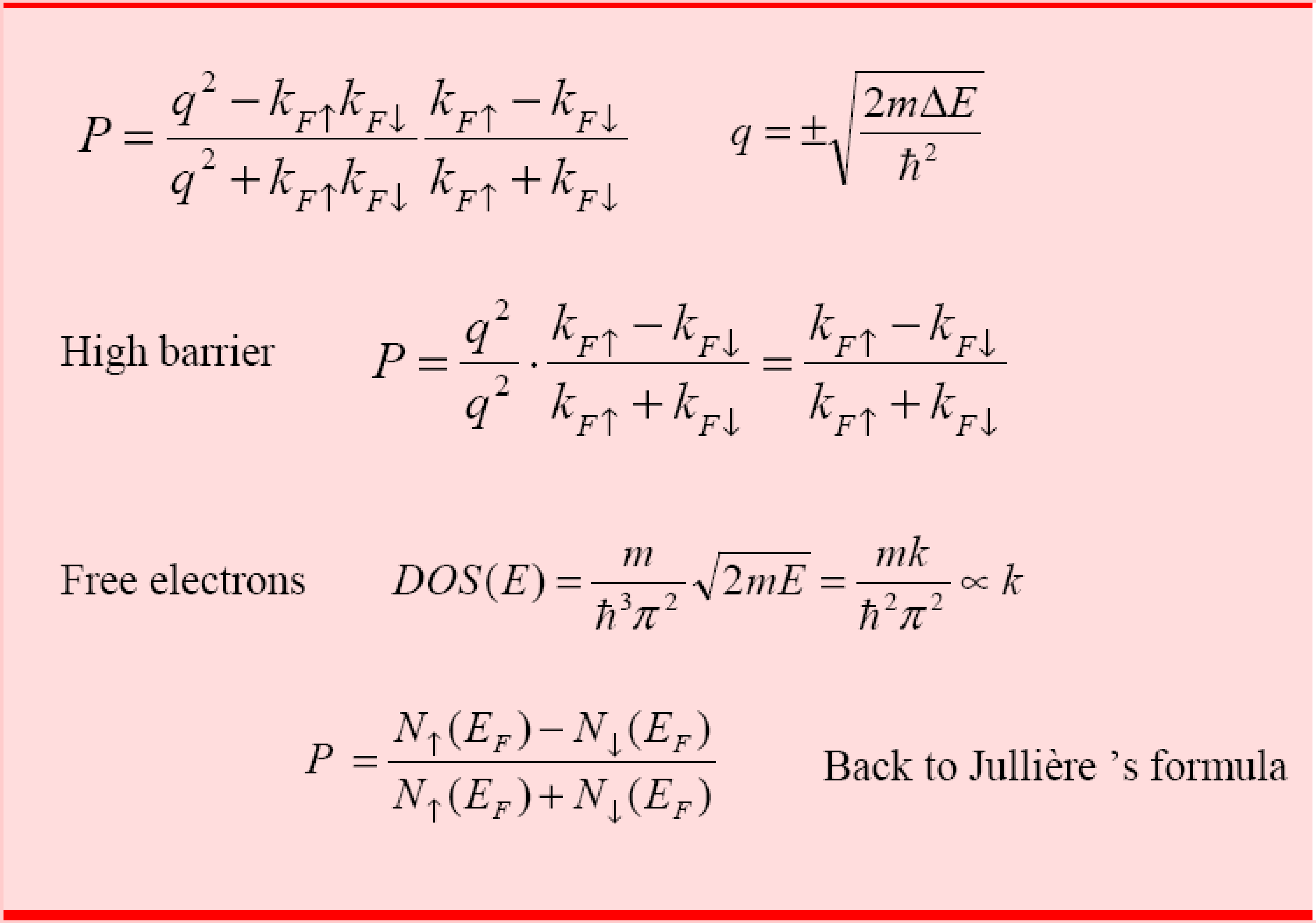
P(Co) IS POSITIVE

$$\mathbf{TMR \propto P_{(LSMO)}P_{(Co)}/[1+P_{(LSMO)}P_{(Co)}]};\ \mathbf{with\ P_{(LSMO)} > 0}$$

J.M. De Teresa et al., Phys. Rev. Lett. 82 (1999) 4288; J.M. De Teresa et al., Science 286 (1999) 507; Hayakawa et al., J. Appl. Phys. 91 (2002) 8792; Hayakawa et al., Jpn J. Appl. Phys. 41 (2002) 1340

if the insulator has d electrons the Co d structure is dominant. For the measurement we can deduce with STO the d tunneling is favored and with ALO the s structure.

http://magnetism.eu/esm/2005-constanta/slides/deteresa-slides.pdf



$$P=\frac{q^2-k_{F\uparrow}k_{F\downarrow}}{q^2+k_{F\uparrow}k_{F\downarrow}}\frac{k_{F\uparrow}-k_{F\downarrow}}{k_{F\uparrow}+k_{F\downarrow}} \qquad q=\pm\sqrt{\frac{2m\Delta E}{\hbar^2}}$$

High barrier $$P=\frac{q^2}{q^2}\cdot\frac{k_{F\uparrow}-k_{F\downarrow}}{k_{F\uparrow}+k_{F\downarrow}}=\frac{k_{F\uparrow}-k_{F\downarrow}}{k_{F\uparrow}+k_{F\downarrow}}$$

Free electrons $$DOS(E)=\frac{m}{\hbar^3\pi^2}\sqrt{2mE}=\frac{mk}{\hbar^2\pi^2}\propto k$$

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

Back to Jullière 's formula

from L. Ranno http://magnetism.eu/esm/2003-brasov/slides/ranno-slides-1.pdf

Improved models :

Bratkovsky :

Correction to Slonczewski's model (different effective mass in the barrier)

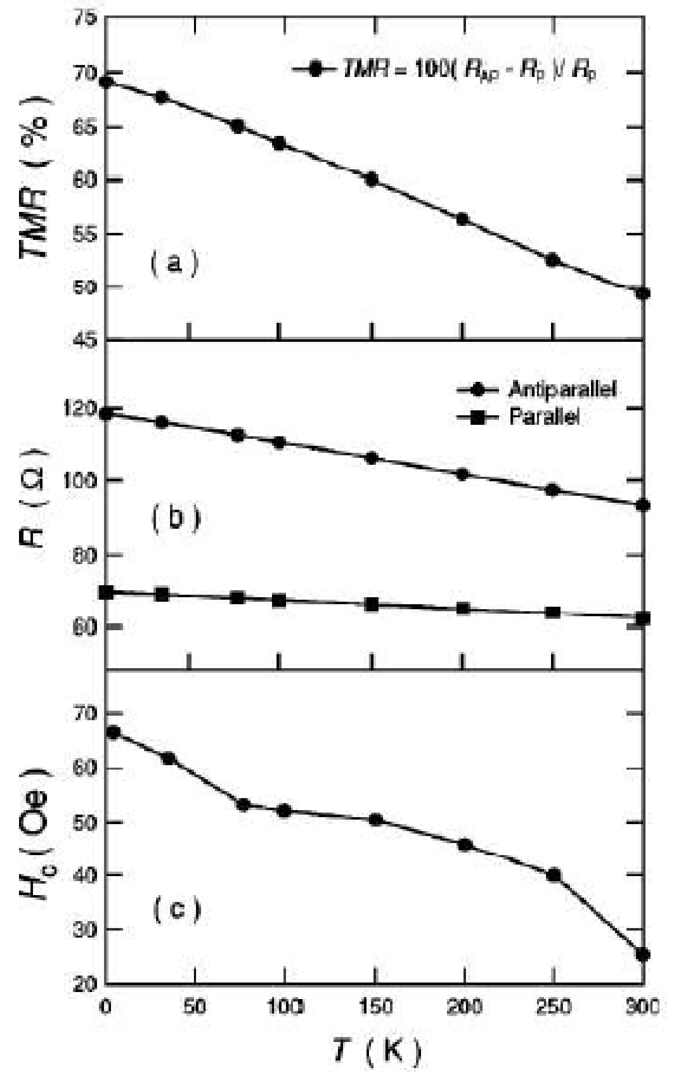
$$P = \frac{q^2 - m_b^2 \cdot k_{F\uparrow}k_{F\downarrow}}{q^2 + m_b^2 \cdot k_{F\uparrow}k_{F\downarrow}} \frac{k_{F\uparrow} - k_{F\downarrow}}{k_{F\uparrow} + k_{F\downarrow}} \qquad q = \pm\sqrt{\frac{2m_b\Delta E}{\hbar^2}}$$

$m_b/m=0.4$ for Fe/Al_2O_3

Ab initio band structure calculations :

