Ecole Franco-Roumaine
Magnétisme des systèmes nanoscopiques et structures hybrides
Brasov, septembre 2003

Spin tunnel and Spin Polarisation

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Summary

I- Introduction to Tunnel Effect

II-Magnetic Tunnel Effect

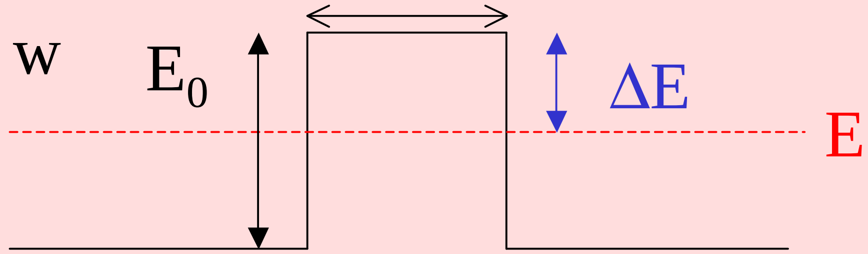
III-Bias Voltage and Temp Dependence

IV-Spin Polarisation

V- Half Metals

I- Introduction to Tunnel Effect

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)

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

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

Plane waves

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

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

Evanescent waves

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

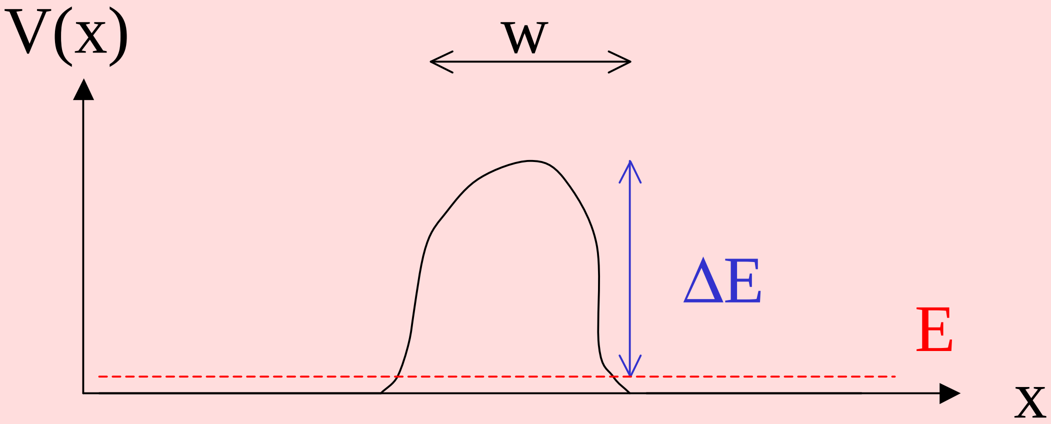
$$q = \pm\sqrt{\frac{2m\Delta E}{\hbar^2}}$$

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

Tunnel barriers must be very thin insulating layers

Width = w < 10 nm

For a more general barrier shape



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

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

W. K. B. Approximation $\psi(x) = e^{\pm\int_0^x k(u)du}$

What is neglected ?

$$\psi(x) = e^{\pm\int_0^x k(u)du}$$

$$\frac{d\psi(x)}{dx} = \pm k(x)\psi(x)$$

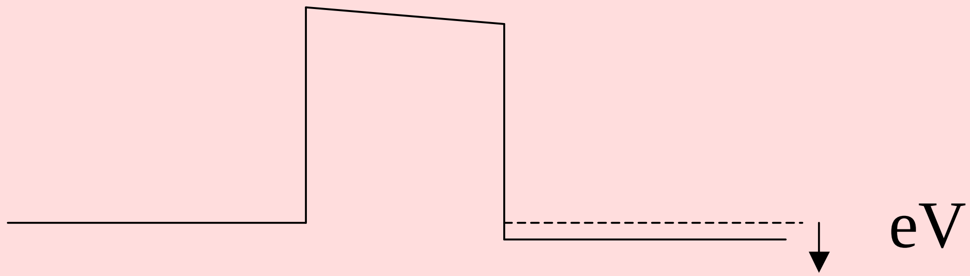
$$\frac{d^2\psi(x)}{dx^2} = \pm\frac{dk(x)}{dx}\psi(x) \pm k(x)\frac{d\psi(x)}{dx}$$

$$= \pm\cancel{\frac{dk(x)}{dx}}\psi(x) + k^2(x)\psi(x)$$

$k(x) = \sqrt{\frac{2m}{\hbar^2}(V(x) - E)}$ The barrier potential should vary smoothly

We are dealing with transport. What about the current ?

To pass a current,
we must apply a bias voltage across the barrier.



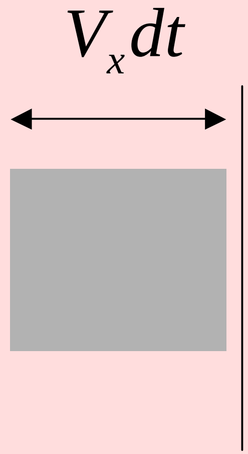
the barrier has a transmission coefficient T

Simmons

The probability to find the electron (energy E) on the other side of the barrier is :

$$P(E) = \langle \psi | \psi \rangle = \psi^2 = e^{-2\int_0^w \sqrt{\frac{2m(V(u)-E)}{\hbar^2}}du}$$

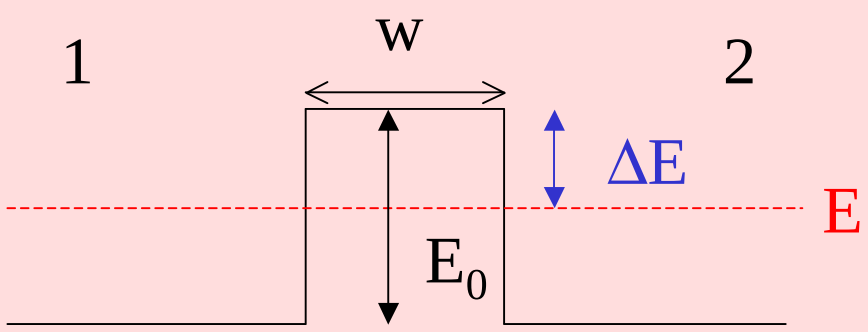
Electrons coming from the left to the right



$$dN = \int_0^\infty V_x n(V_x) P(E_x) dV_x dt$$

$$\frac{dN}{dt} = \frac{4\pi m^2}{h^3} \int_0^E P(E_x) dE_x \int_0^\infty f(E) dE_{//}$$

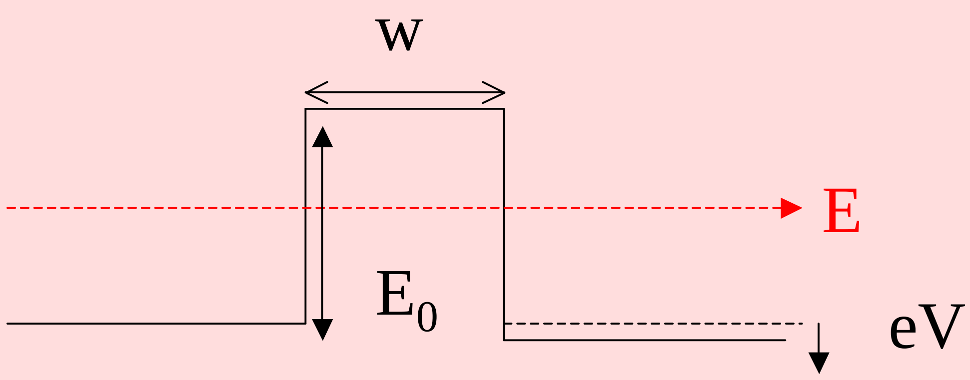
No bias voltage



Current 1 $\rightarrow$ 2 = Current 2 $\rightarrow$ 1

$J(V=0)=0$

Bias voltage $eV \ll E_0$

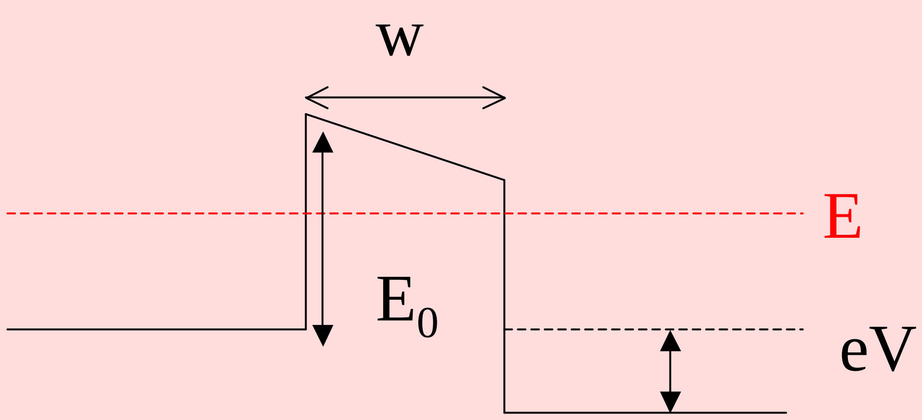


$$J = e\left(\frac{dN_1}{dt} - \frac{dN_2}{dt}\right) = \frac{4e\pi m^2}{h^3} \int_0^E P(E_x)\,dE_x \int_0^\infty [f(E) - f(E+eV)]\,dE_{//}$$

Simmons (1963) has calculated approximate recipes $J = 3.16\ 10^{10} \sqrt{E_0}\,\frac{V}{S}\, e^{-1.02 S \sqrt{E_0}}$

⇒ Linear J(V) at low bias

Bias voltage 0<eV<E_0



$$\Rightarrow \quad J = \alpha(V + \beta V^3)$$

Simmons ' parabolic fit $$\frac{dJ}{dV} = \alpha(1 + 3\beta V^2)$$

β contains the barrier height and the barrier width

Why $\dfrac{dJ}{dV}$?

From the experimental point of view :

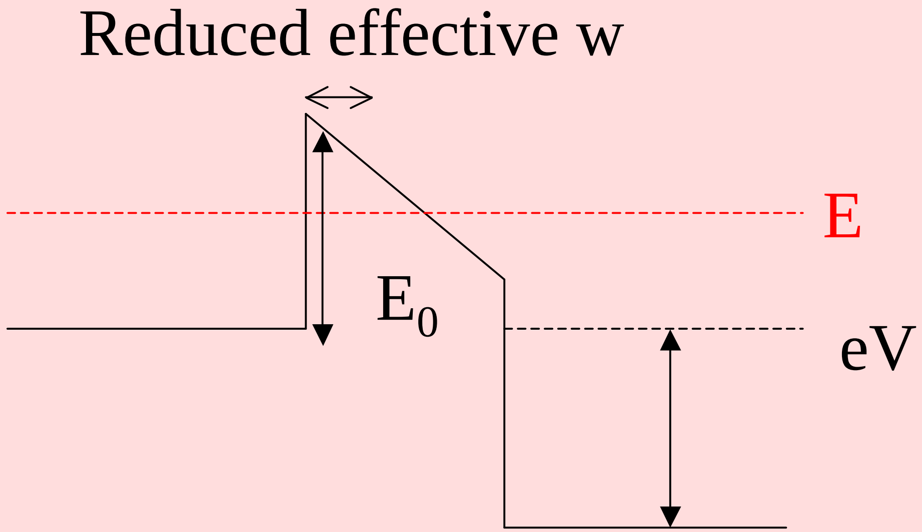
Using a voltage source : $V(t) = V_0 + v\cos(\omega t)$ $\quad v << V_0$

$$J(V) = J(V_0 + v\cos(\omega t)) = J(V_0) + v\cos(\omega t)\frac{dJ}{dV}(V_0)$$

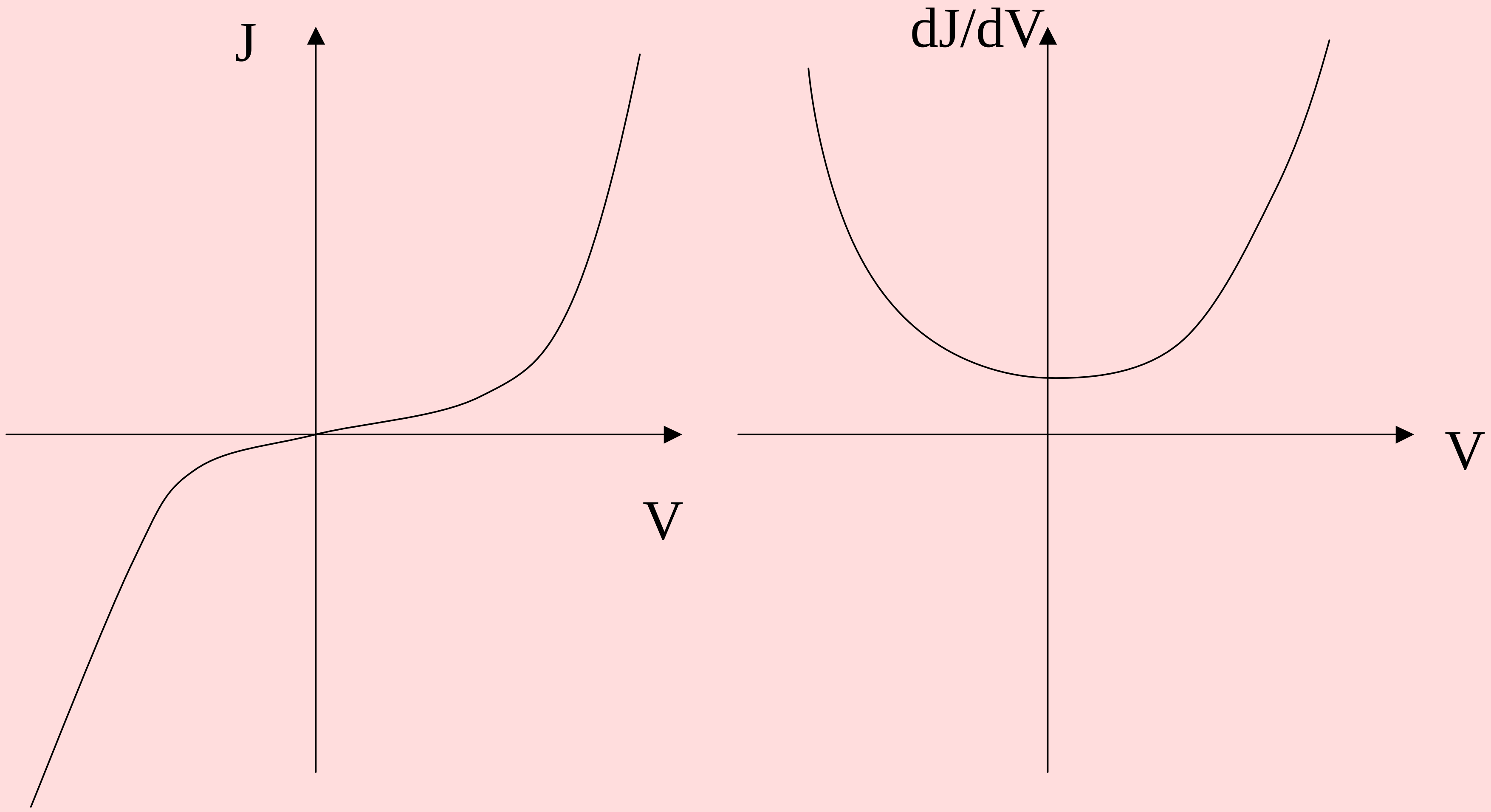
Measuring the ω component of the signal with a lock-in amplifier gives directly the differential conductance

Filter all the constant voltage and non-ω noise

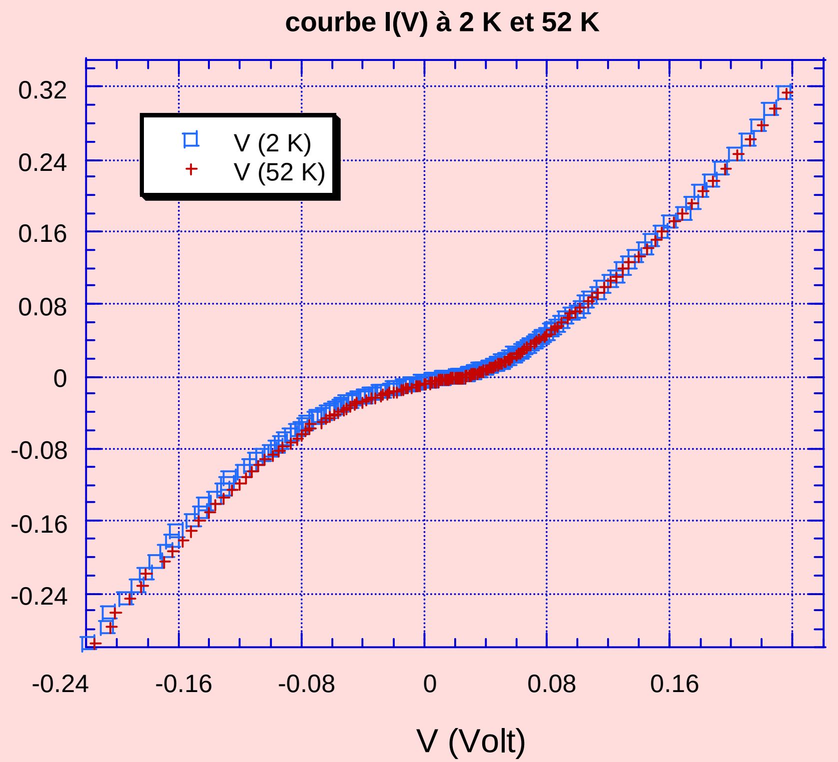
Bias voltage $eV>E_0$



J increases rapidly but in fact such a bias voltage corresponds to the electrical breakdown regime


J
V
dJ/dV
V

I-V non linear curves (ferromagnetic/insulator/ferromagnetic)



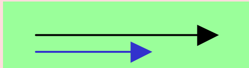
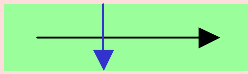
No temperature dependence of tunnel effect (1st order)

Thèse E. Favre-Nicolin (Grenoble 2003)

II-Magnetic Tunnel Effect

In 1972 Gittleman et al. measured the resistance and MR of Ni grains in a SiO_2 matrix

Longitudinal MR is <0 contrary to the sign of the bulk Ni AMR $\rho_{//} > \rho_{perp}$

R  > R 

M J M J

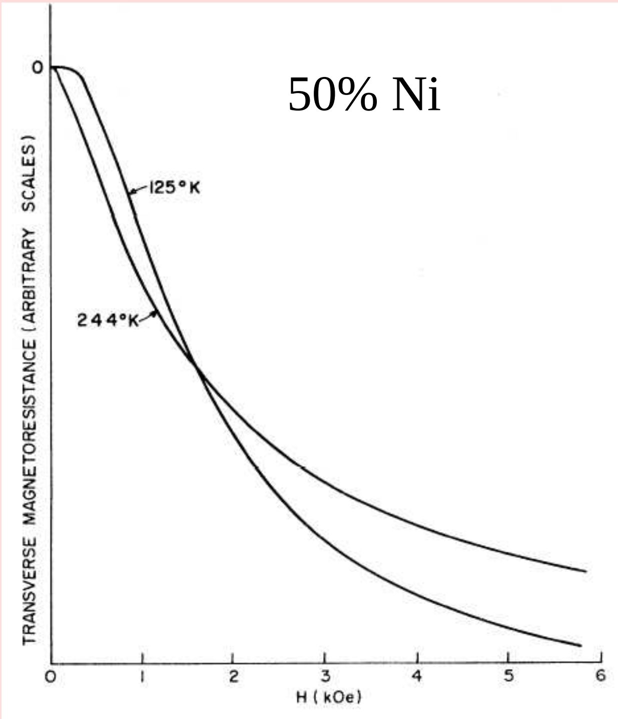


FIG. 5. Transverse magnetoresistance vs applied magnetic field for 50 vol% Ni.

Gittleman et al. Phys. Rev. 5 (1972) 3609

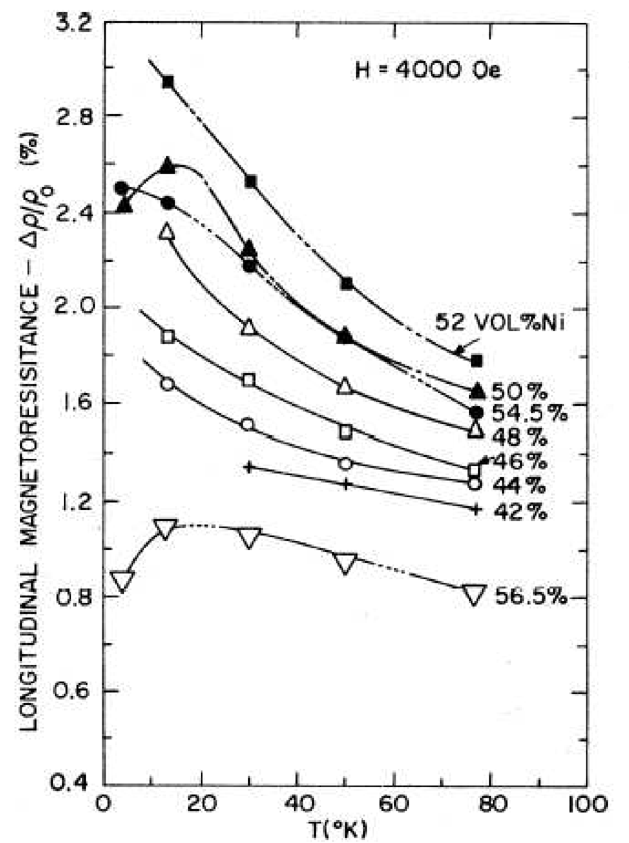


FIG. 10. Longitudinal magnetoresistance vs T (H = 4000 Oe).

Gittleman et al. 1972 :

than the total resistivity of nickel. Accordingly we conclude that the electronic tunneling probability t and ρ_t are magnetic-field dependent. Such a field dependence of the tunneling probability can arise from the fact that as an electron tunnels into a neighboring grain its spin must be rotated whenever the moments of the grains are not aligned. This

$$\sigma(T,H) = \sigma_0(T) + \sigma_1(T)\left\langle \frac{\vec{m}_1 \cdot \vec{m}_2}{m^2} \right\rangle$$

Volume 54A, number 3 PHYSICS LETTERS 8 September 1975

TUNNELING BETWEEN FERROMAGNETIC FILMS

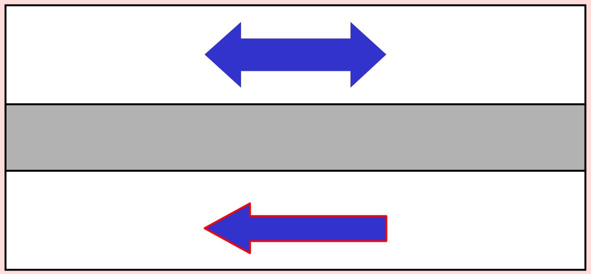
M. JULLIERE
Institut National des Sciences Appliquées, 35031 Rennes Cedex, France

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

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

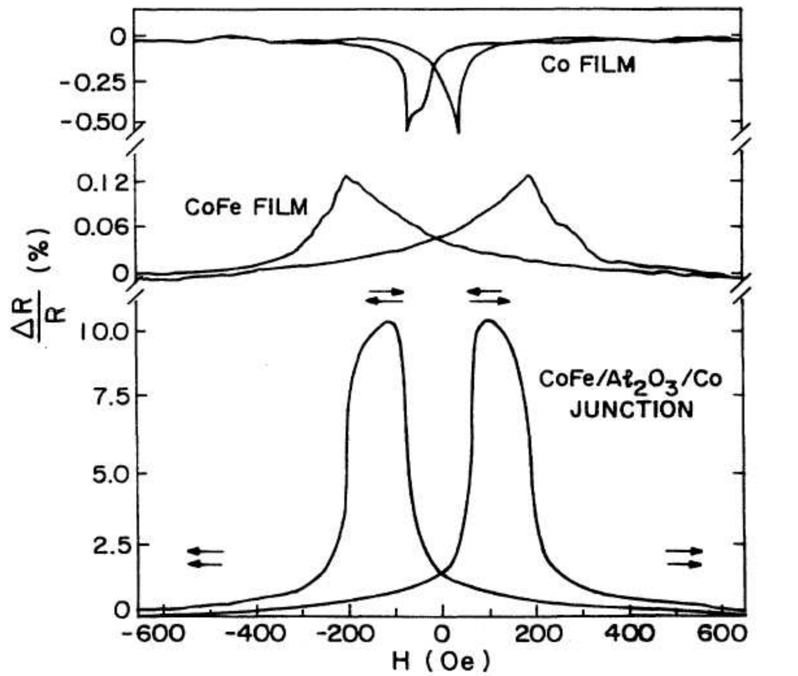
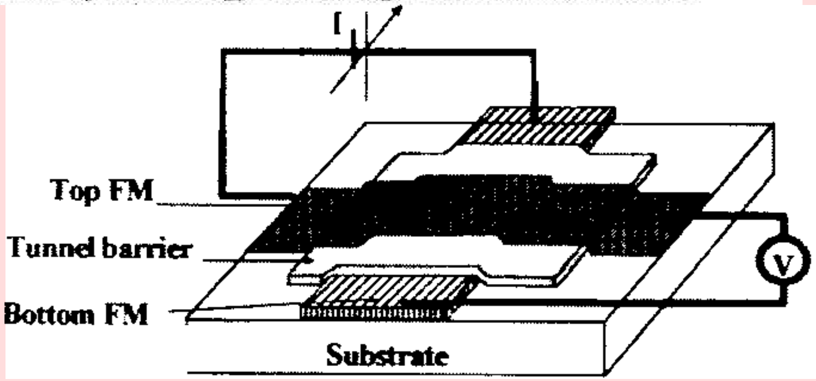


FIG. 2. Resistance of CoFe/Al_2O_3/Co junction plotted as a function of H in the film plane, at 295 K. Also shown is the variation in the CoFe and Co film resistance. The arrows indicate the direction of M in the two films (see text).



200µm x 300 µm

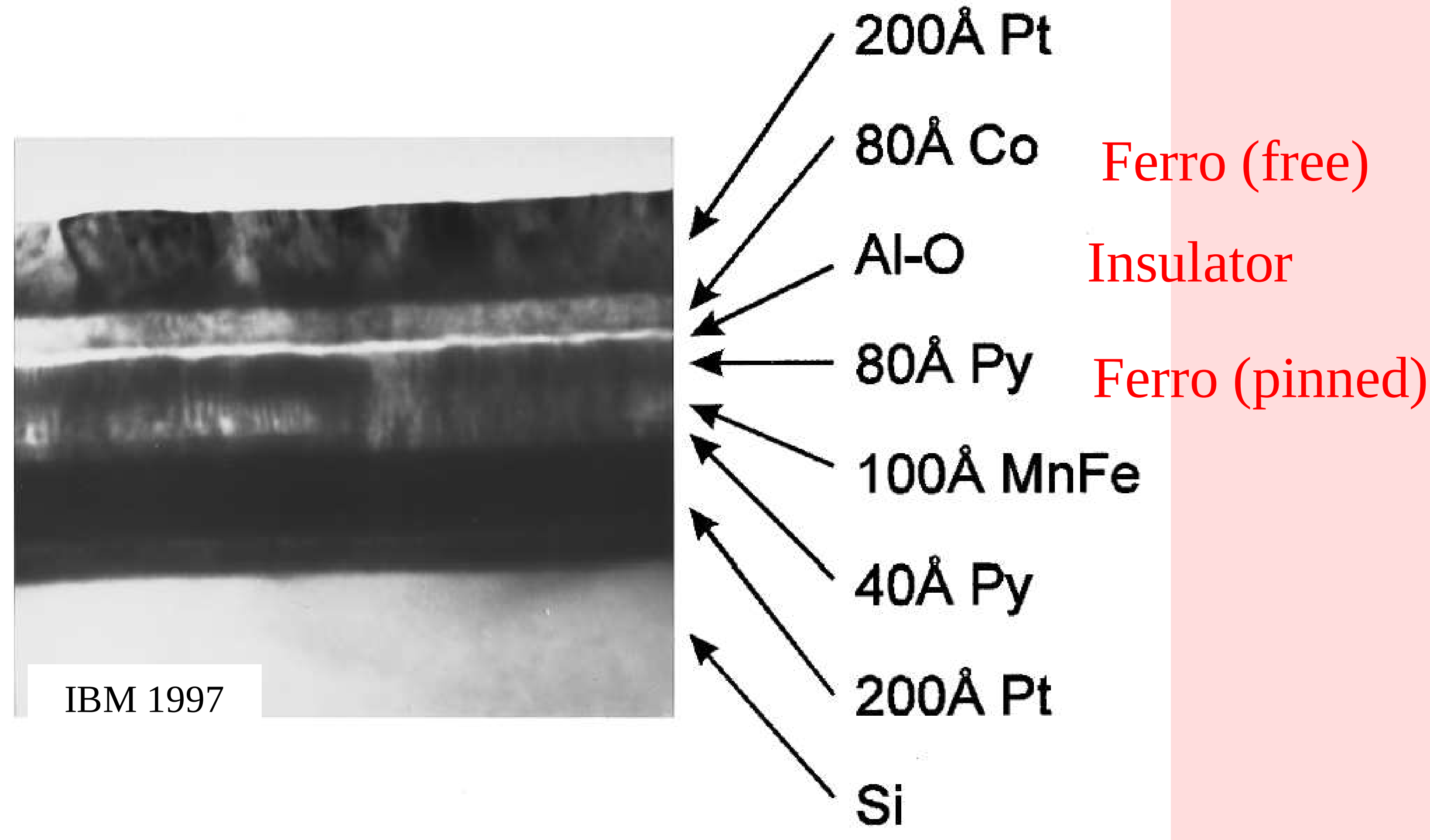
11.8% at 300 K
24% at 24 K

ϕ=1.9 eV and t=1.6 nm

$V_{50\%}$=200mV

And also Miyazaki, Tezuka JMMM 139 (1995) L231

Magnetic Tunnel Junction



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)