to get the band structure close to the interface

http://magnetism.eu/esm/2003-brasov/slides/ranno-slides-1.pdf

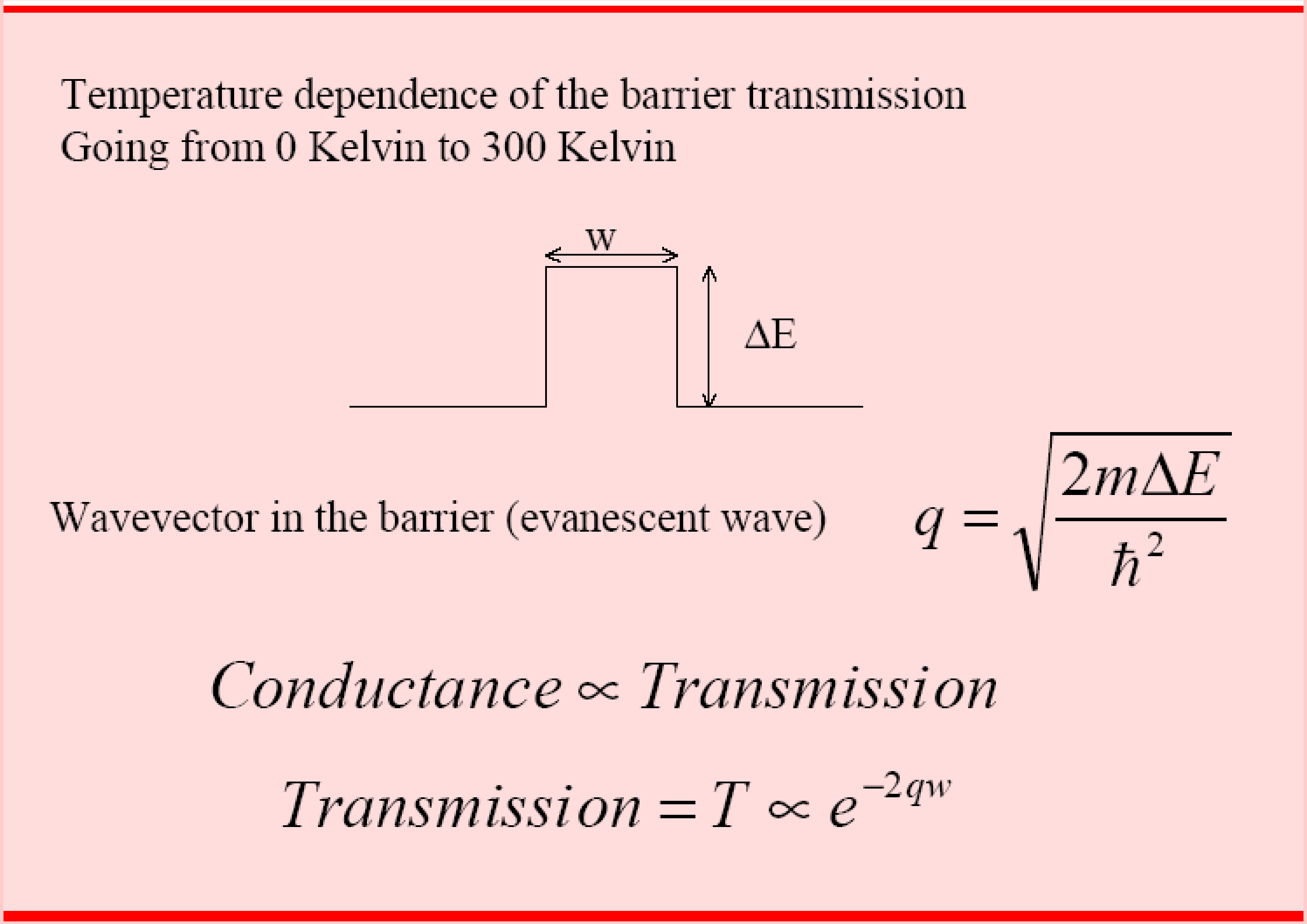


Miyazaki group (Tohoku) APL 2000

TMR temperature dependence

Resistance Temperature dependence

http://magnetism.eu/esm/2003-brasov/slides/ranno-slides-1.pdf



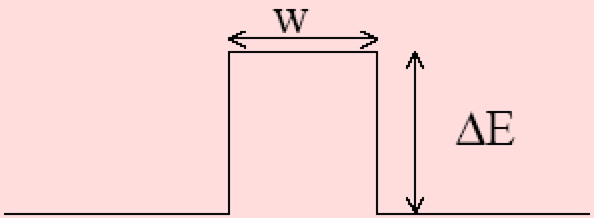
Temperature dependence of the barrier transmission
Going from 0 Kelvin to 300 Kelvin

Wavevector in the barrier (evanescent wave) $q = \sqrt{\dfrac{2m\Delta E}{\hbar^2}}$

$$Conductance \propto Transmission$$

$$Transmission = T \propto e^{-2qw}$$

http://magnetism.eu/esm/2003-brasov/slides/ranno-slides-1.pdf



$$q = \sqrt{\frac{2m\Delta E}{\hbar^2}}$$

$$Transmission = T \propto e^{-2qw}$$

$$\frac{dT}{T} = d(-2qw) = -2w \cdot dq = -wq\frac{d\Delta E}{\Delta E}$$

$$q = 1\,\mathring{\mathrm{A}}^{-1}, w = 1\,nm,$$

$$\Delta E = 2eV, \mathrm{d}\Delta E = kT = 25\,meV$$

$$\boxed{\frac{\Delta T}{T} = \frac{\Delta G}{G} = \frac{\Delta R}{R} = 12.5\%}$$

Temperature dependence of TMR

Different contributions may rule this behaviour :

- Polarisation is related to magnetisation

$$M(T) = M_s(T)(1-\alpha T^{3/2})$$

$$P(T) = P_s(T)(1-\alpha T^{3/2})$$

- Inelastic processes can appear

$$e^{\uparrow} \Rightarrow e^{\downarrow} + magnon$$

$$e^{\uparrow} + magnon \Rightarrow e^{\downarrow}$$

Opens a spin-flip conductance channel
conductance increases
TMR decreases

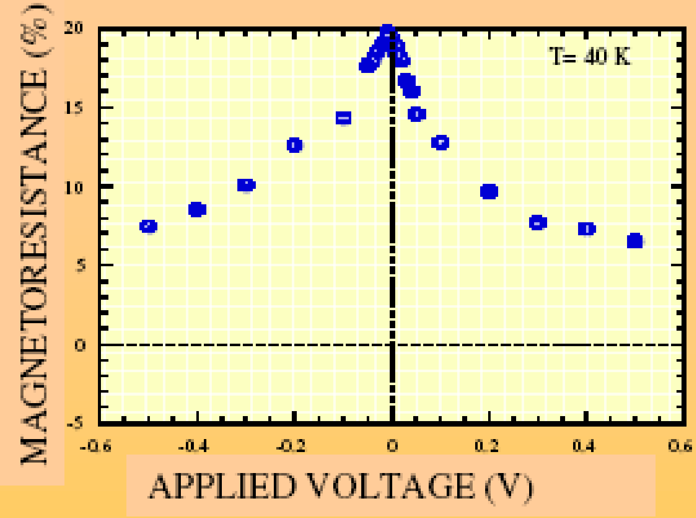
- Surface magnetisation is less robust to thermal fluctuations

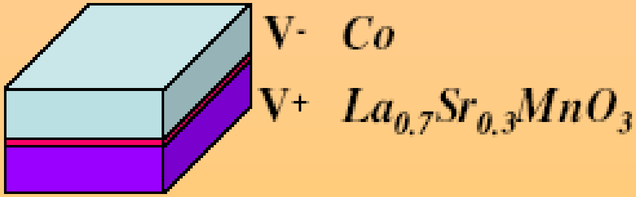
No general results, depends on the studied system (T_c, surface state …)

http://magnetism.eu/esm/2003-brasov/slides/ranno-slides-1.pdf

DEPENDENCE OF THE TUNNEL MAGNETORESISTANCE WITH VOLTAGE

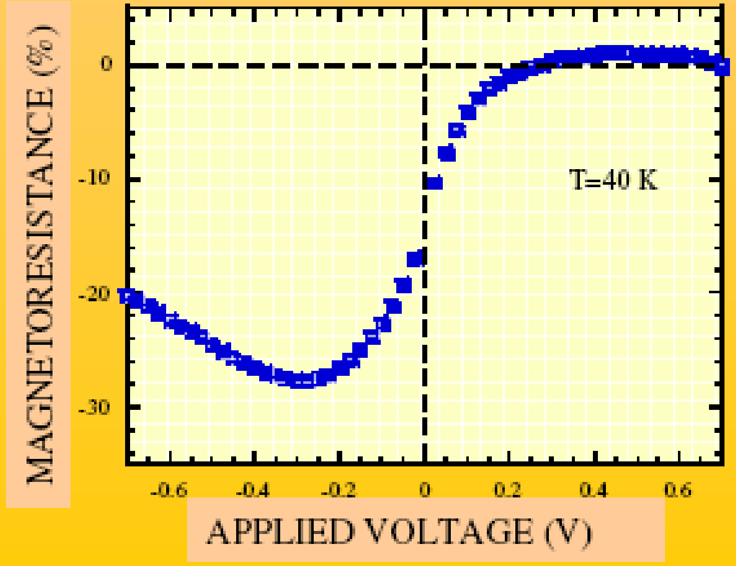
J.M. de Teresa,
Universidad de
Zaragoza,
Spain, ESM
2005 Constanta



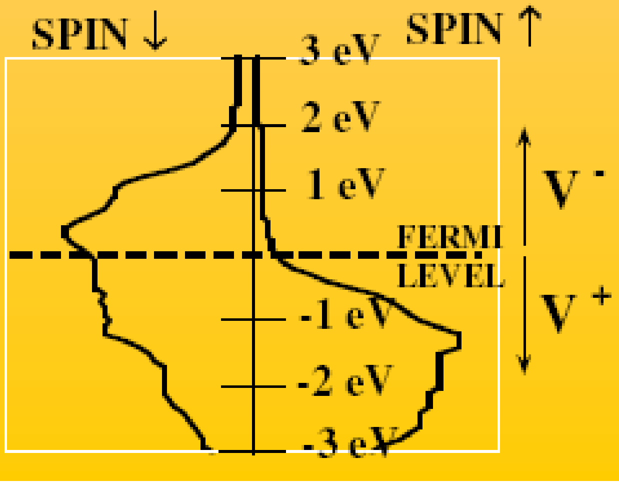


I= Al_2O_3: CURRENT BY "s-type" ELECTRONS

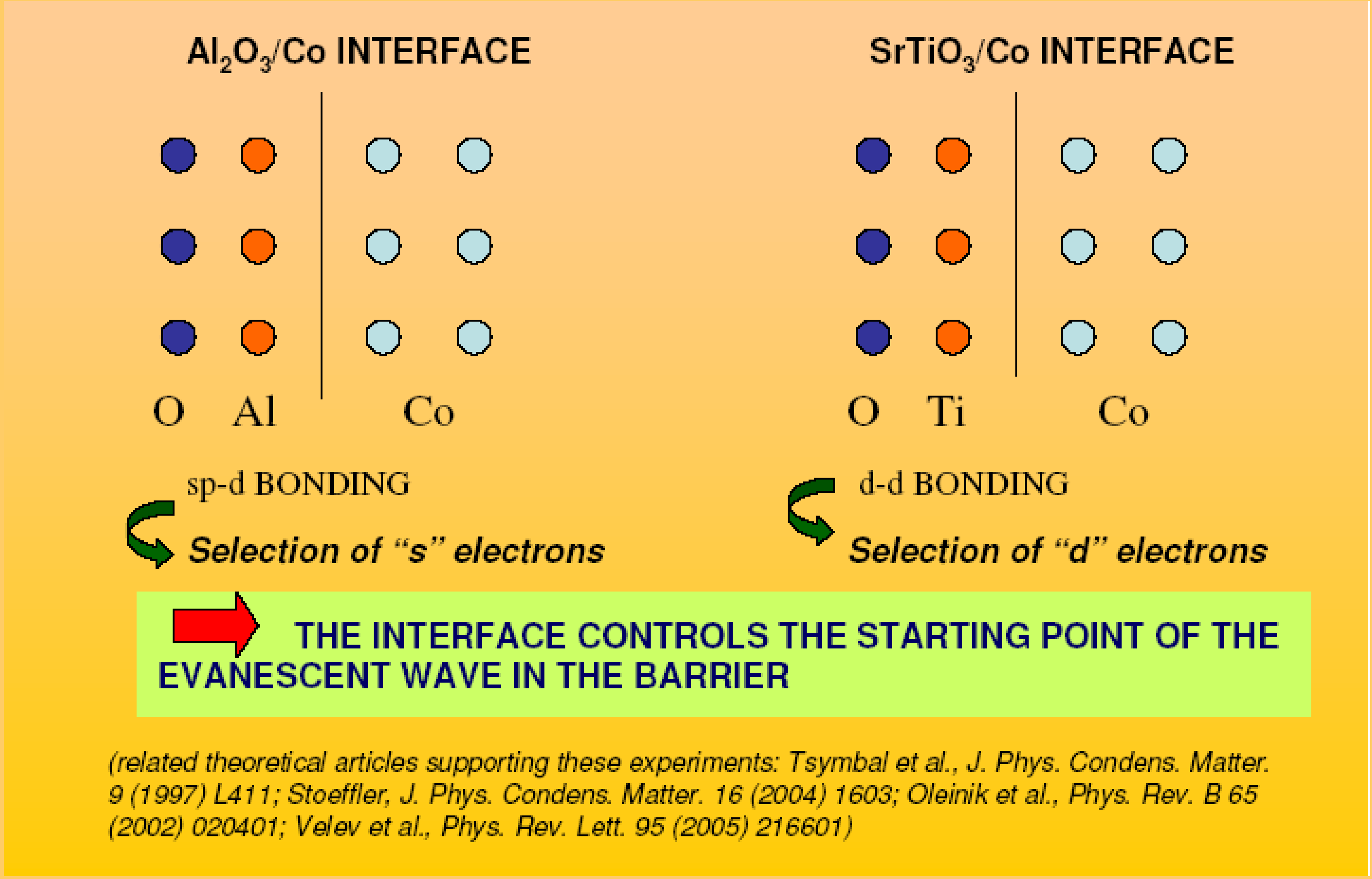
I= $SrTiO_3$: CURRENT BY "d-type" ELECTRONS



Co "d" electrons



J.M. de Teresa,
Universidad de
Zaragoza,
Spain, ESM
2005 Constanta



Al_2O_3/Co INTERFACE

sp-d BONDING

Selection of "s" electrons

$SrTiO_3$/Co INTERFACE

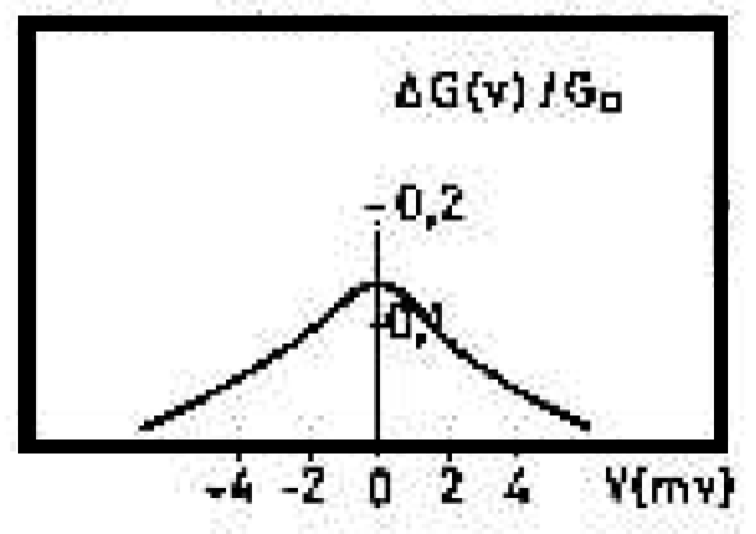
d-d BONDING

Selection of "d" electrons

THE INTERFACE CONTROLS THE STARTING POINT OF THE EVANESCENT WAVE IN THE BARRIER

(related theoretical articles supporting these experiments: Tsymbal et al., J. Phys. Condens. Matter. 9 (1997) L411; Stoeffler, J. Phys. Condens. Matter. 16 (2004) 1603; Oleinik et al., Phys. Rev. B 65 (2002) 020401; Velev et al., Phys. Rev. Lett. 95 (2005) 216601)

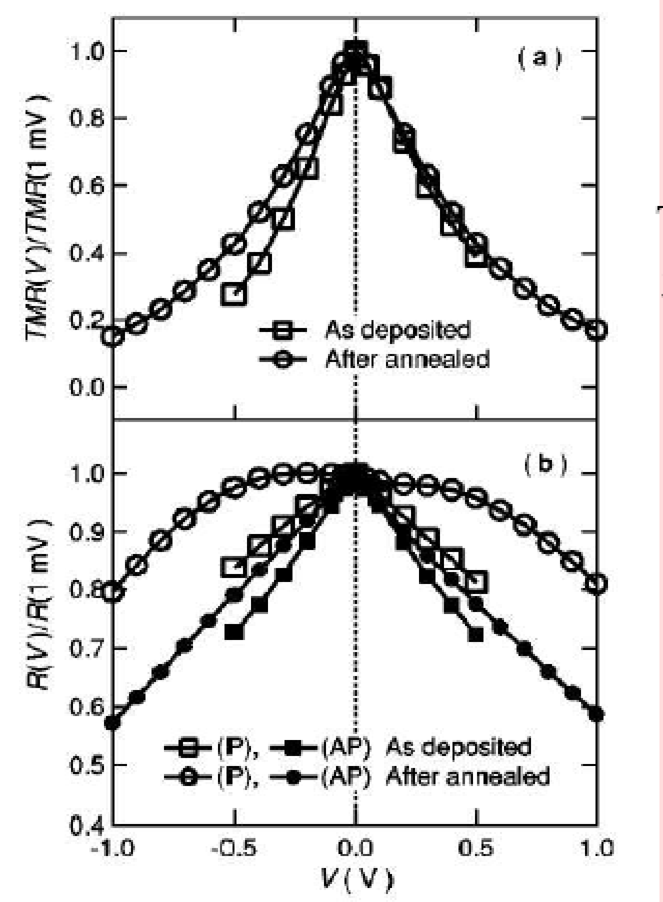
Voltage dependence of TMR



$\mathrm{TMR}_{50\%}$=3mV

50% MR at 3mV

Jullière, Phys. Lett. 1975

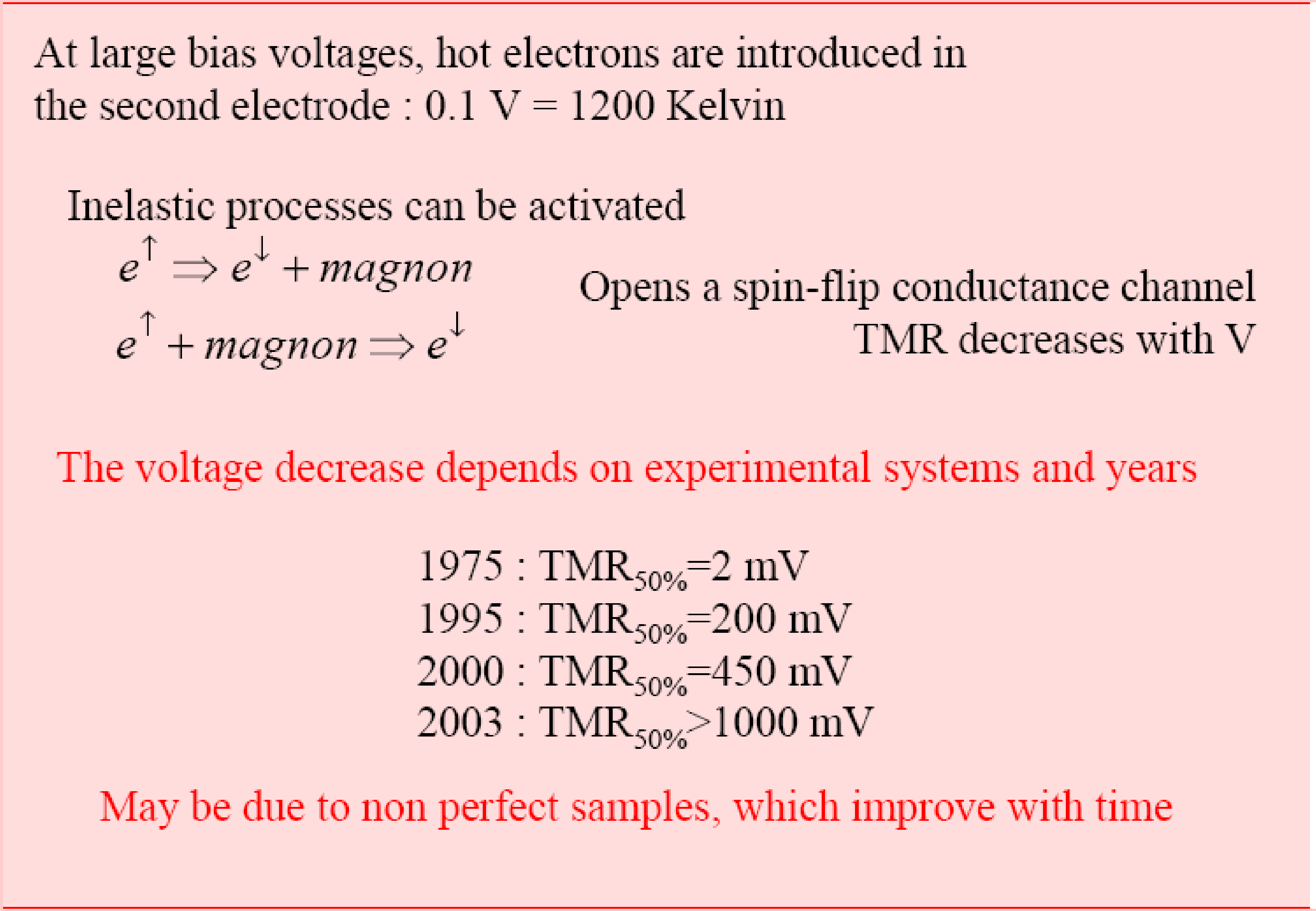


Miyazaki group (Tohoku) APL 2000

TMR - bias voltage dependence
50% decrease TMR for 400mV

R - bias voltage dependence

http://magnetism.eu/esm/2003-brasov/slides/ranno-slides-1.pdf



At large bias voltages, hot electrons are introduced in the second electrode : 0.1 V = 1200 Kelvin