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

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

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

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

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

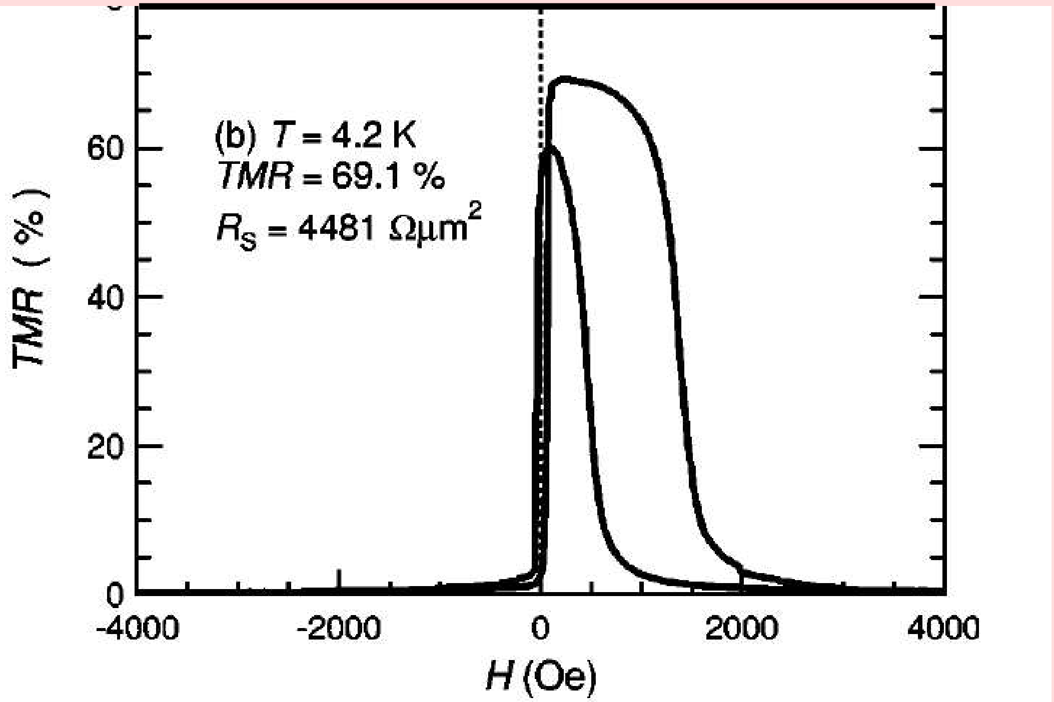
Does not depend on the barrier (height, width)

because of assumption about G_0

i.e. no spin dependence of transmission

Fe/a-Ge/Co (Jullière)

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



69.1% at 4.2 K

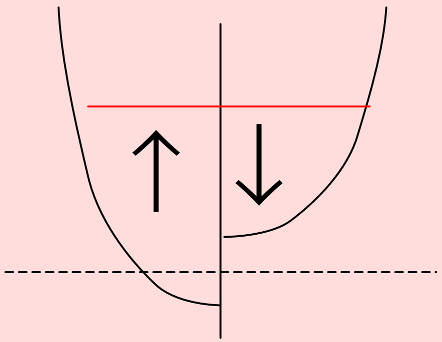
From Jullière 's formula

P_{CoFe}=50.7%
similar to expected

CoFe TMR junction (Tohoku 2000)

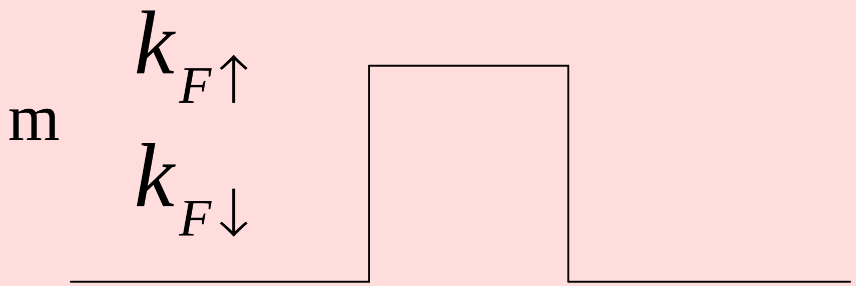
Slonczewski 's model (1989)

Ferromagnetic electrodes



$$E = \frac{\hbar^2 k^2}{2m} \pm E_{exch}$$

Barrier in the model



Solve Schrödinger for both channels, calculate conductances

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

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

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

Improved models :

Bratkovsky :

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

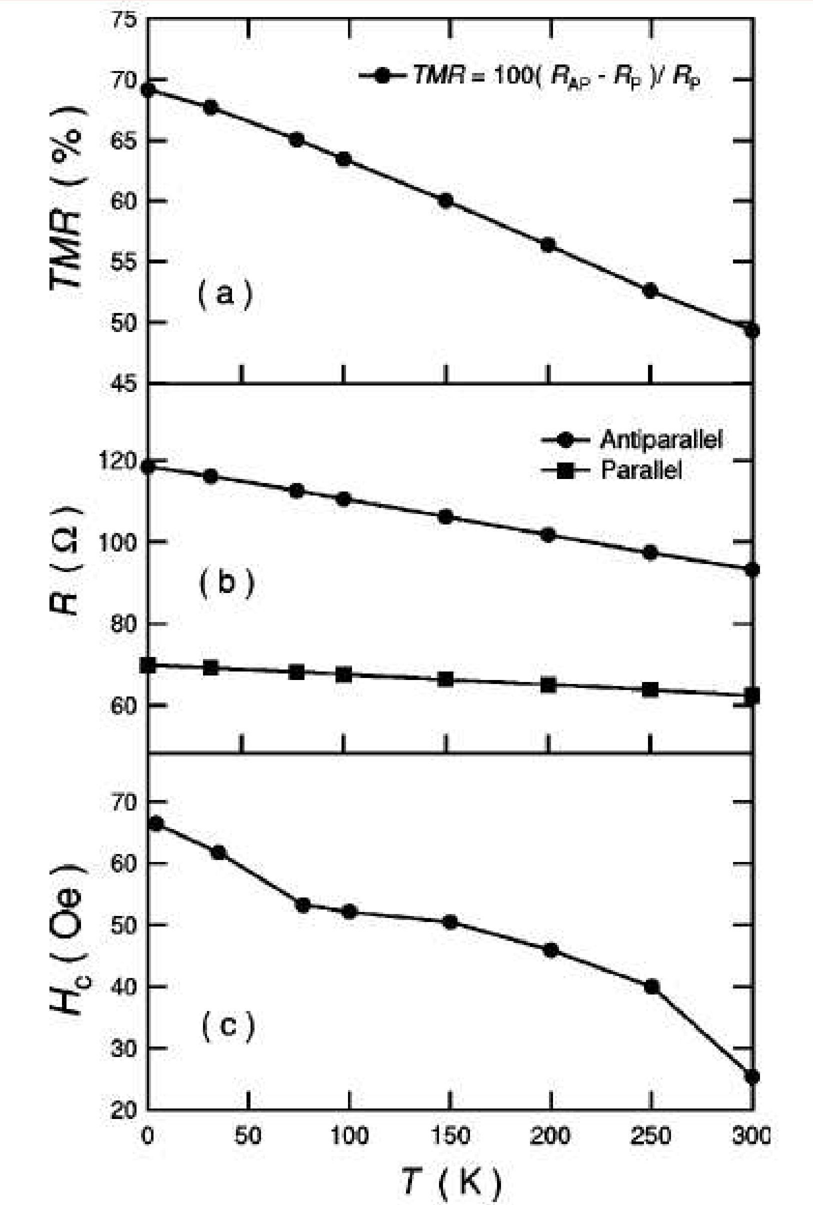
$$P = \frac{q^2 - m_b^2 \cdot k_{F\uparrow} k_{F\downarrow}}{q^2 + m_b^2 \cdot k_{F\uparrow} k_{F\downarrow}} \frac{k_{F\uparrow} - k_{F\downarrow}}{k_{F\uparrow} + k_{F\downarrow}} \qquad q = \pm\sqrt{\frac{2m_b \Delta E}{\hbar^2}}$$

$m_b/m=0.4$ for Fe/Al_2O_3

Ab initio band structure calculations :

to get the band structure close to the interface

III-Bias and Temp Dependence



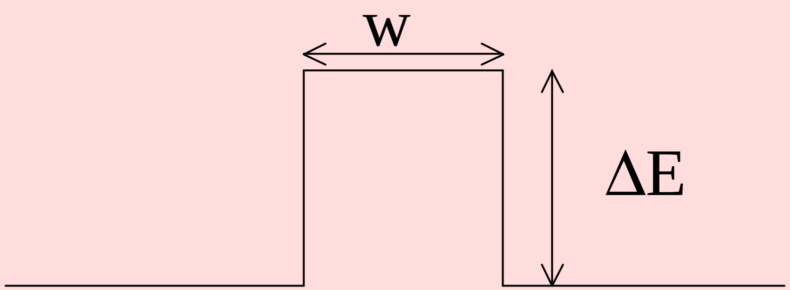
Miyazaki group (Tohoku) APL 2000

TMR temperature dependence

Resistance Temperature dependence

Temperature dependence of resistance

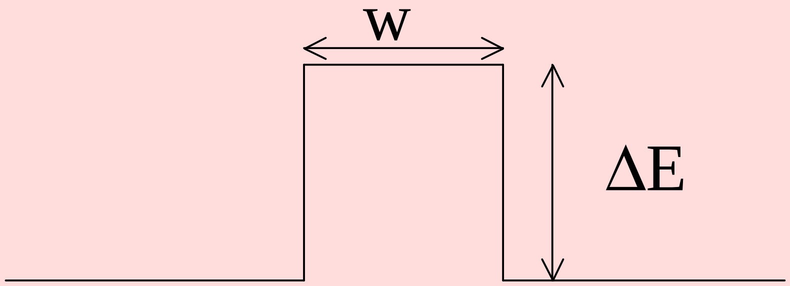
Temperature dependence of the barrier transmission
Going from 0 Kelvin to 300 Kelvin



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

$$Conductance \propto Transmission$$

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



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

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

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

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

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

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

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

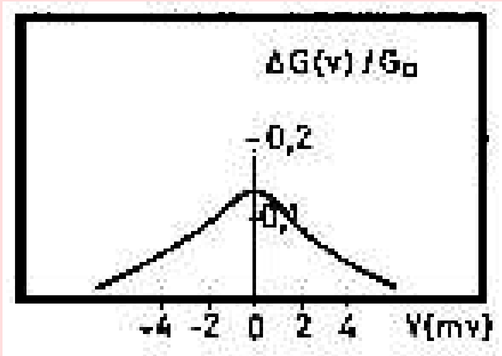
$$e^{\uparrow} \Rightarrow e^{\downarrow} + magnon$$
$$e^{\uparrow} + magnon \Rightarrow e^{\downarrow}$$

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 …)