Inelastic processes can be activated

$$e^{\uparrow} \Rightarrow e^{\downarrow} + magnon$$

$$e^{\uparrow} + magnon \Rightarrow e^{\downarrow}$$

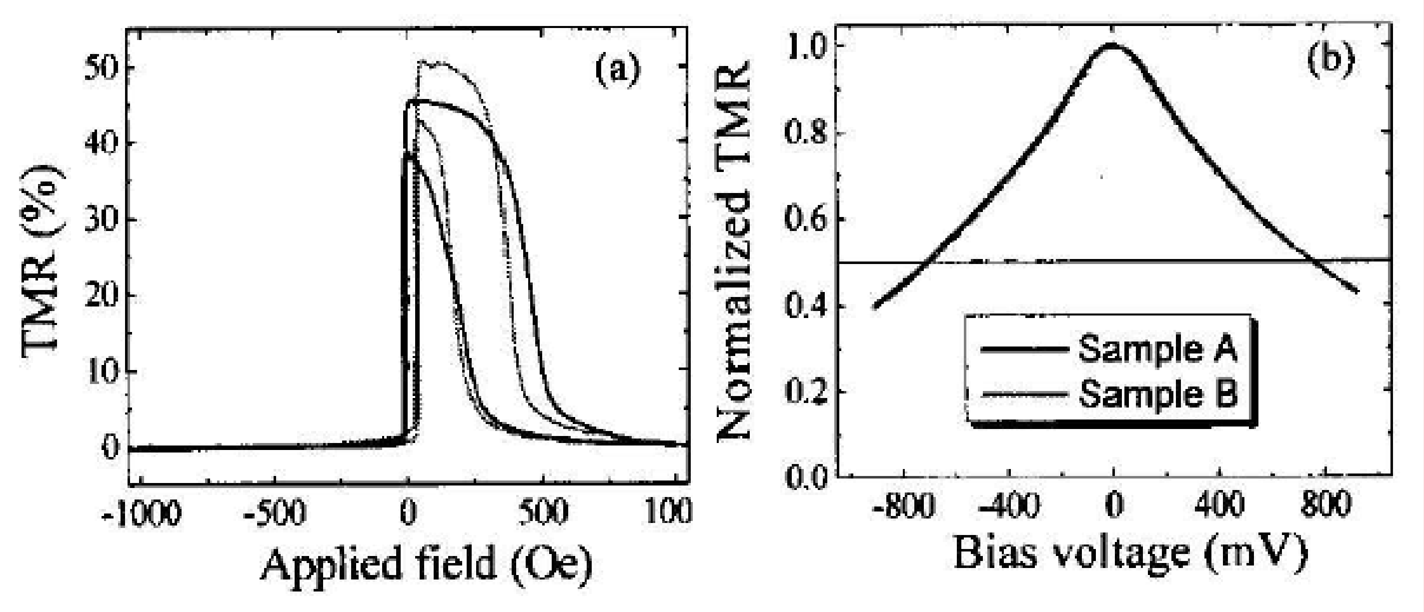
Opens a spin-flip conductance channel
TMR decreases with V

The voltage decrease depends on experimental systems and years

1975 : $TMR_{50\%}$=2 mV
1995 : $TMR_{50\%}$=200 mV
2000 : $TMR_{50\%}$=450 mV
2003 : $TMR_{50\%}$>1000 mV

May be due to non perfect samples, which improve with time

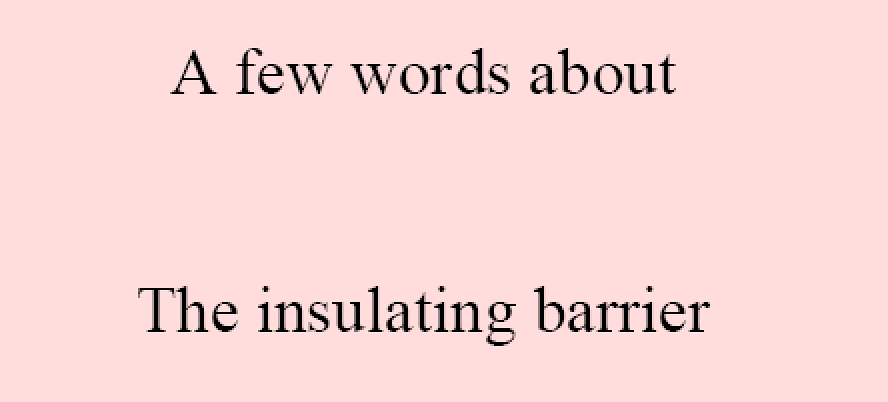
http://magnetism.eu/esm/2003-brasov/slides/ranno-slides-1.pdf



Epitaxial NiFe electrode : 50 % decrease of TMR at 750 mV

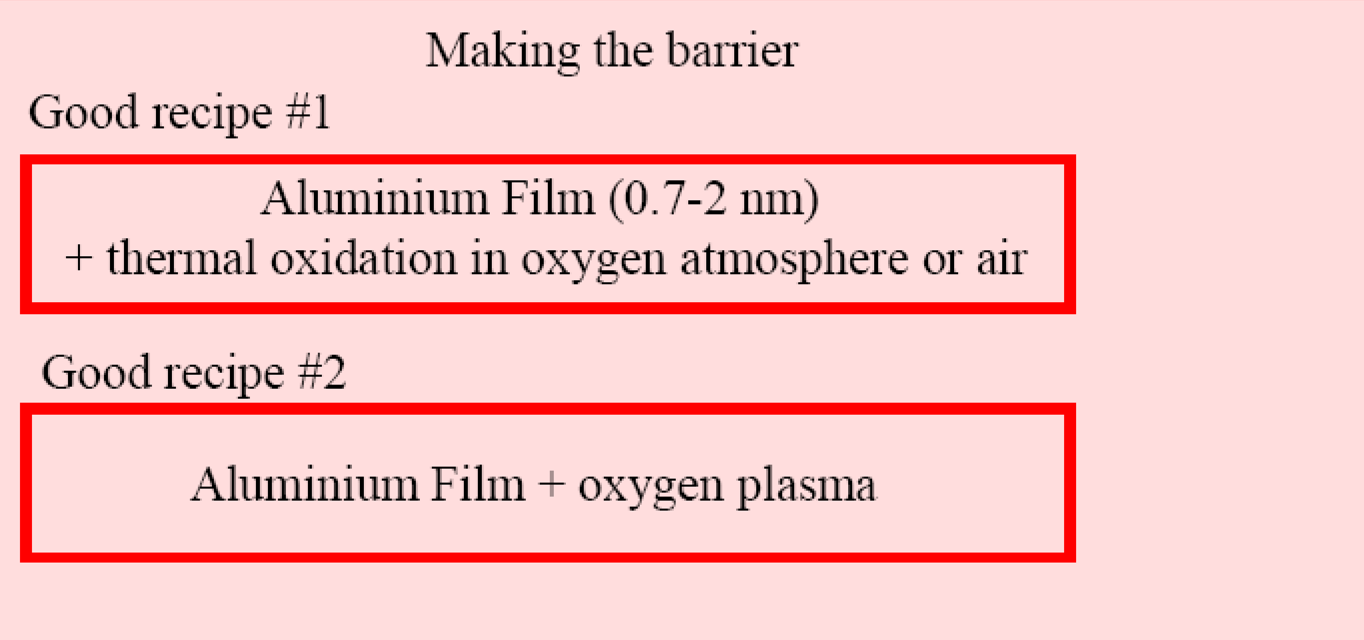
Yu et al. APL 2003

http://magnetism.eu/esm/2003-brasov/slides/ranno-slides-1.pdf



A few words about

The insulating barrier



Making the barrier

Good recipe #1

Aluminium Film (0.7-2 nm)
+ thermal oxidation in oxygen atmosphere or air

Good recipe #2

Aluminium Film + oxygen plasma

http://magnetism.eu/esm/2003-brasov/slides/ranno-slides-1.pdf

Giant room-temperature magnetoresistance in single-crystal Fe/MgO/Fe magnetic tunnel junctions

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[1]NanoElectronics Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki 305-8568, Japan
[2]PRESTO, Japan Science and Technology Agency, Kawaguchi, Saitama 332-0012, Japan

nature materials | VOL 3 | DECEMBER 2004 | www.nature.com/naturematerials

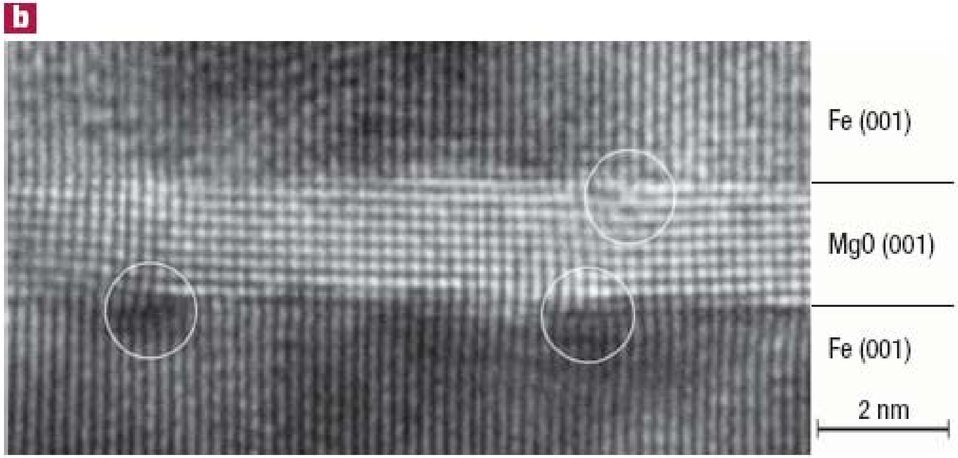


Figure 1 **TEM images of a single-crystal MTJ with the Fe(001)/MgO(001)(1.8 nm)/Fe(001) structure. b** is a magnification of **a**. The vertical and horizontal directions respectively correspond to the MgO[001] (Fe[001]) axis and MgO[100] (Fe[110]) axis. Lattice dislocations are circled. The lattice spacing of MgO is 0.221 nm along the [001] axis and 0.208 nm along the [100] axis. The lattice of the top Fe electrode is slightly expanded along the [110] axis.

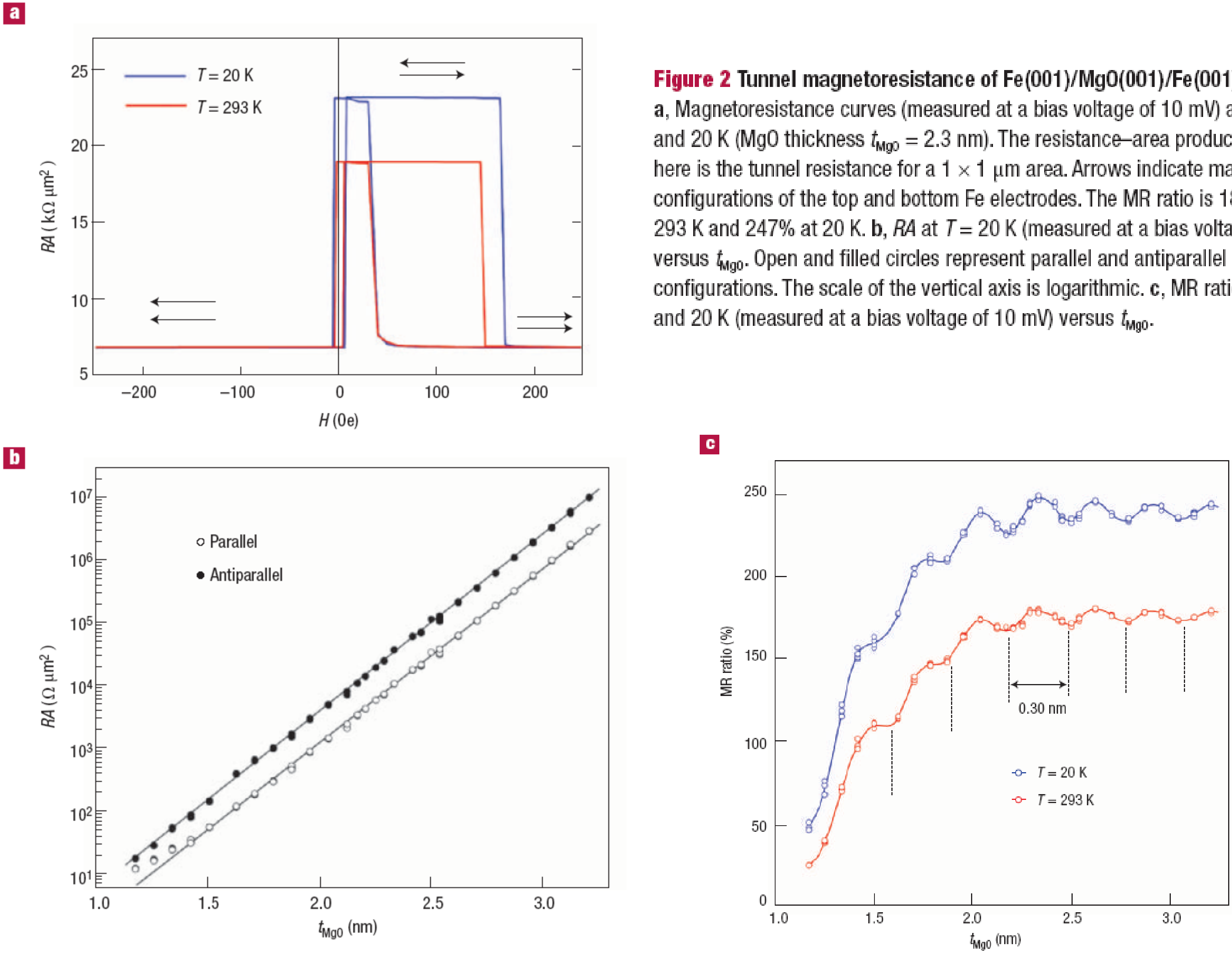
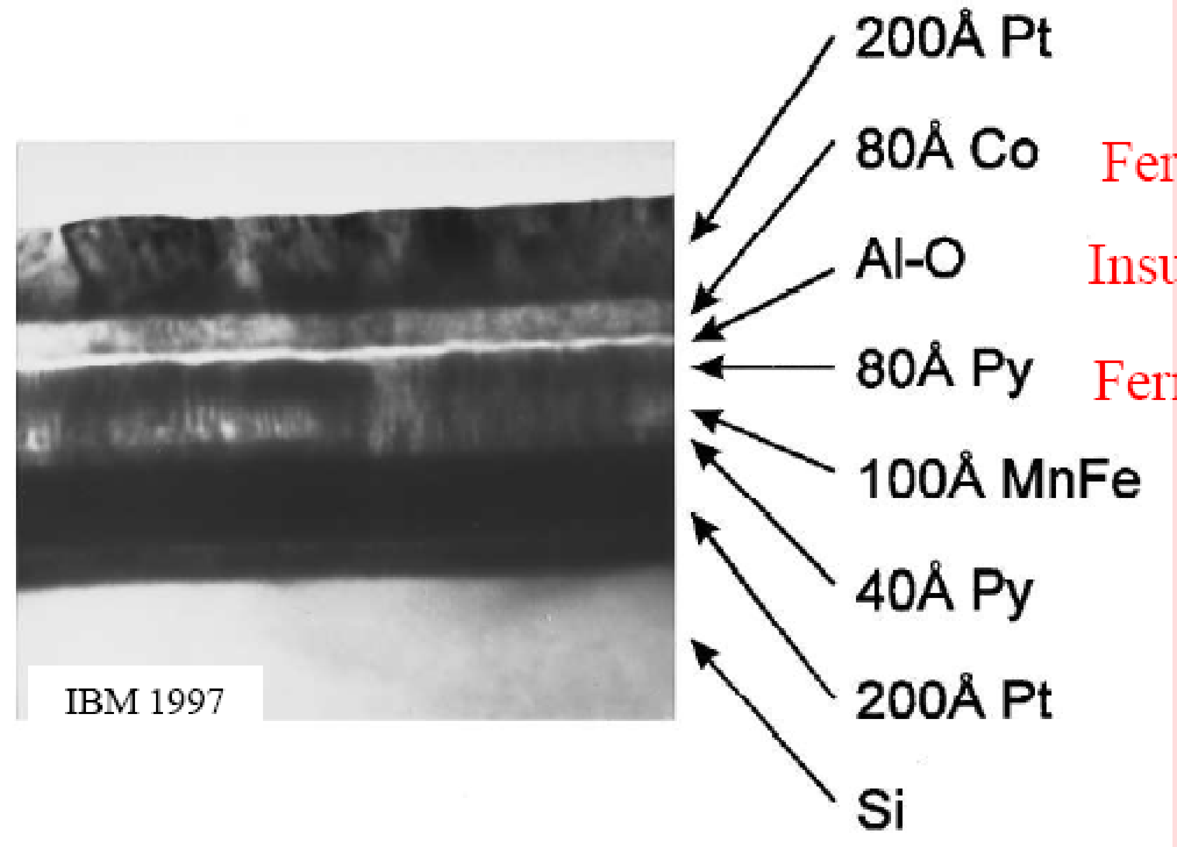


Figure 2 Tunnel magnetoresistance of Fe(001)/MgO(001)/Fe(001) junctions. **a**, Magnetoresistance curves (measured at a bias voltage of 10 mV) at $T = 293$ K and 20 K (MgO thickness $t_{MgO} = 2.3$ nm). The resistance–area product *RA* plotted here is the tunnel resistance for a 1 × 1 μm area. Arrows indicate magnetization configurations of the top and bottom Fe electrodes. The MR ratio is 180% at 293 K and 247% at 20 K. **b**, *RA* at $T = 20$ K (measured at a bias voltage of 10 mV) versus t_{MgO}. Open and filled circles represent parallel and antiparallel magnetic configurations. The scale of the vertical axis is logarithmic. **c**, MR ratio at $T = 293$ K and 20 K (measured at a bias voltage of 10 mV) versus t_{MgO}.

S. Yuasa et al., Nature Materials 3, 868 (2004).

Magnetic Tunnel Junction



IBM 1997

200Å Pt

80Å Co Ferro (free)

Al-O Insulator

80Å Py Ferro (pinned)

100Å MnFe

40Å Py

200Å Pt

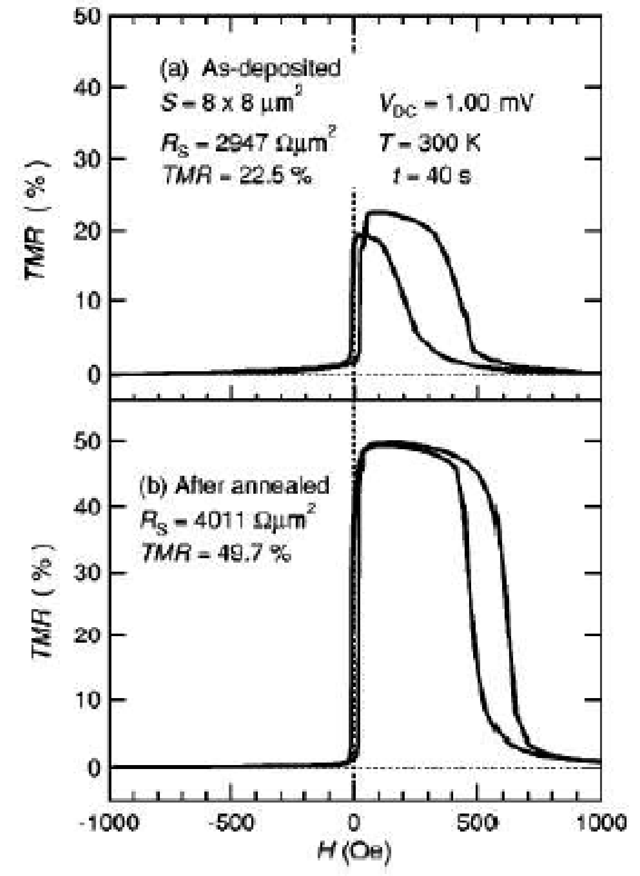
Si

Same technical solutions as GMR structures to get 2 different coercive fields i.e. well defined parallel and antiparallel states.