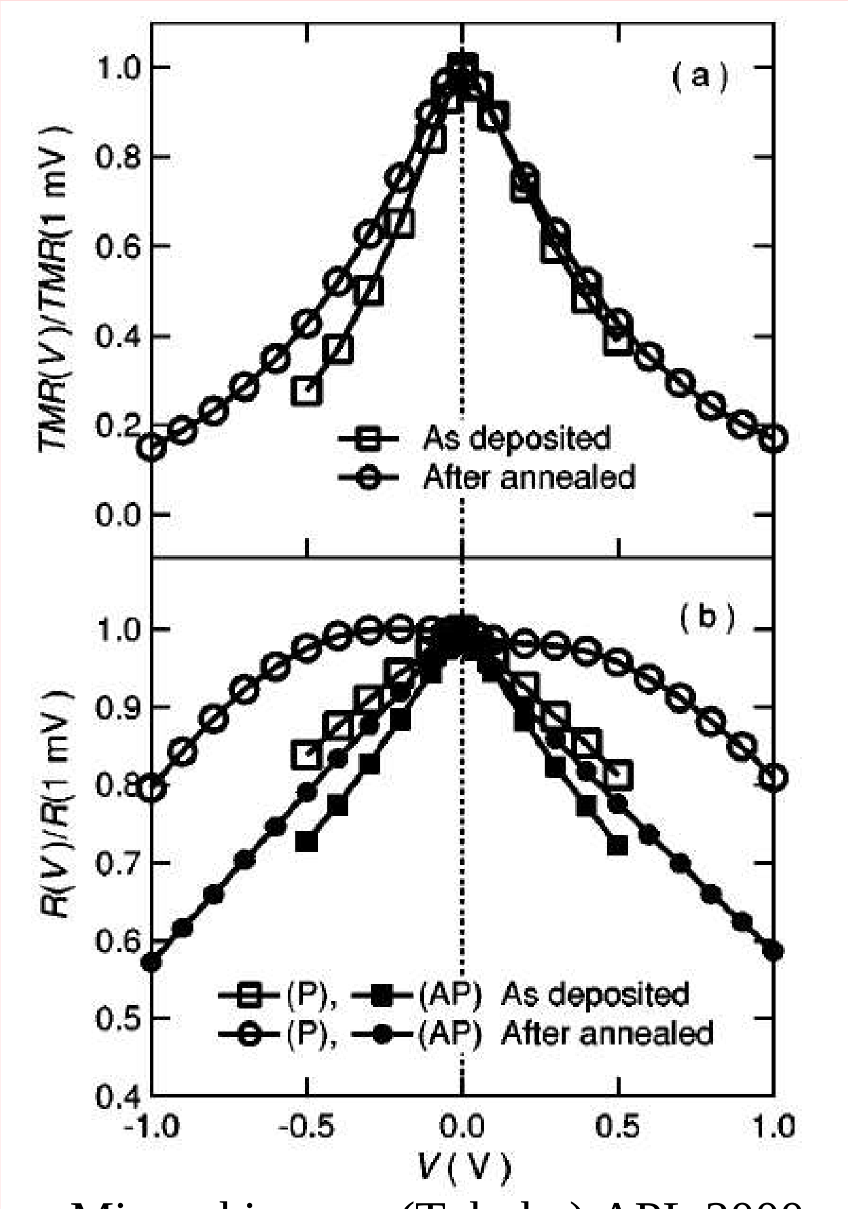
Voltage dependence of TMR



$TMR_{50\%}$=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

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

Inelastic processes can be activated

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

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

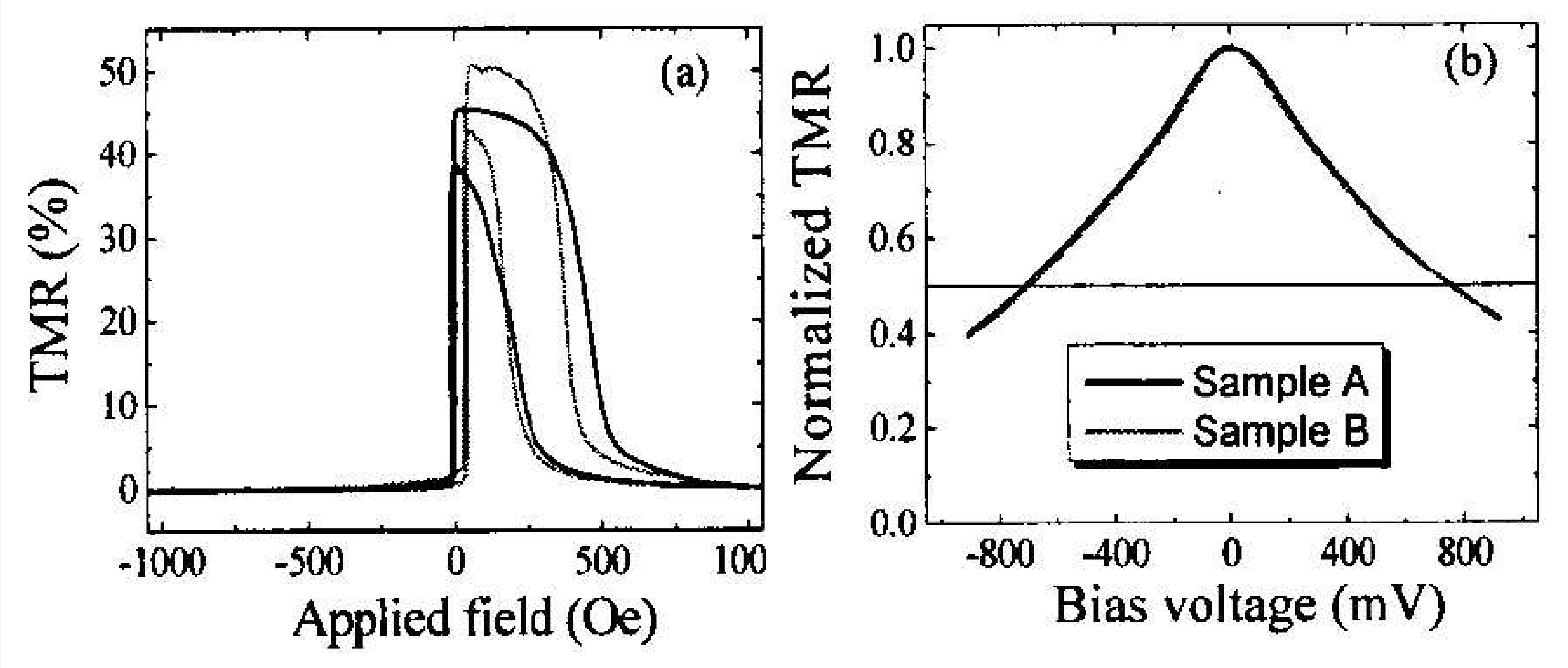
Opens a spin-flip conductance channel

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

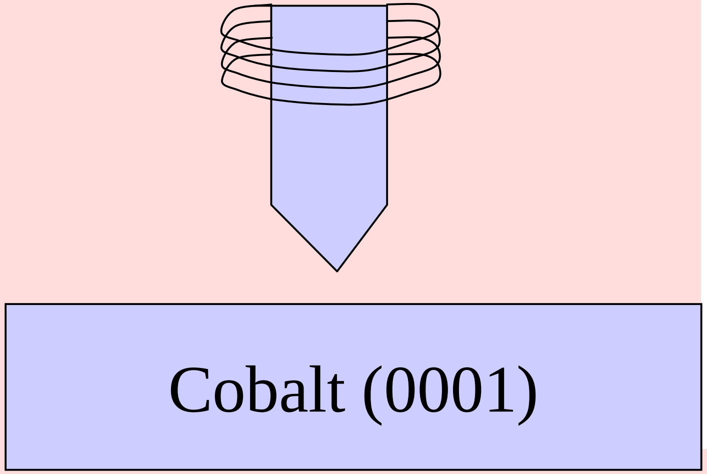


Epitaxial NiFe electrode : 50 % decrease of TMR at 750 mV

Yu et al. APL 2003

Tunnel junction with « perfect barrier » : STM with ferromagnetic electrodes in vacuum

Magnetic amorphous tip



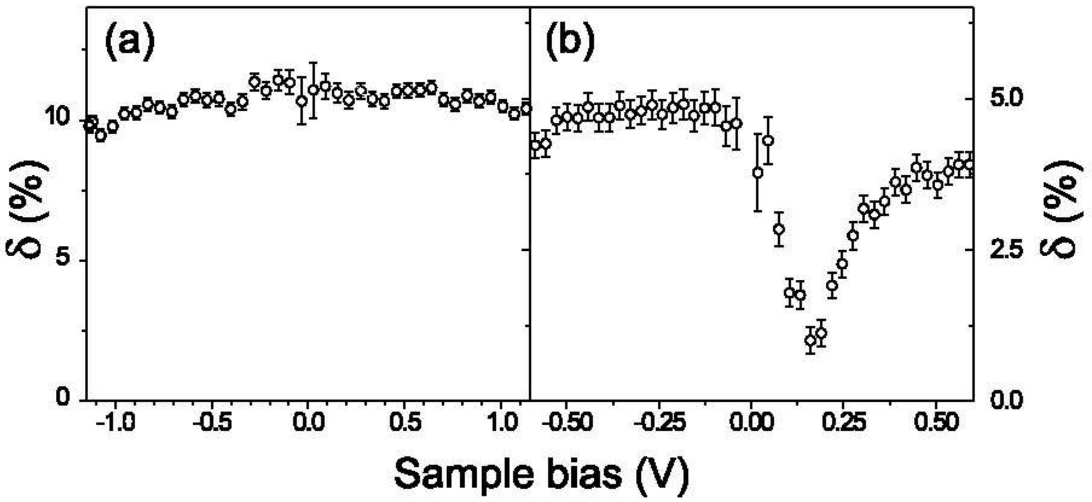


FIG. 1. Tunnel magnetoresistance δ and its error of a clean Co(0001) surface vs bias voltage U, obtained with a magnetic tip stabilized at 1 V, 1 nA (a) and at 100 mV, 1 nA (b).

Ding et al. (M.P.I. Halle) PRL 2003

Voltage dependence of TMR not related to magnon excitations or surface magnetisation but more likely to defects in the barrier

to be confirmed ...

A few words about

The insulating barrier

Making the barrier

Good recipe #1

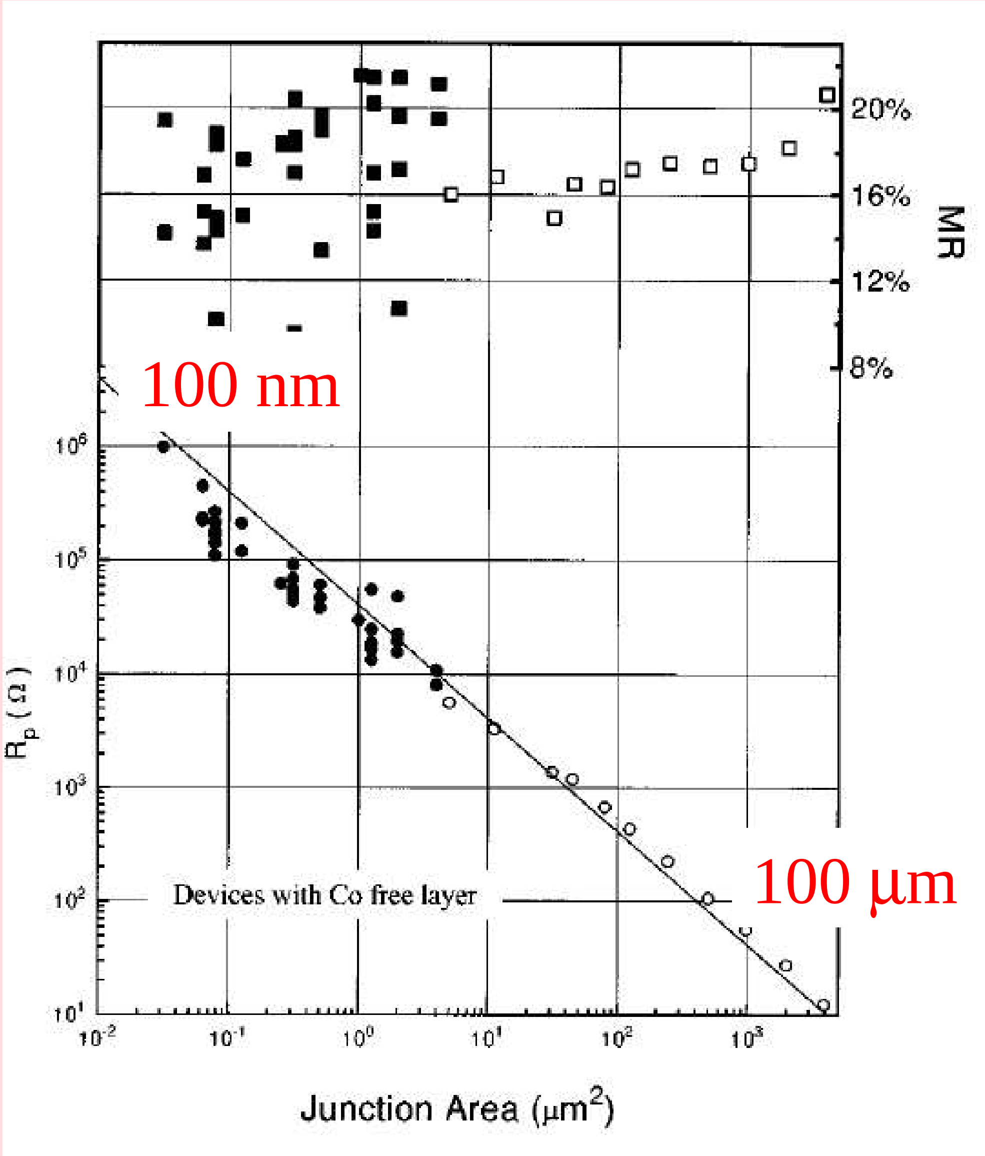
Aluminium Film (0.7-2 nm)
+ thermal oxidation in oxygen atmosphere or air

Good recipe #2

Aluminium Film + oxygen plasma

Bad recipe #1

Deposition of Alumina (Al_2O_3) produces a less dense barrier with poor electrical properties



Gallagher et al. JAP 1997

Constant thickness barrier

$$R \propto \frac{1}{S}$$

5 orders of magnitude

The barrier should be uniform

- flat
- 0 roughness
- fully oxidised, homogeneously
- no oxidation of the ferromagnetic metals

! Electrical Breakdown

1 Volt across a 1 nm barrier is E = 1 GigaV/m

This is the order of magnitude of the electrical field necessary to ionise an atom

A 0.1 nm fluctuation means 100 mV decrease of the breakdown voltage

Formation enthalpy ΔH (298K)
kJ/mol metallic atom

Ta2O5	-1023	HfO2	-1144
Nb2O5	-949	ZrO2	-1100
		CeO2	-1088
Y2O3	-952	TiO2	-944
Gd2O3	-909	SiO2	-910
Nd2O3	-903	NbO2	-796
La2O3	-896	CrO2	-598
Al2O3	-837	MnO2	-520
V2O3	-609		
Cr2O3	-570	MgO	-601
Ga2O3	-544	NbO	-405
Mn2O3	-479	MnO	-385
Fe2O3	-412	ZnO	-350
		FeO	-272
Mn3O4	-462	NiO	-238
Fe3O4	-372	CoO	-237
Co3O4	-297	CuO	-157
		SiO	-99
		Ga2O	-178
		Cu2O	-84

Al-O bond is stronger than
3d metal -O bonds

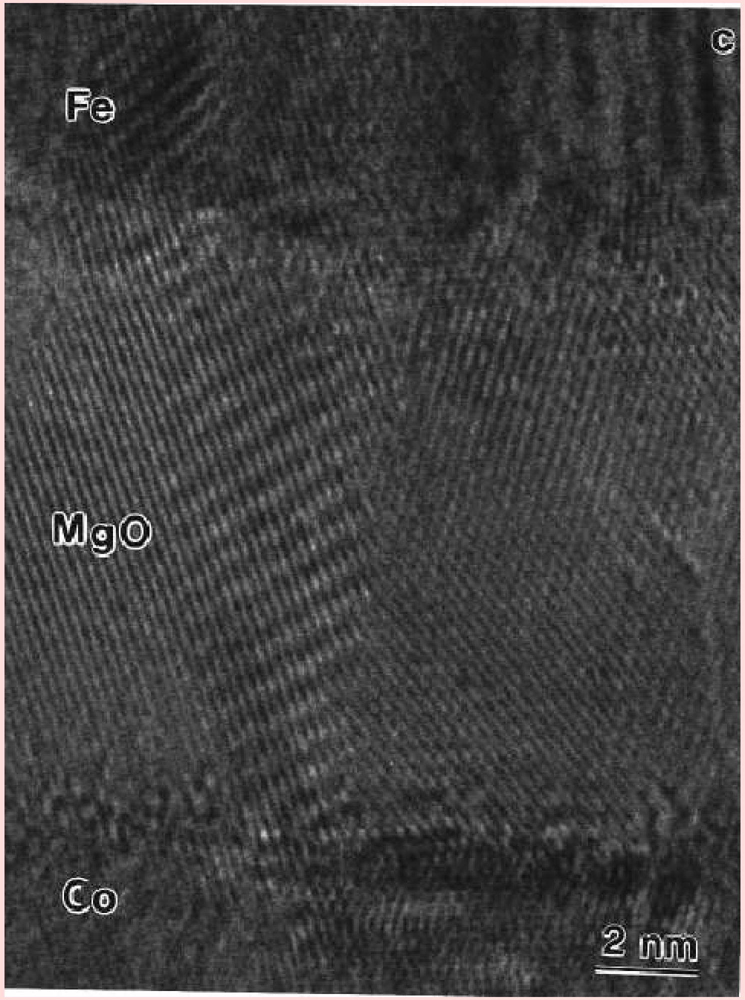
Better oxides exist : $HfO_{2,}$, Rare earth-O