Hard - Soft materials (Co - NiFe)
Different shape anisotropies for both electrodes
Pinning to AF layer (MnFe) or Artificial AF layer (Co/Ru/Co)

L. RannO, http://magnetism.eu/esm/2003-brasov/slides/ranno-slides-1.pdf

Best present TMR junctions : 50% Room temperature (non exotic materials)



Miyazaki group (Tohoku) APL 2000

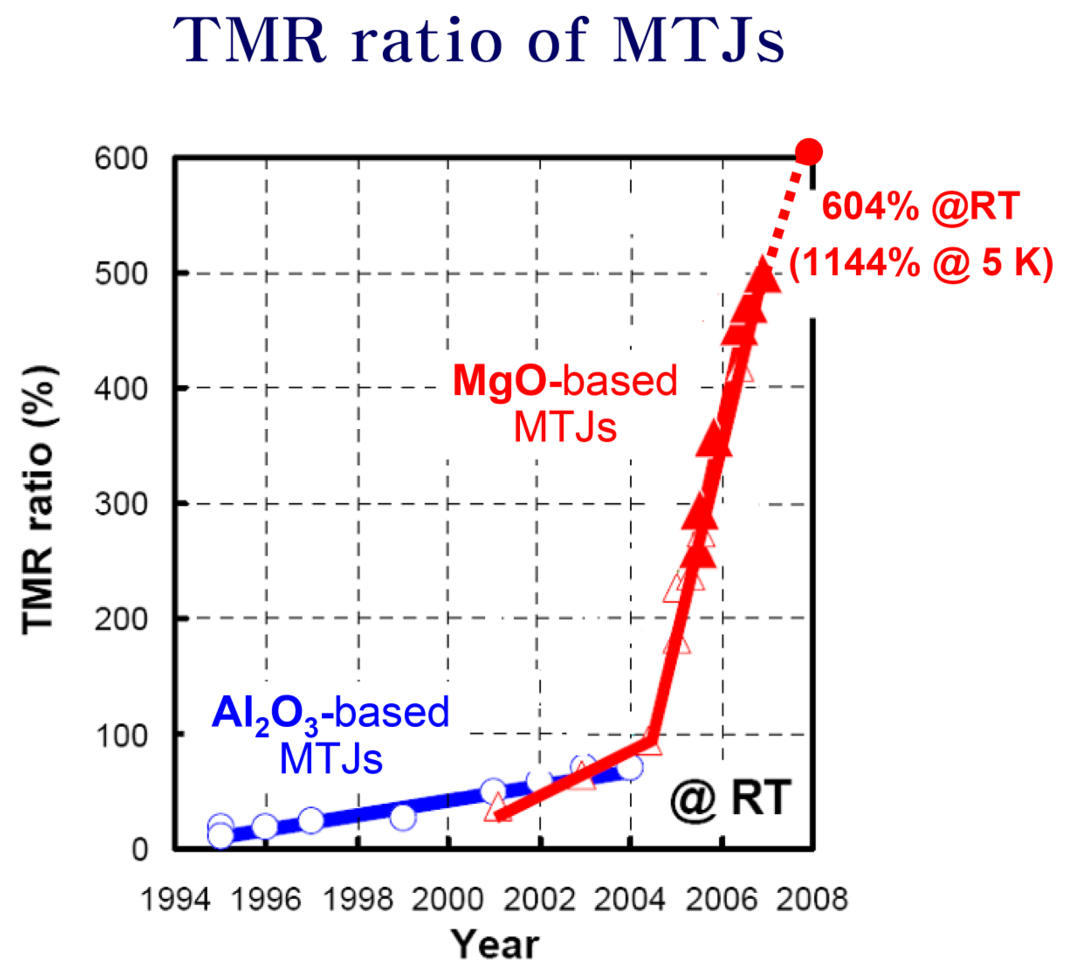
Ta (5 nm)/
$Ni_{79}Fe_{21}$ (3 nm)/
Cu (20 nm)/
$Ni_{79}Fe_{21}$(3 nm)/
$Ir_{22}Mn_{78}$(10nm)/
$Co_{75}Fe_{25}$(4 nm)/
Al (0.8 nm)-oxide/
$Co_{75}Fe_{25}$(4 nm)/
$Ni_{79}Fe_{21}$(20 nm)/
Ta (5nm)

Pinned layer

Free layer

L. RannO, http://magnetism.eu/esm/2003-brasov/slides/ranno-slides-1.pdf

Summary of TMR record values in MTJs



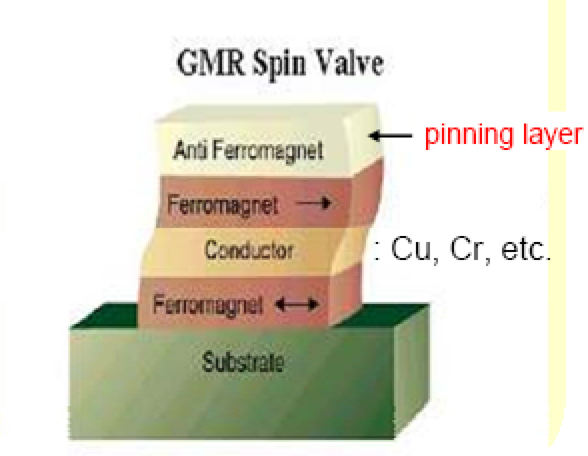
S. Yuasa et al., Nature Materials 3, 868 (2004).

GMR vs. TMR

GMR

(Giant MagnetoResistance)

- **Spin Valve**



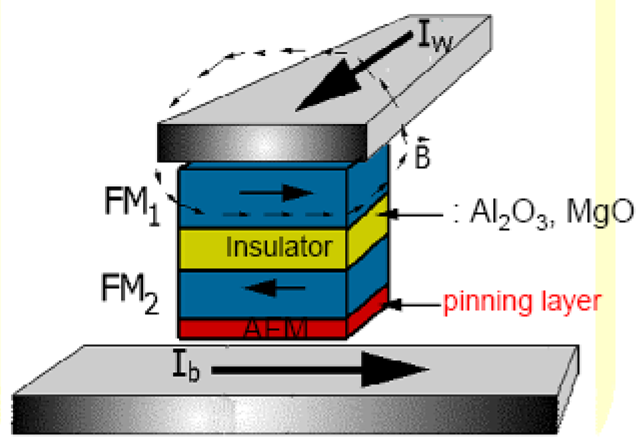
Short spin relaxation length

→ Low GMR (~ 20%)

TMR

(Tunnelling MagnetoResistance)

- **MTJ (Magnetic Tunnel Junction)**

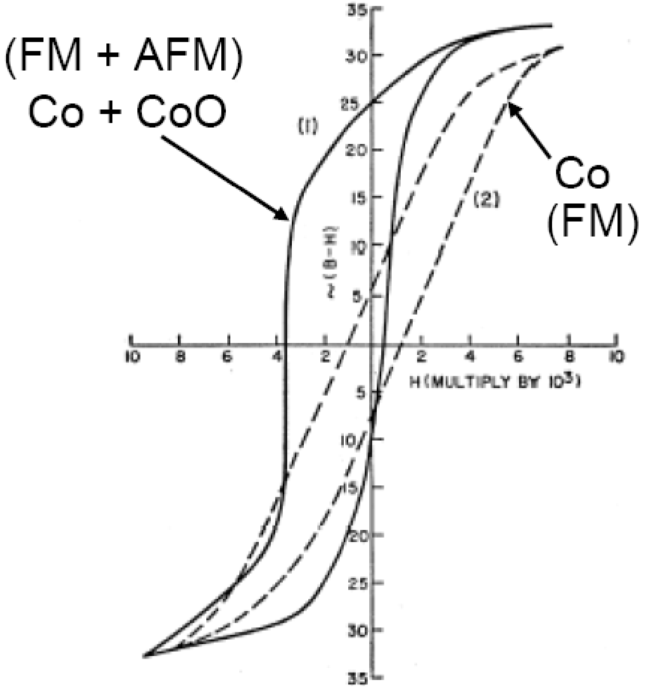


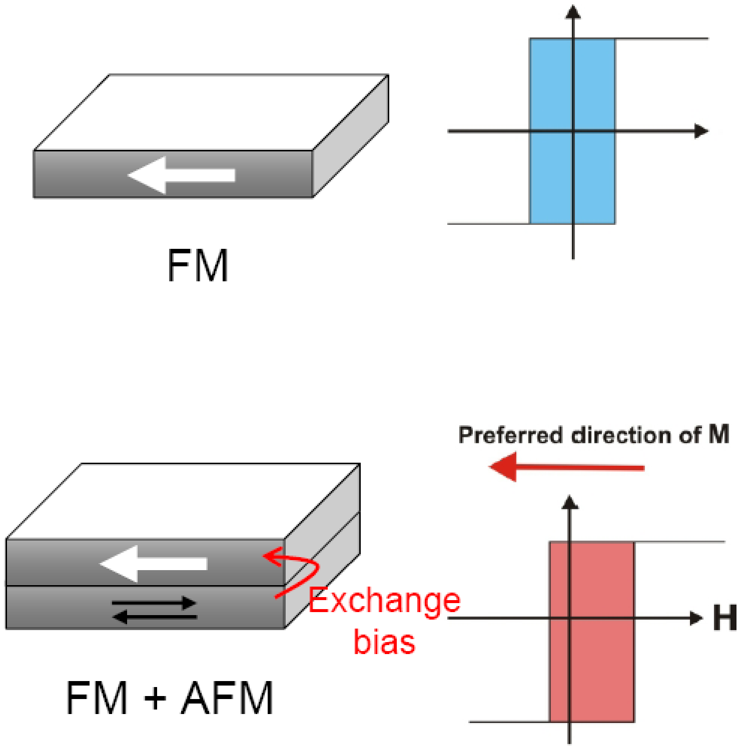
Long spin relaxation length

→ High TMR (< 600%)

Exchange bias in FM/AFM system

Oxygen-coated Co particles





- ***Exchange bias***

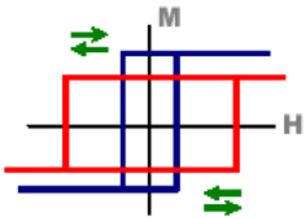
  Neel (1964)

AFM (pinning layer): FeMn, MnIr, PtMn, etc.