But
kinetics : (Al passivated « automatically » 1 nm thick),

local state : (amorphous, nanocrystallised, crystallised) when RT deposition

Crystallised barrier

Amorphous barrier



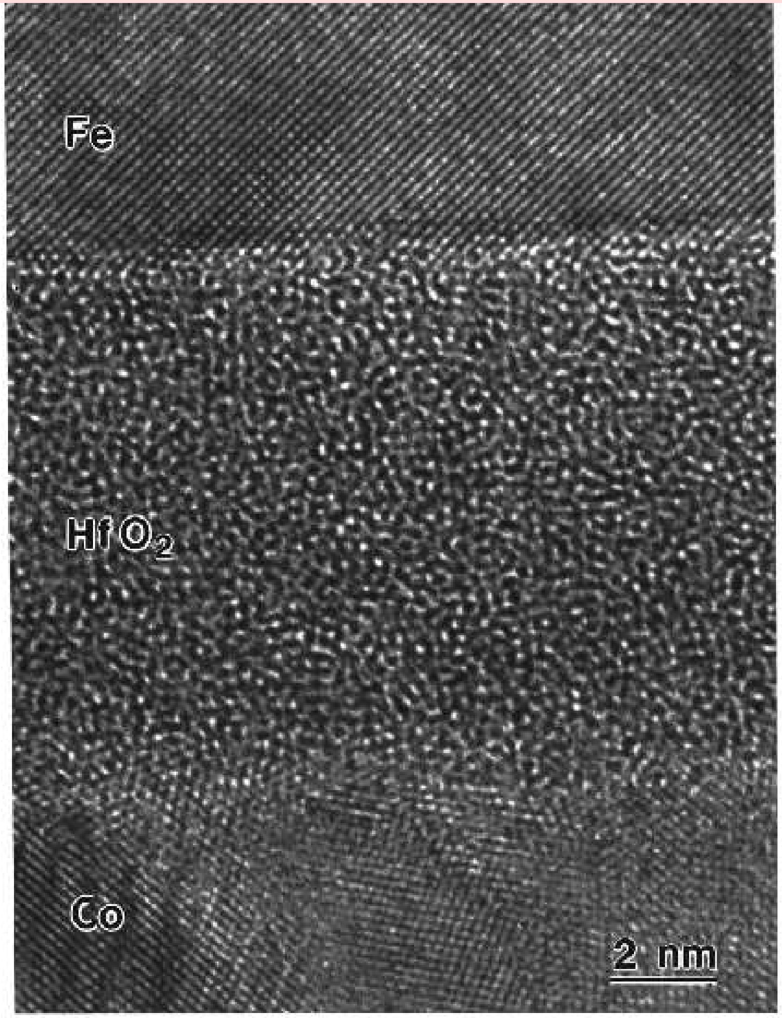


FIG. 3. High-resolution, cross-sectional electron micrograph of a [50 nm Co/10 nm HfO_2/50 nm Fe] junction showing abrupt, smooth interfaces and amorphous oxide structure.

Smith et al. JAP,83 ,5154 (1998)

Role of annealing a tunnel junction

NiFe(100 Å)/CoFe(20 Å)/Al_2O_3/CoFe(40 Å)/MnRh(170 Å)

Appl. Phys. Lett., Vol. 73, No. 22, 30 November 1998

Sousa et al. (Lisbon)

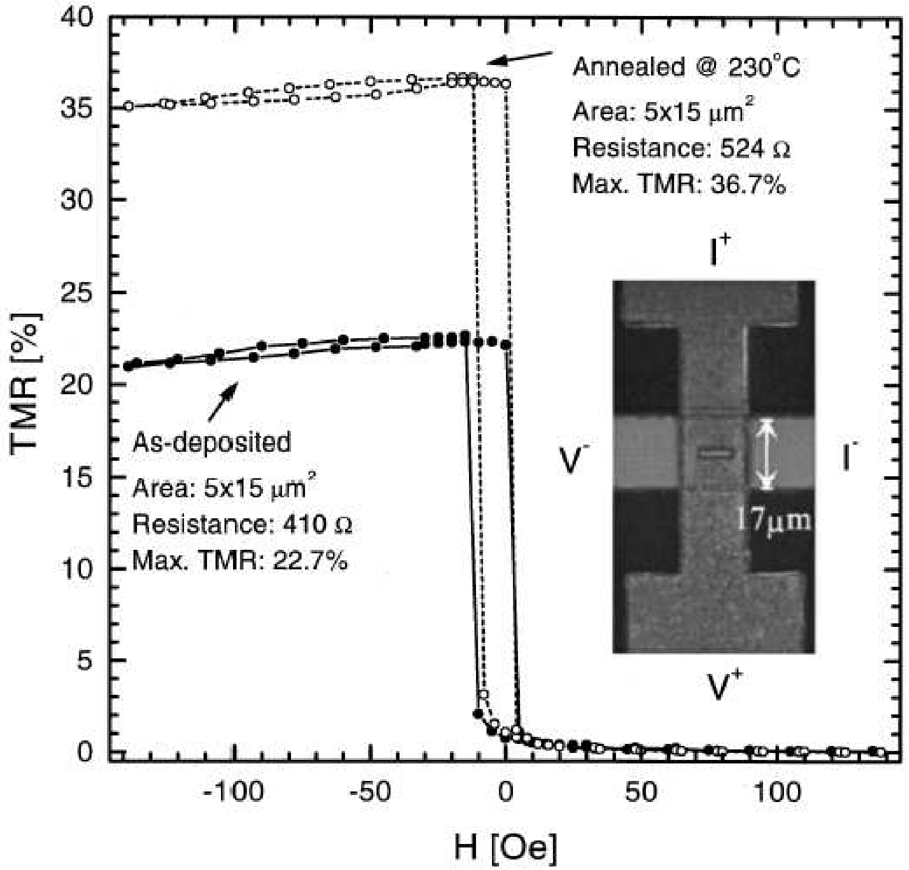


FIG. 1. Tunneling magnetoresistance vs field for an as-deposited spin tunnel junction, and for the same junction after consecutive anneals up to 230 °C. In the inset, the four-probe measuring scheme is illustrated using an optical microscope picture of the junction.

Barrier (Simmons' fit)

after anneal :
thickness :0.87 to 0.77 nm wide
barrier height :1.8 eV to 2.5 eV

RBS measurement of Al and O distributions

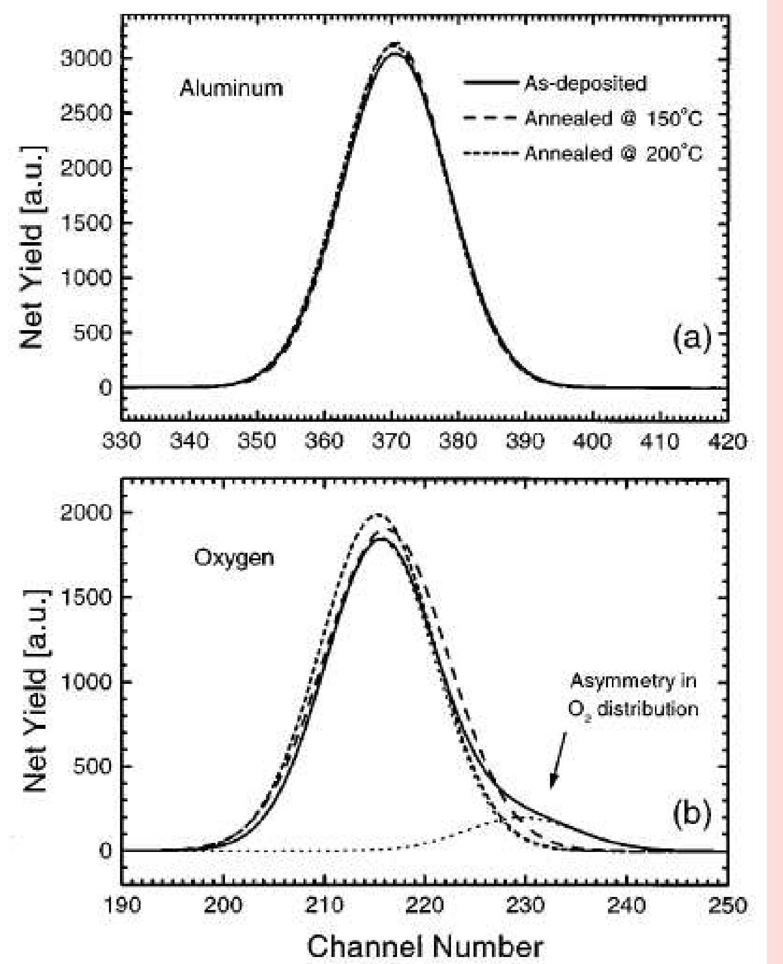
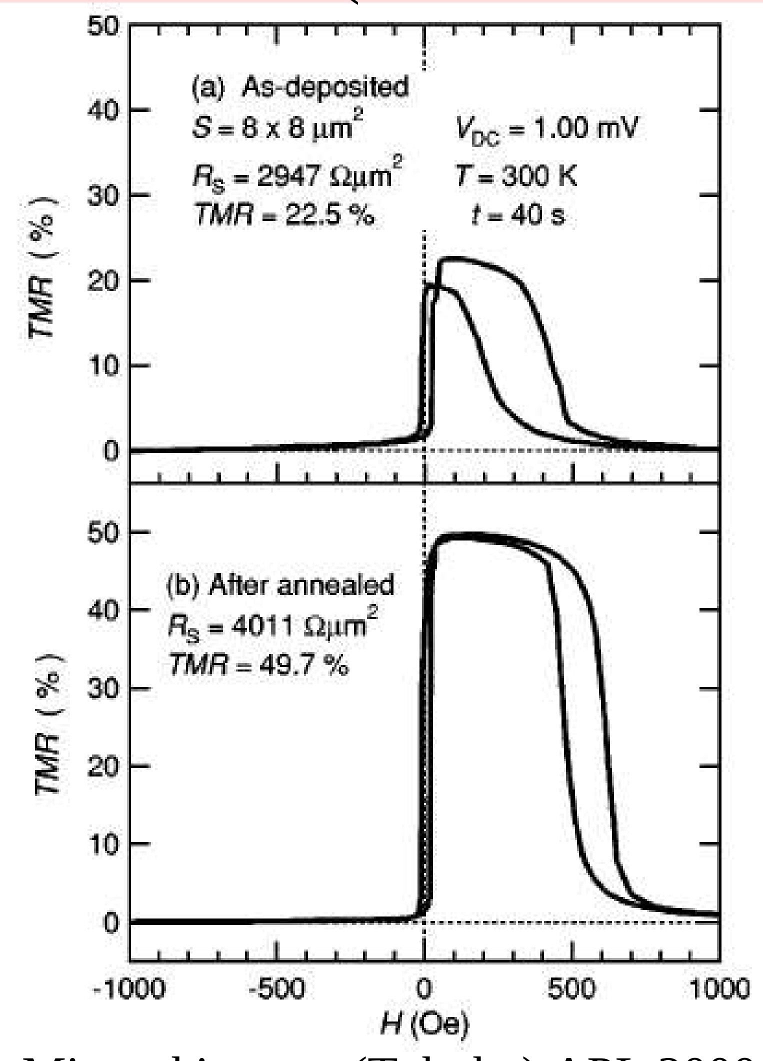


FIG. 5. Gaussian curve fits to the aluminum (a) and oxygen (b) peaks obtained by Rutherford backscattering analysis, for as-deposited junctions, and for junctions annealed at 150 and 200 °C.

O from the CoFe electrodes goes back to Al_2O_3

Sousa et al. APL 98

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

IV-Spin polarisation

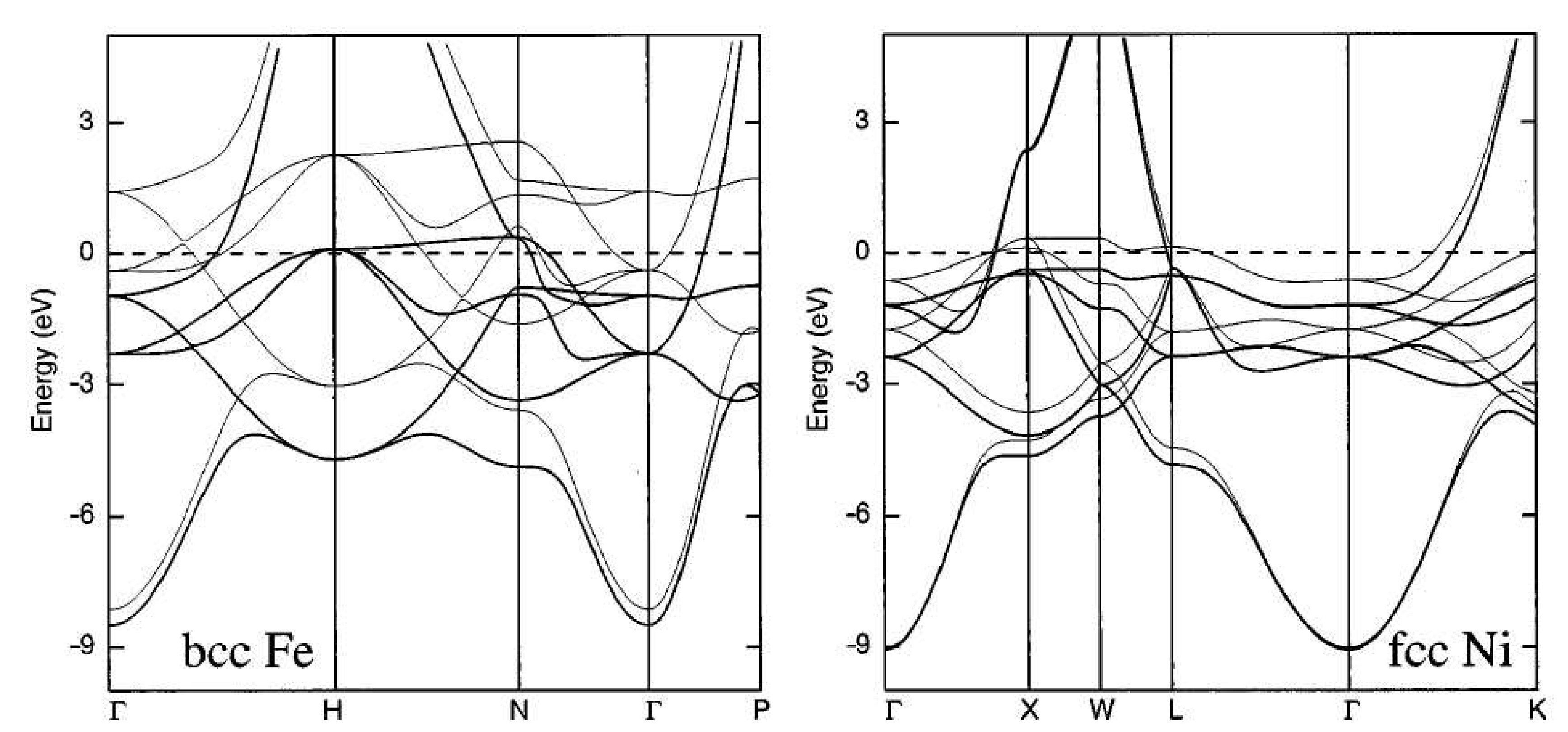
We have been using values for P.

Where do they come from ?

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

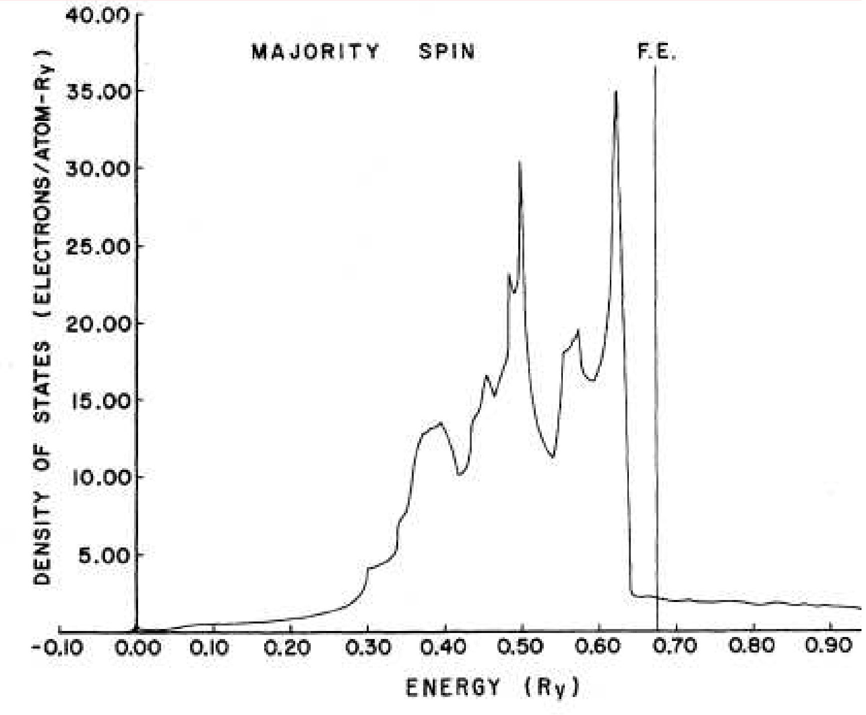
How to measure them ?

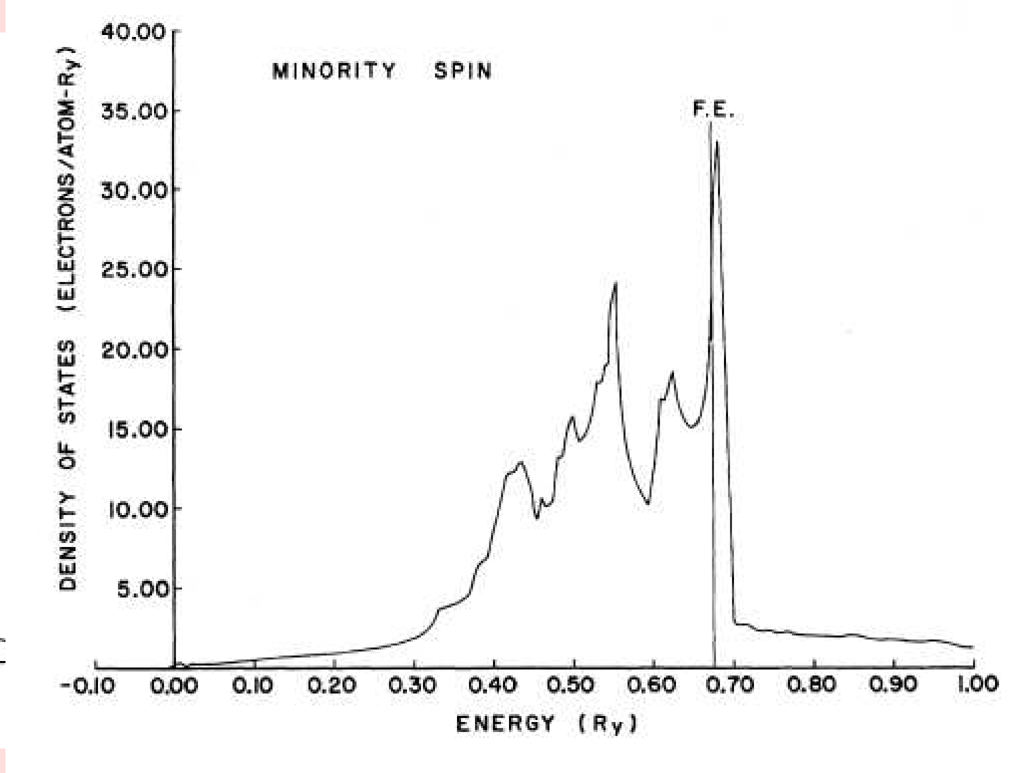
Density of States Band structure calculations (spin resolved)



[000] [100] [110] [000] [111] [000] [100][210] [111] [000] [110]

Moroni et al. PRB56 (1997)15629





Nickel integrated density of states

Polarisation at Fermi level should be NEGATIVE

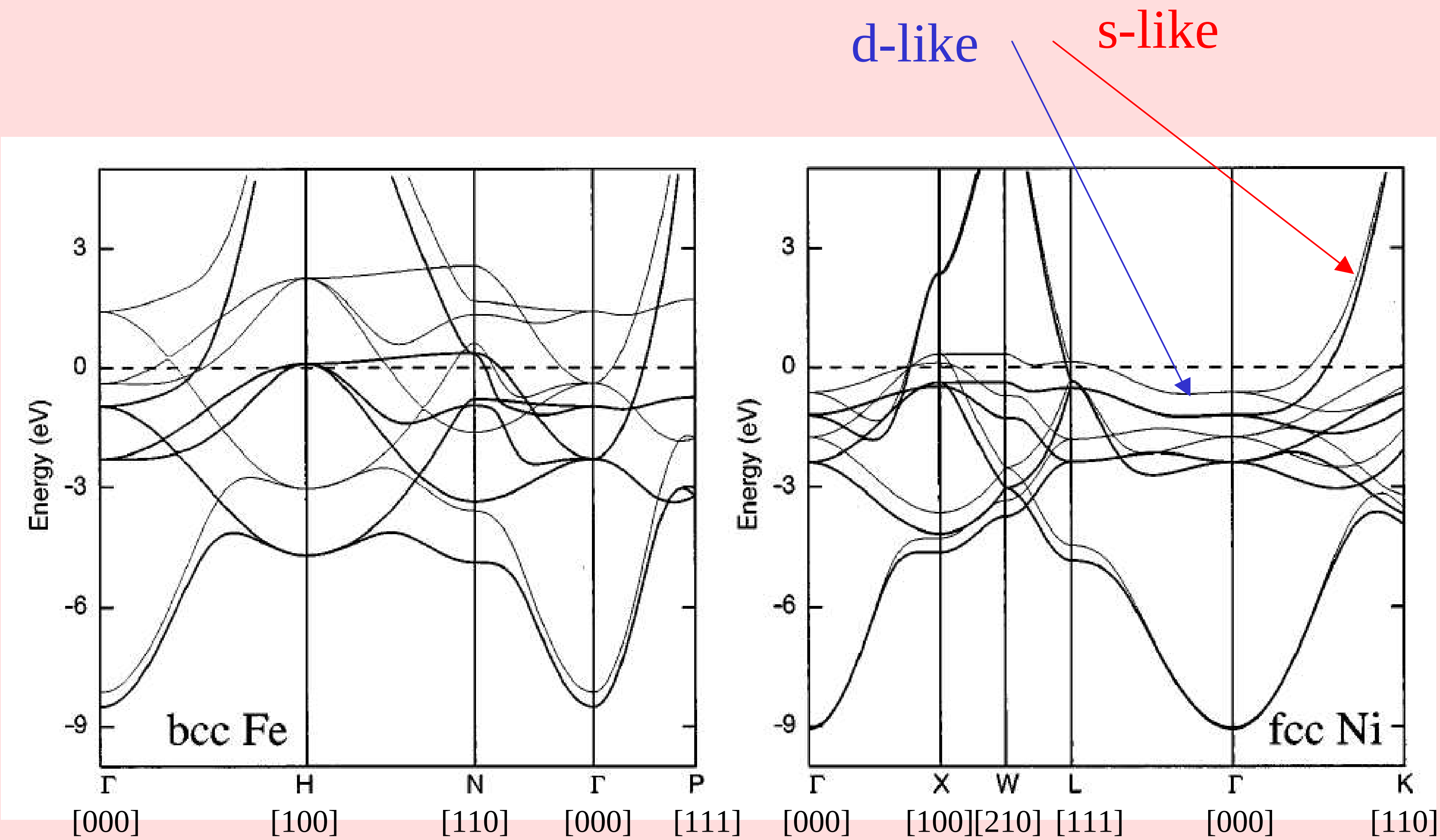
Be careful (M. B. Stearns JMMM,5 ,167 (1977))

$$m^* = \frac{\hbar^2}{\frac{\partial^2 E}{\partial k^2}}$$

Bands do not have the same effective mass at E_F

Electrons at Fermi level have different mobilities

d-like electrons are more localised (narrow bands)
s-like electrons are less localised (wide bands)
and more mobile


d-like
s-like
3
0
-3
-6
-9
Energy (eV)
bcc Fe
Γ
H
N
Γ
P
[000]
[100]
[110]
[000]
[111]
3
0
-3
-6
-9
Energy (eV)
fcc Ni
Γ
X
W
L
Γ
K
[000]
[100][210]
[111]
[000]
[110]

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s-like electrons are less localised (wide bands)
and more mobile

Ferromagnetism comes from the 3d bands but transport comes from s-electrons. s electrons are not supposed to be polarised !

Difficult to predict the polarisation of conduction electrons

When it is difficult to predict, let us measure !

Ferromagnetic / insulating / superconducting junctions
M. I. T. speciality (Tedrow/Meservey)

$$J \propto \int_0^\infty |M|^2 N_1(E) N_2(E) [f(E) - f(E+eV)] dE$$

$$|M|^2 \propto e^{-2qw}$$

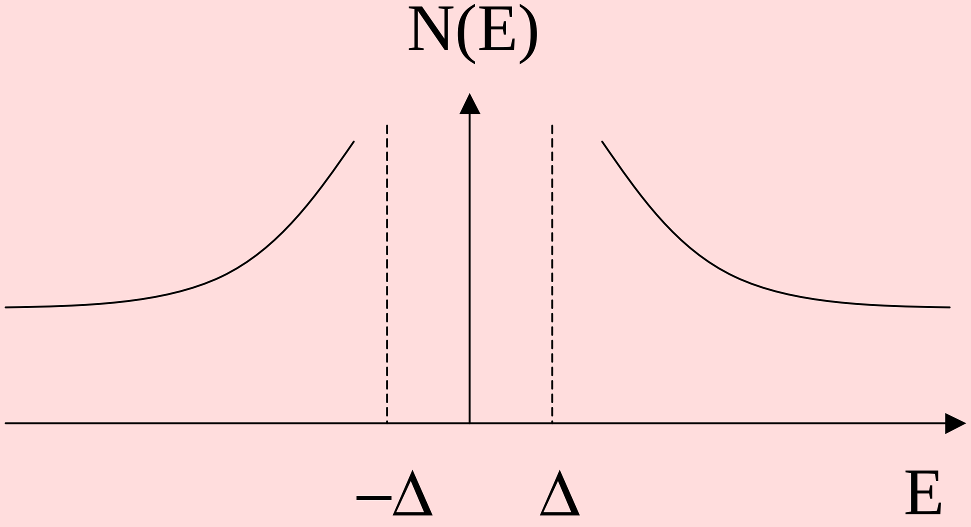
N(E) non magnetic metal

$N\ (E) \propto$ constant

N(E) in a superconductor

$$N(E) = 0 \text{ if } |\mathrm{E}| < \Delta$$

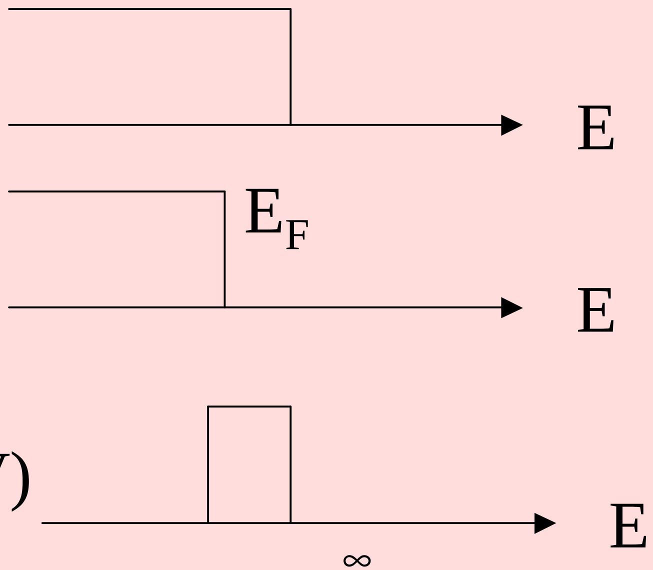
$$N(E) = \frac{|\mathrm{E}|}{\sqrt{E^2 - \Delta^2}} \text{ if } |\mathrm{E}| > \Delta$$



f(E)

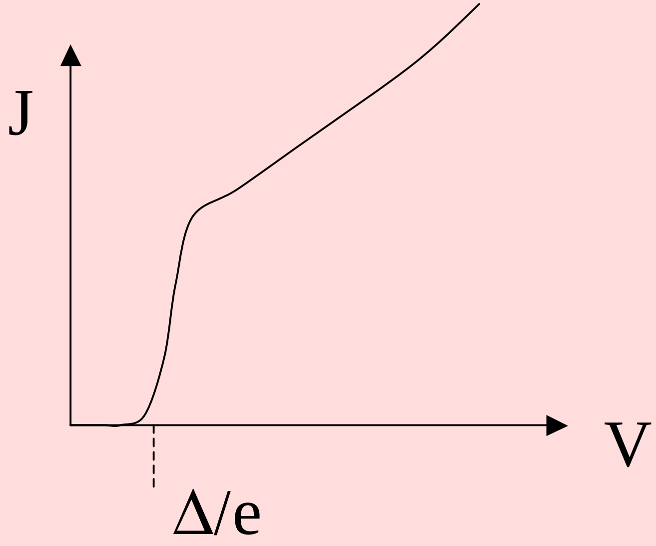
f(E+eV)

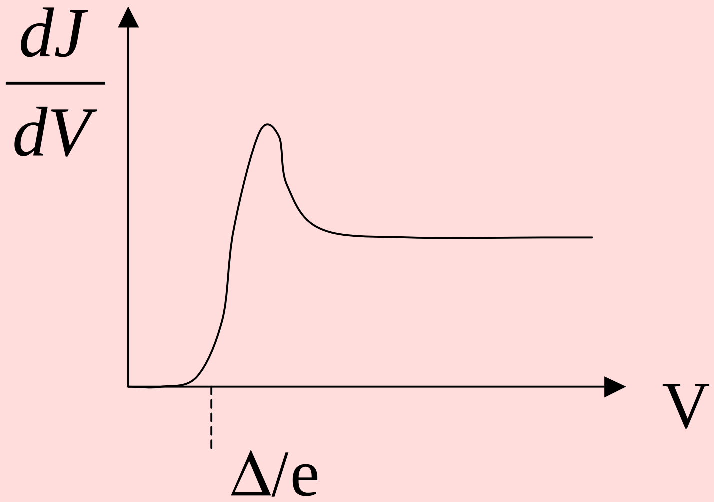
f(E)-f(E+eV)



$$J \propto \int_0^\infty N_1(E) N_2(E) [f(E) - f(E + eV)] dE$$

$$J \propto \int_0^{\infty} N_{\text{metal}}(E) N_{\text{super}}(E)[f(E) - f(E+eV)]dE$$