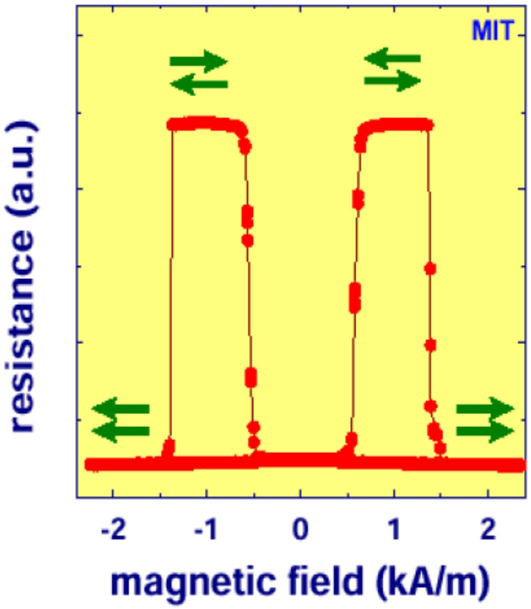
Two types of MTJ

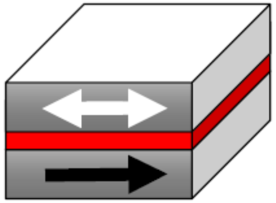
(Magnetic Tunnel Junction)

Different coercivities



$Co / Al_2O_3 / NiFe$



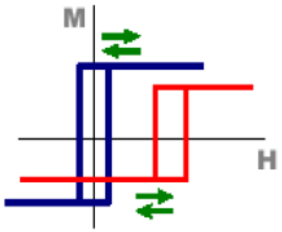


NiFe: Free layer

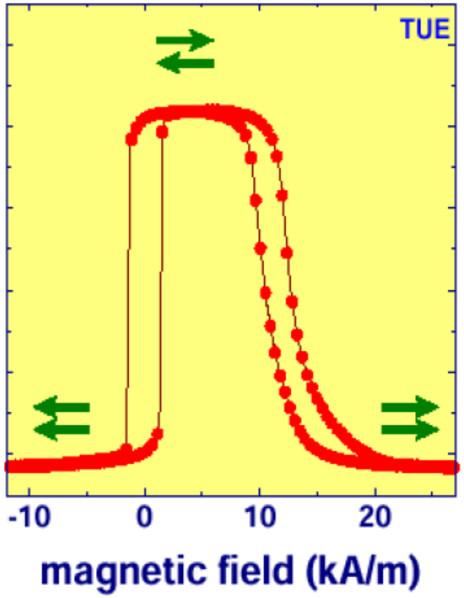
Al_2O_3: Tunnel barrier

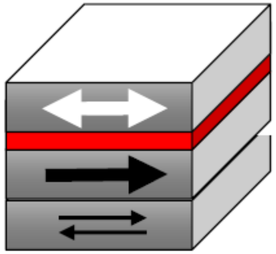
Co: Pinned layer

Exchange biasing using antiferromagnet



$FeMn / Co / Al_2O_3 / Co$





Co: Free layer

Al_2O_3: Tunnel barrier

Co: Pinned layer

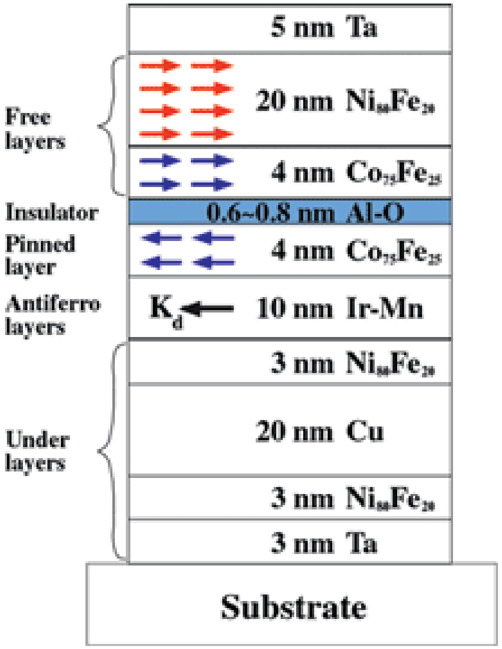
FeMn: Pinning layer

TMR ~ 80%

S. Yuassa et al.

http://www.jst.go.jp/sicp/ws2009_sp1st/presentation/15.pdf

Film deposition scheme

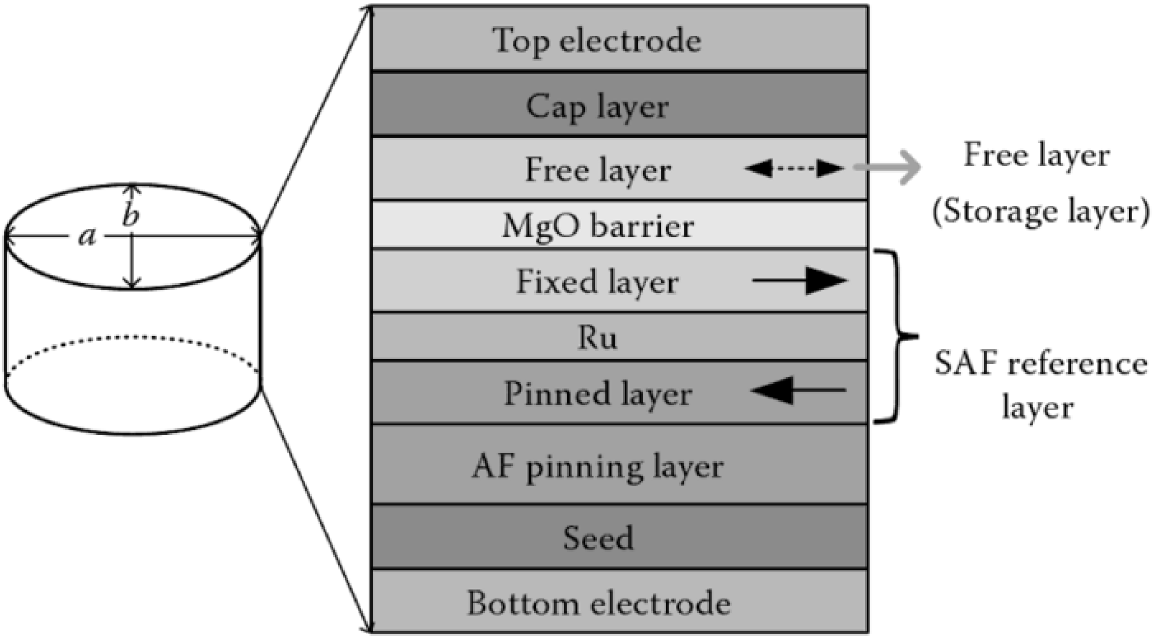


Underlayers: to make a flat interface induce crystalline oriented structure

Antiferro layers : to pin the hard layer

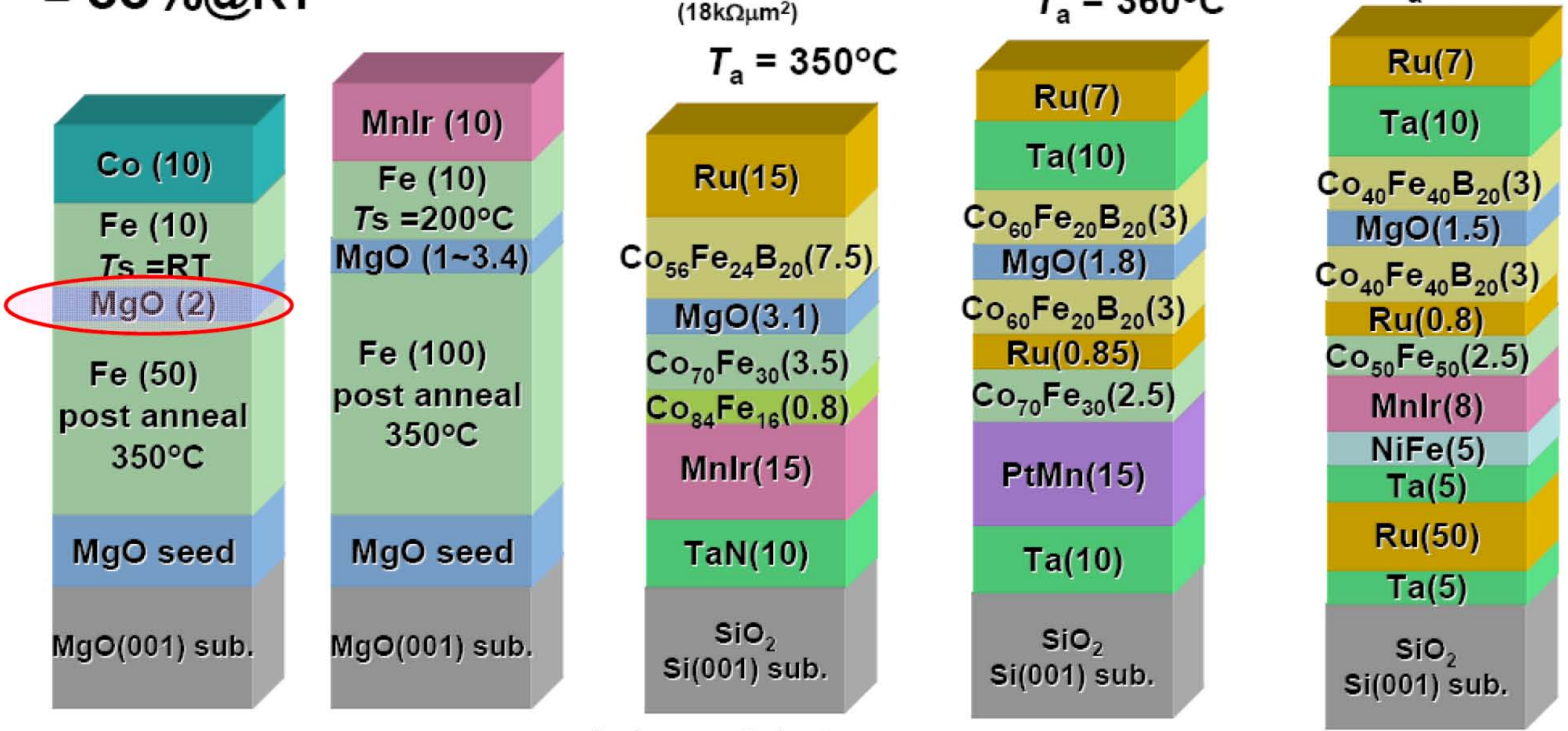
FeMn, IrMn, NiO..

illustration of a typical MTJ structure



Nano-Semiconductors: Devices and Technology
edited by Krzysztof Iniewski

Structures of TMR MTJs



TMR ratio
= 88%@RT

Co (10)
Fe (10)
Ts =RT
MgO (2)
Fe (50)
post anneal
350°C
MgO seed
MgO(001) sub.

MBE

180%

MnIr (10)
Fe (10)
Ts =200°C
MgO (1~3.4)
Fe (100)
post anneal
350°C
MgO seed
MgO(001) sub.

MBE

AIST

220%
(18kΩμm^2)
T_a = 350°C

Ru(15)
$Co_{56}Fe_{24}B_{20}$(7.5)
MgO(3.1)
$Co_{70}Fe_{30}$(3.5)
$Co_{84}Fe_{16}$(0.8)
MnIr(15)
TaN(10)
SiO_2
Si(001) sub.

ion-beam sputtering +
MgO :reactive magnetron
sputtering

IBM

230%
(420Ωμm^2)
T_a = 360°C

Ru(7)
Ta(10)
$Co_{60}Fe_{20}B_{20}$(3)
MgO(1.8)
$Co_{60}Fe_{20}B_{20}$(3)
Ru(0.85)
$Co_{70}Fe_{30}$(2.5)
PtMn(15)
Ta(10)
SiO_2
Si(001) sub.

magnetron sputtering

Canon
ANELVA

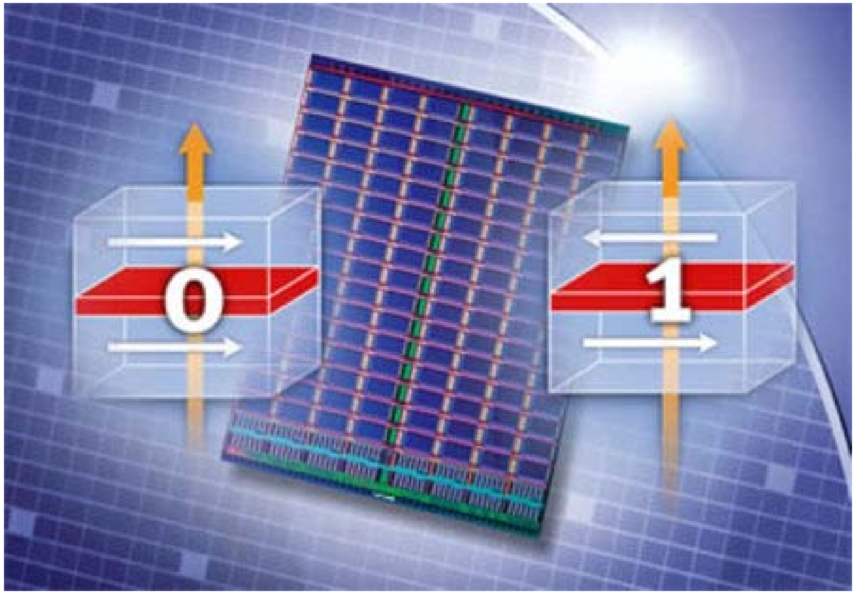
> 355%
(540Ωμm^2)
T_a = 400°C

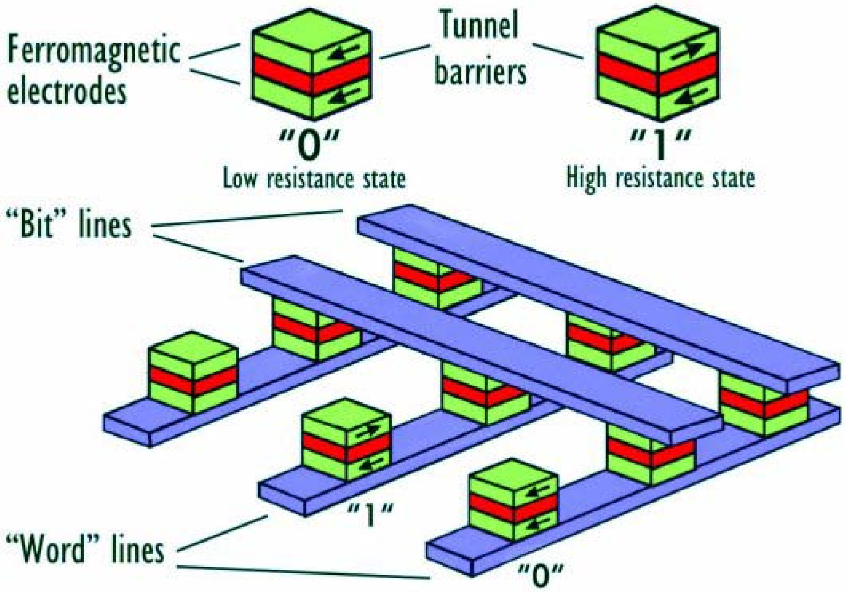
Ru(7)
Ta(10)
$Co_{40}Fe_{40}B_{20}$(3)
MgO(1.5)
$Co_{40}Fe_{40}B_{20}$(3)
Ru(0.8)
$Co_{50}Fe_{50}$(2.5)
MnIr(8)
NiFe(5)
Ta(5)
Ru(50)
Ta(5)
SiO_2
Si(001) sub.

magnetron sputtering

Tohoku Univ.
& Hitachi

MRAM





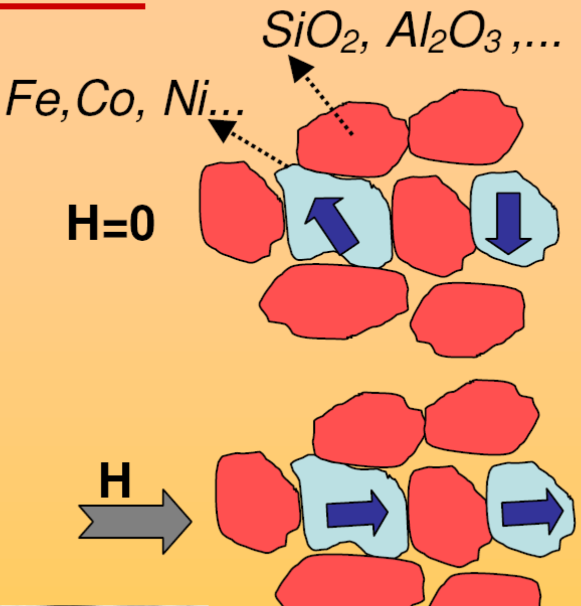
One of the two plates is a permanent magnet set to a particular polarity, the other's field will change to match that of an external field.

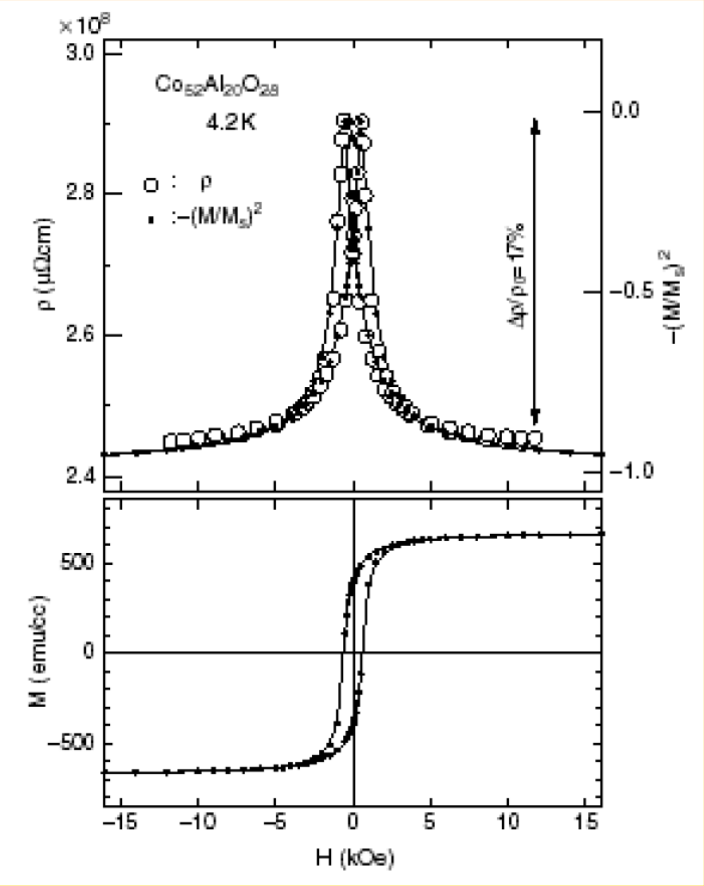
https://www.westfloridacomponents.com

Magneto resistive random access technology (MRAM) for better memory storage

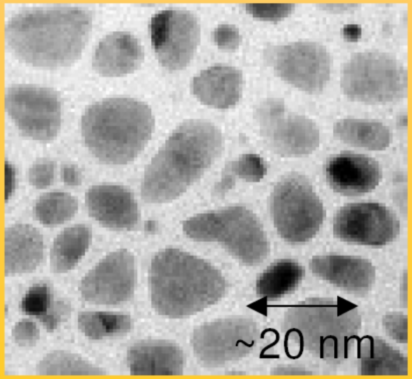
TUNNEL MR (TMR) IN GRANULAR MATERIALS

-The TMR effect can be realized in granular materials / thin films with immiscible magnetic metals / insulators due to the same physical phenomena.





J.M. de Teresa,
Universidad de
Zaragoza,
Spain, ESM
2005 Constanta



Co in Zr_2O_3 matrix

Gittleman et al., Phys. Rev. 5 (1972) 3609; Helman and Abeles, Phys. Rev. Lett. 37 (1976) 1429;Inoue and Maekawa, Phys. Rev. B 53 (1996) R11927; Mitani et al., J. Magn. Mater. 165 (1997) 141; Batlle and Labarta, J. Phys. D: Appl. Phys. 35 (2002) R15