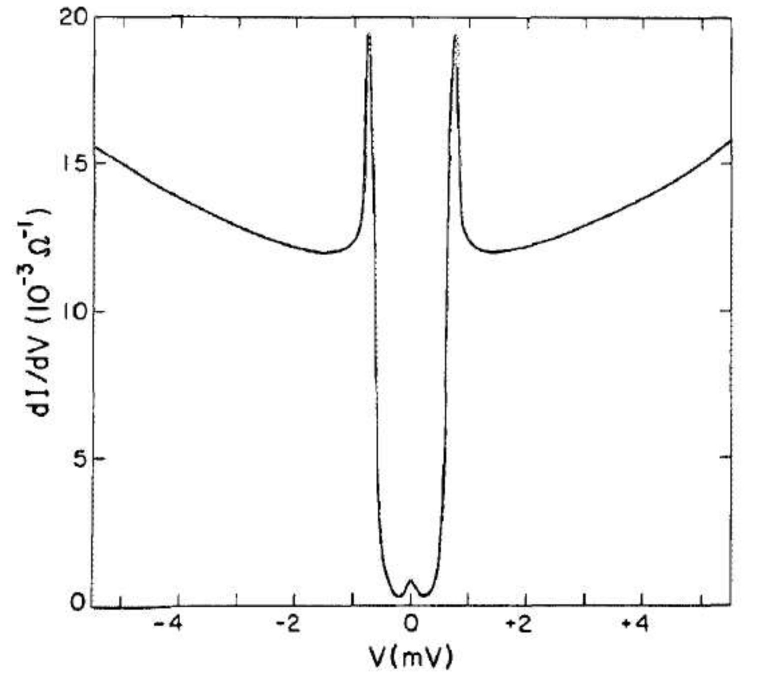
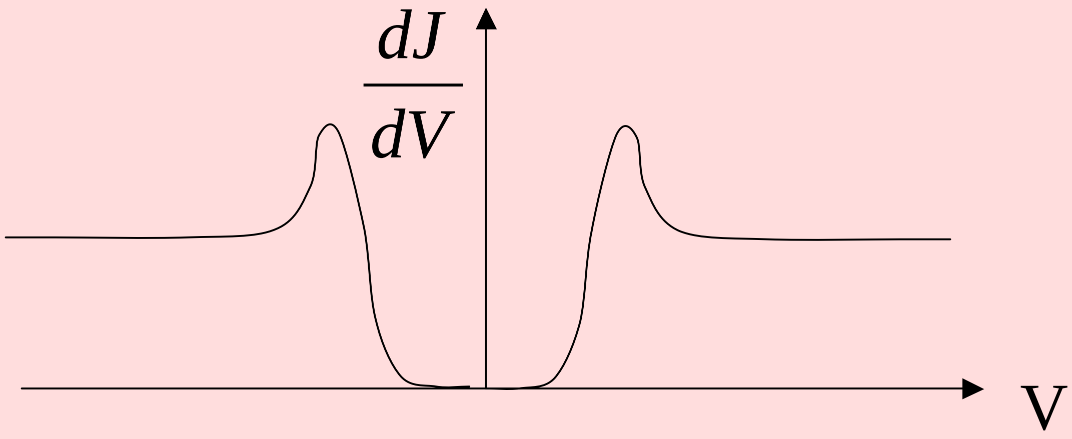


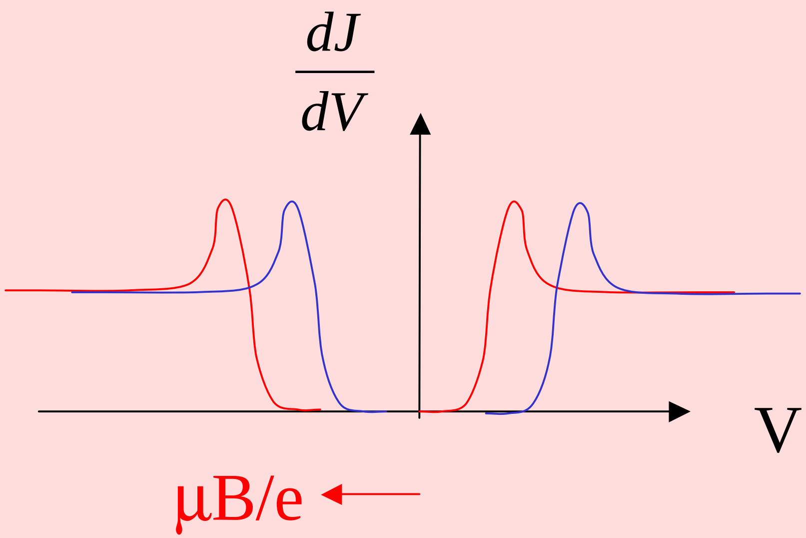
FIG. 6. dI/dV vs V for an Al/a-Ge/Al junction at 1.2 K, when the thin aluminum is superconducting. The superconducting energy gap is clearly visible. The large near-parabolic background is the result of the small effective barrier height. The small peak at zero voltage is characteristic of tunneling between identical superconductors at finite temperature.

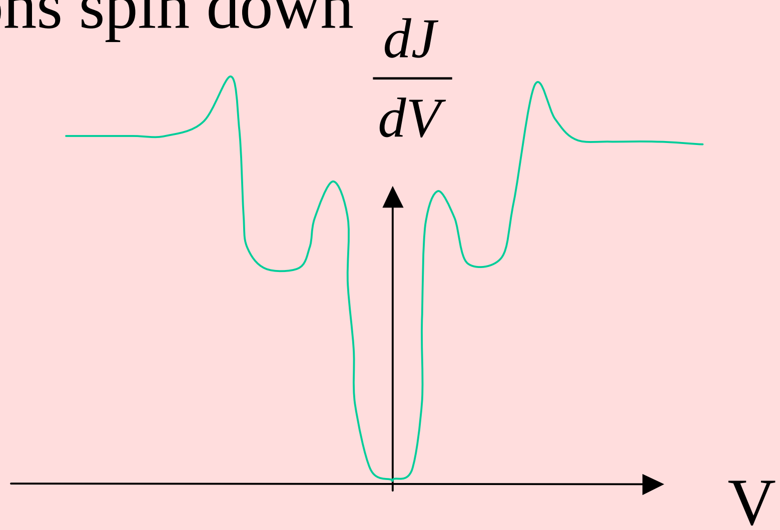


If a magnetic field is applied

$$E(B) = E(B=0) \pm \mu_B B$$

If 50% electrons spin up, 50% electrons spin down





If not 50%-50% ….

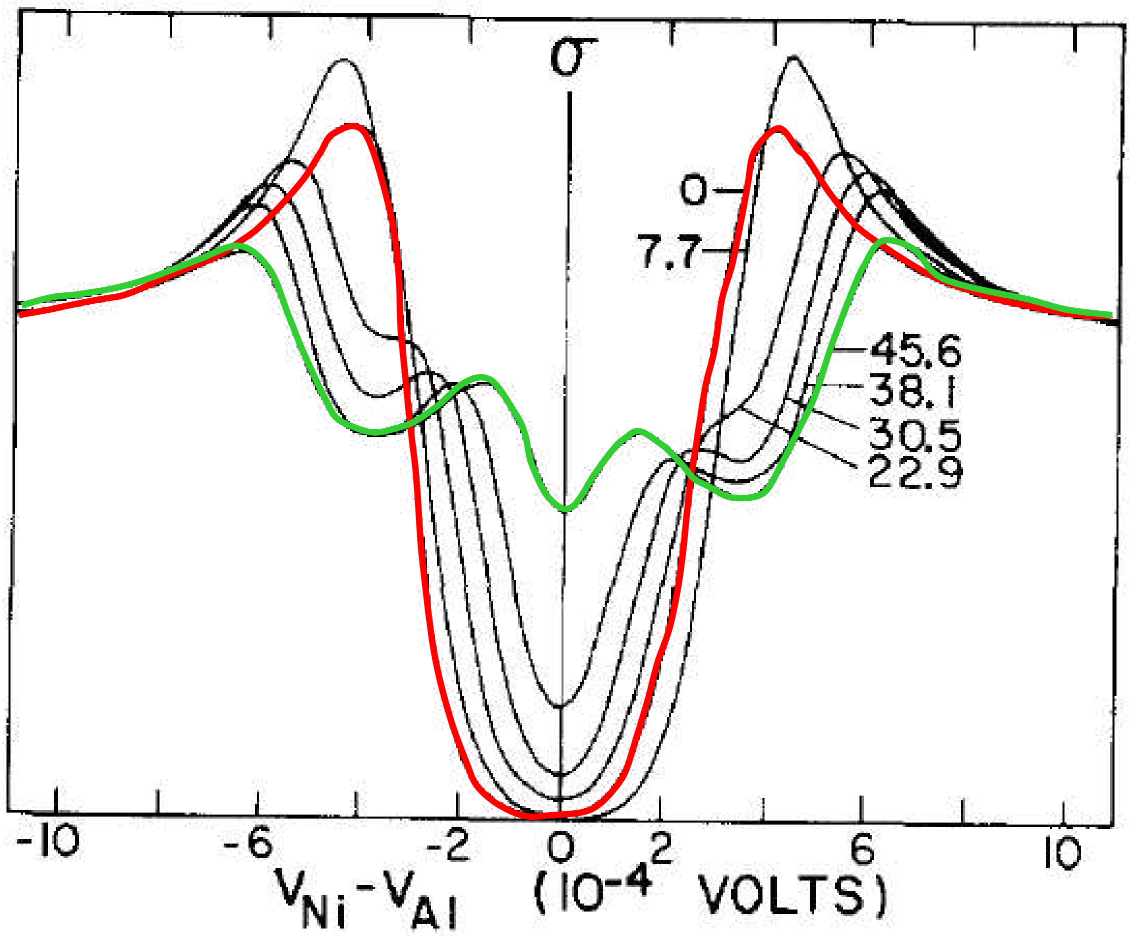
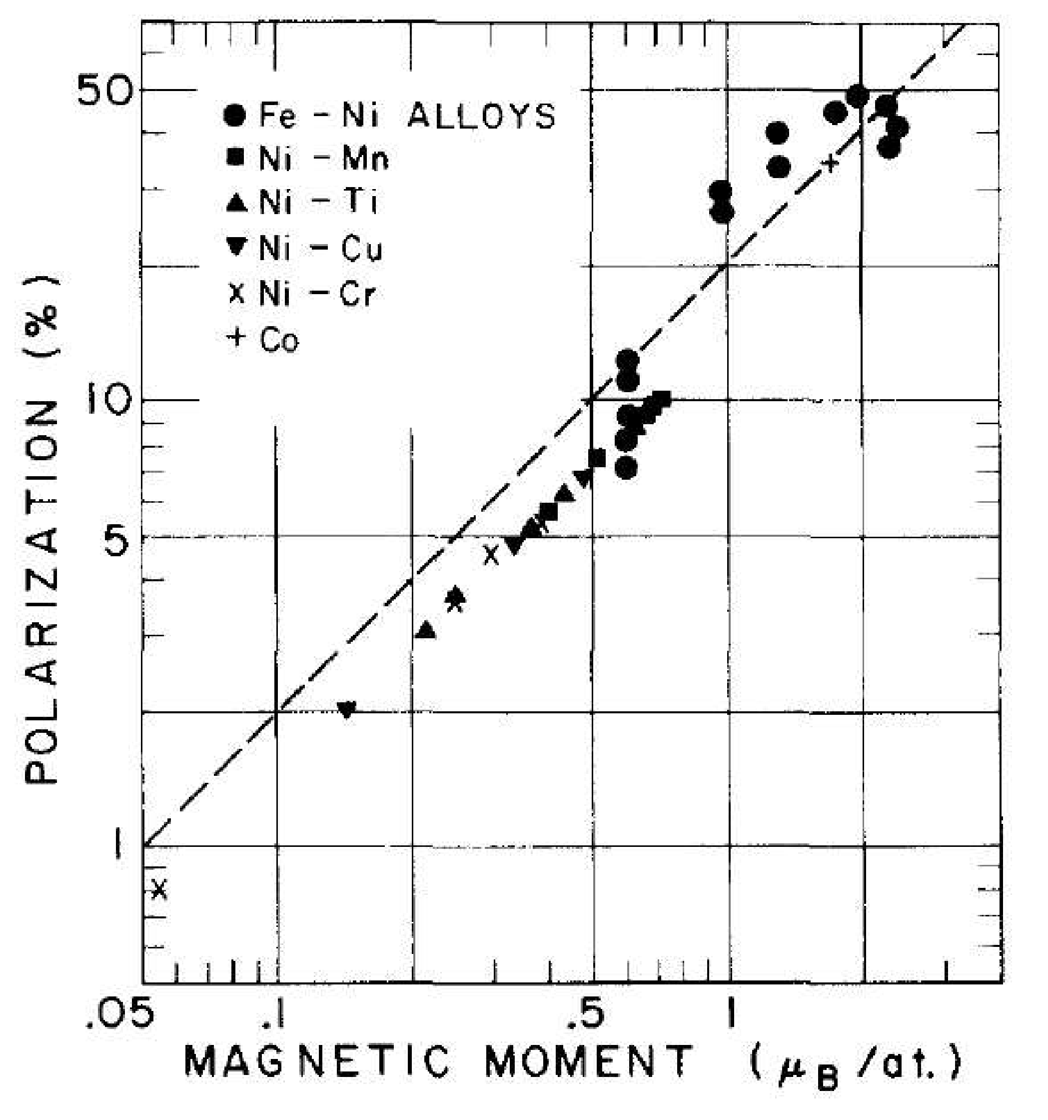


Fig. 1 Measured conductance vs voltage of an $Al-Al_2O_3-Ni$ tunnel junction for several values of the magnetic field H (kOe).

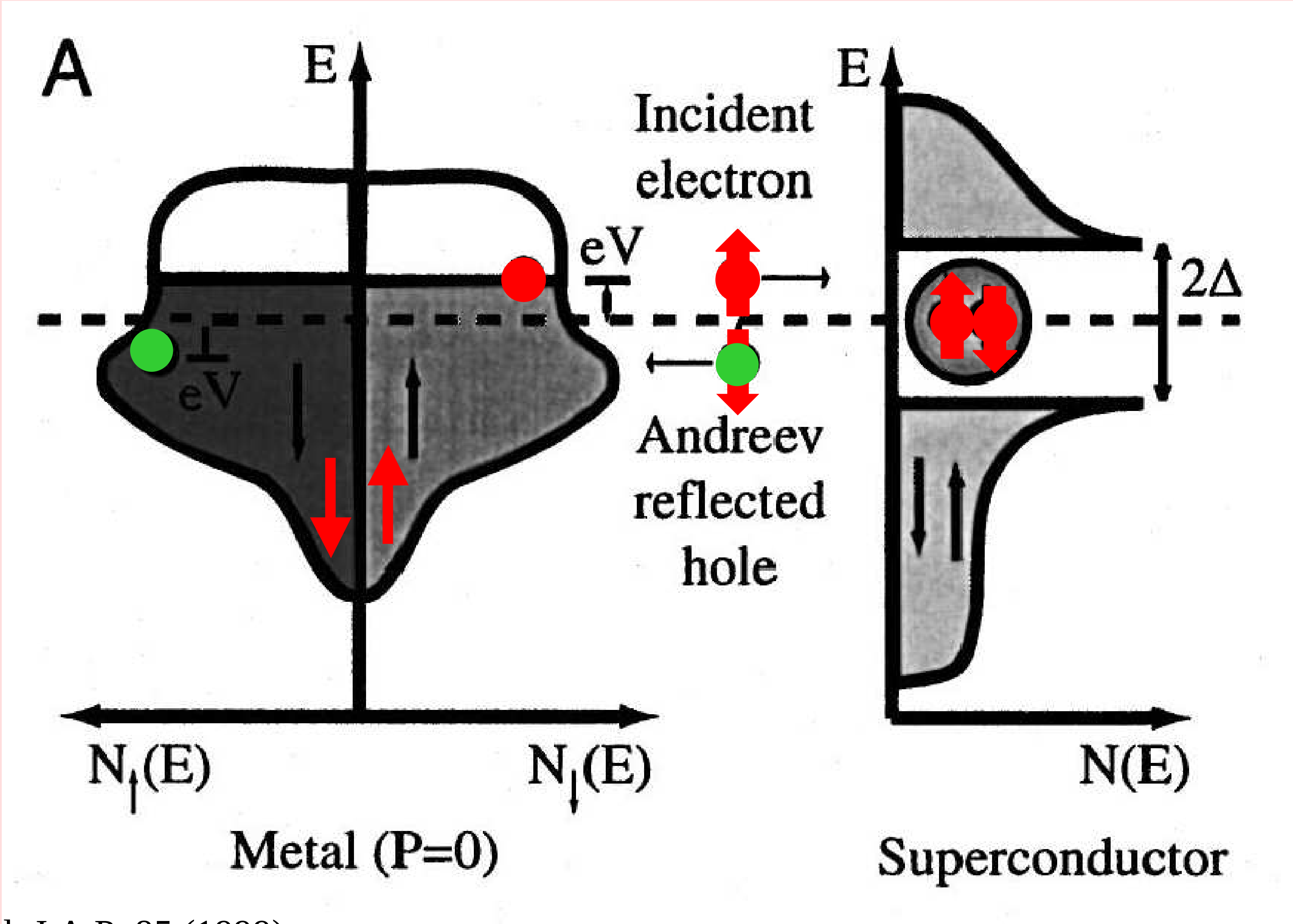
M.I.T group JAP 1979



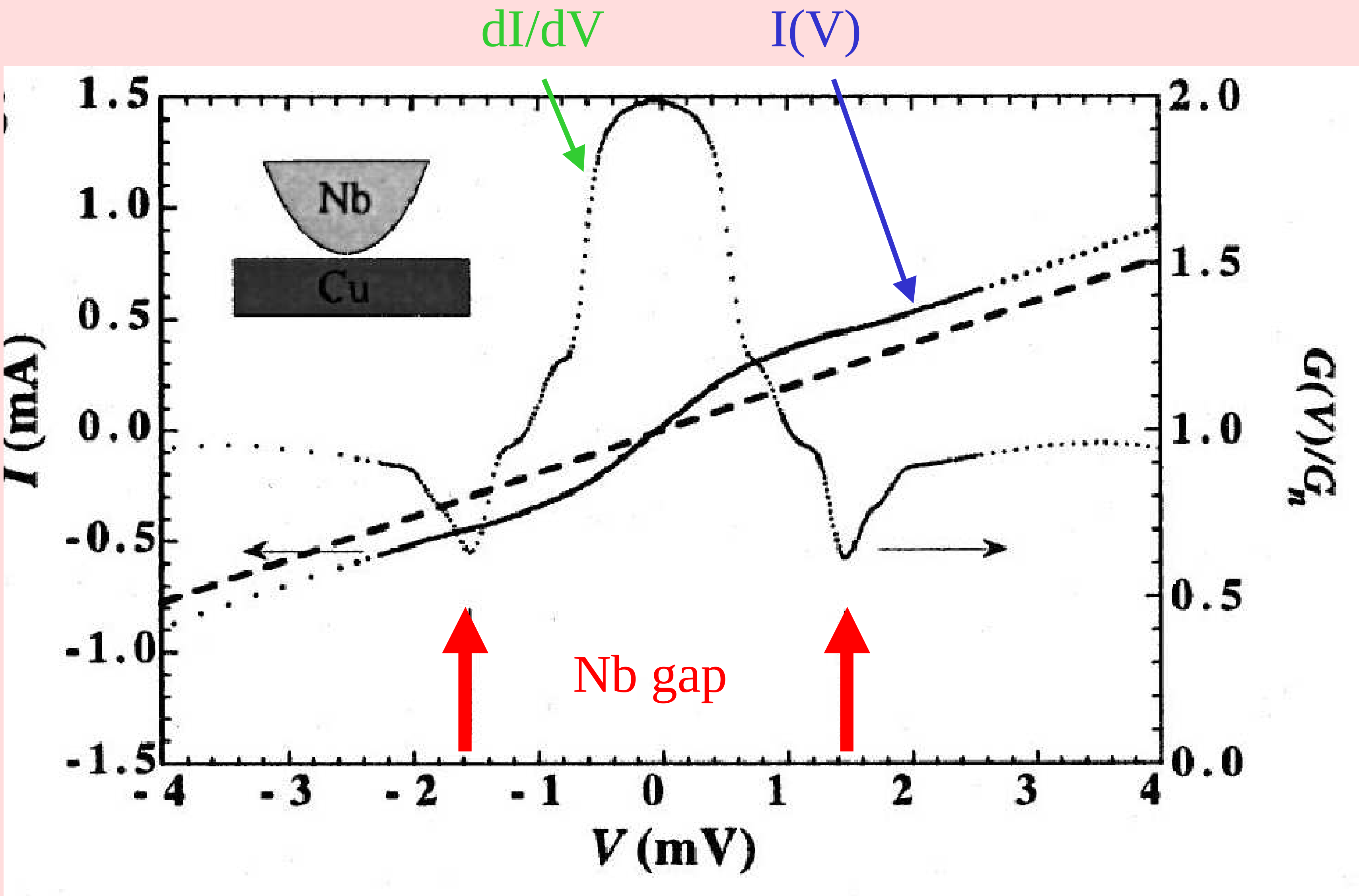
Fe	+44%
Co	+34%
Ni	+11%
Gd	+4%

Meservey et al; J.A.P. 50 (1979)

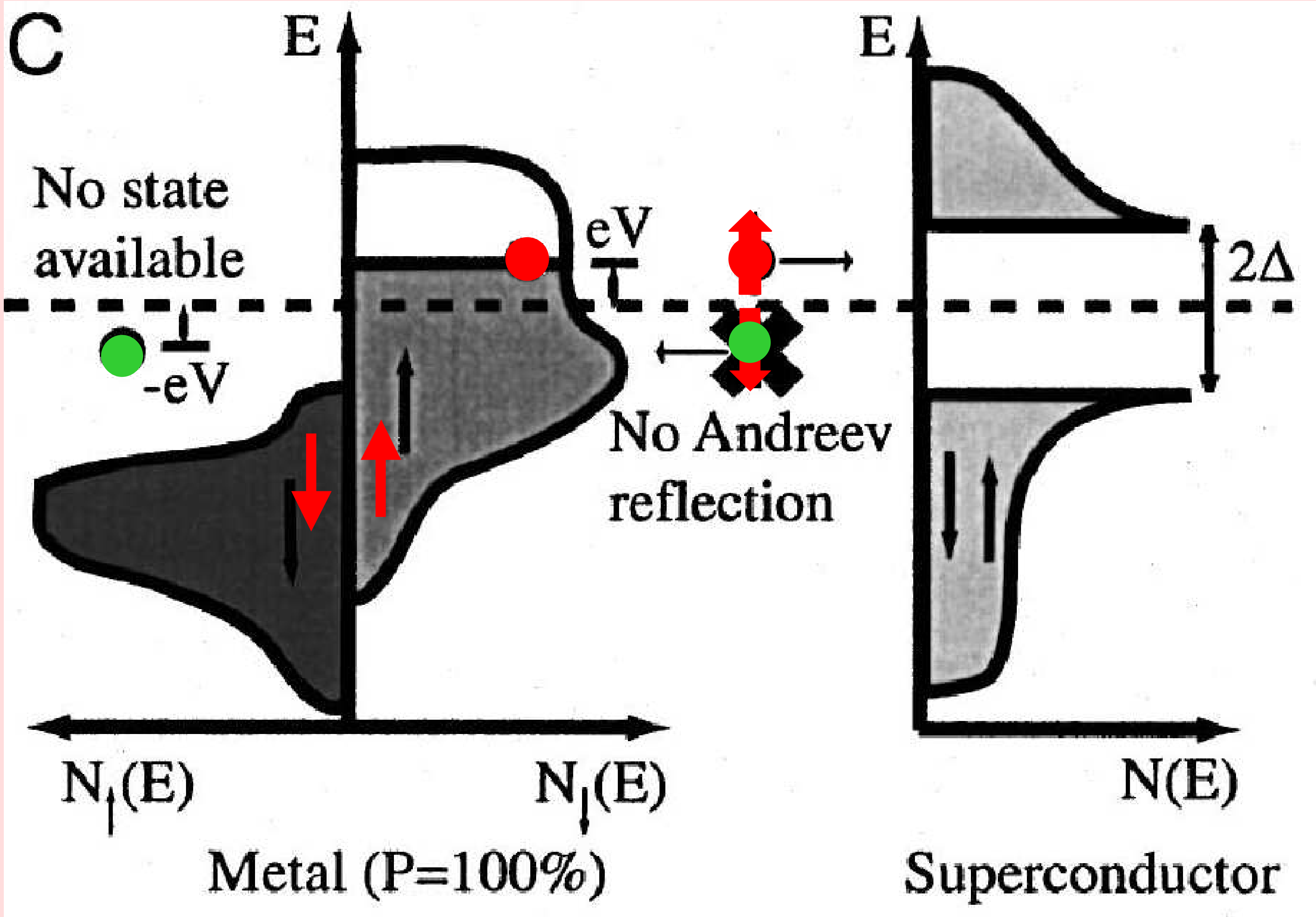
Andreev reflexion : metal / superconductor clean interface

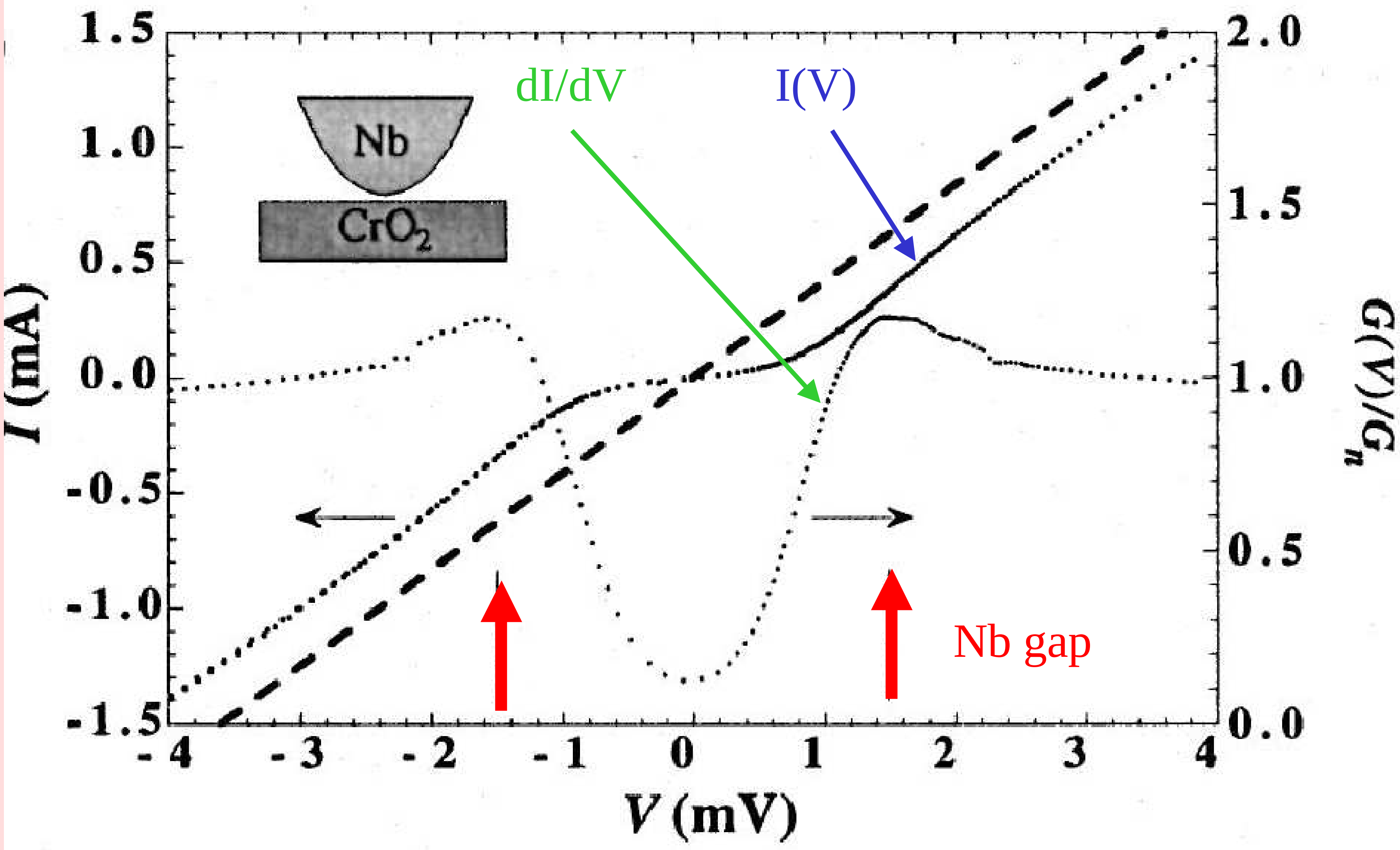


Soulen et al. J.A.P. 85 (1999)

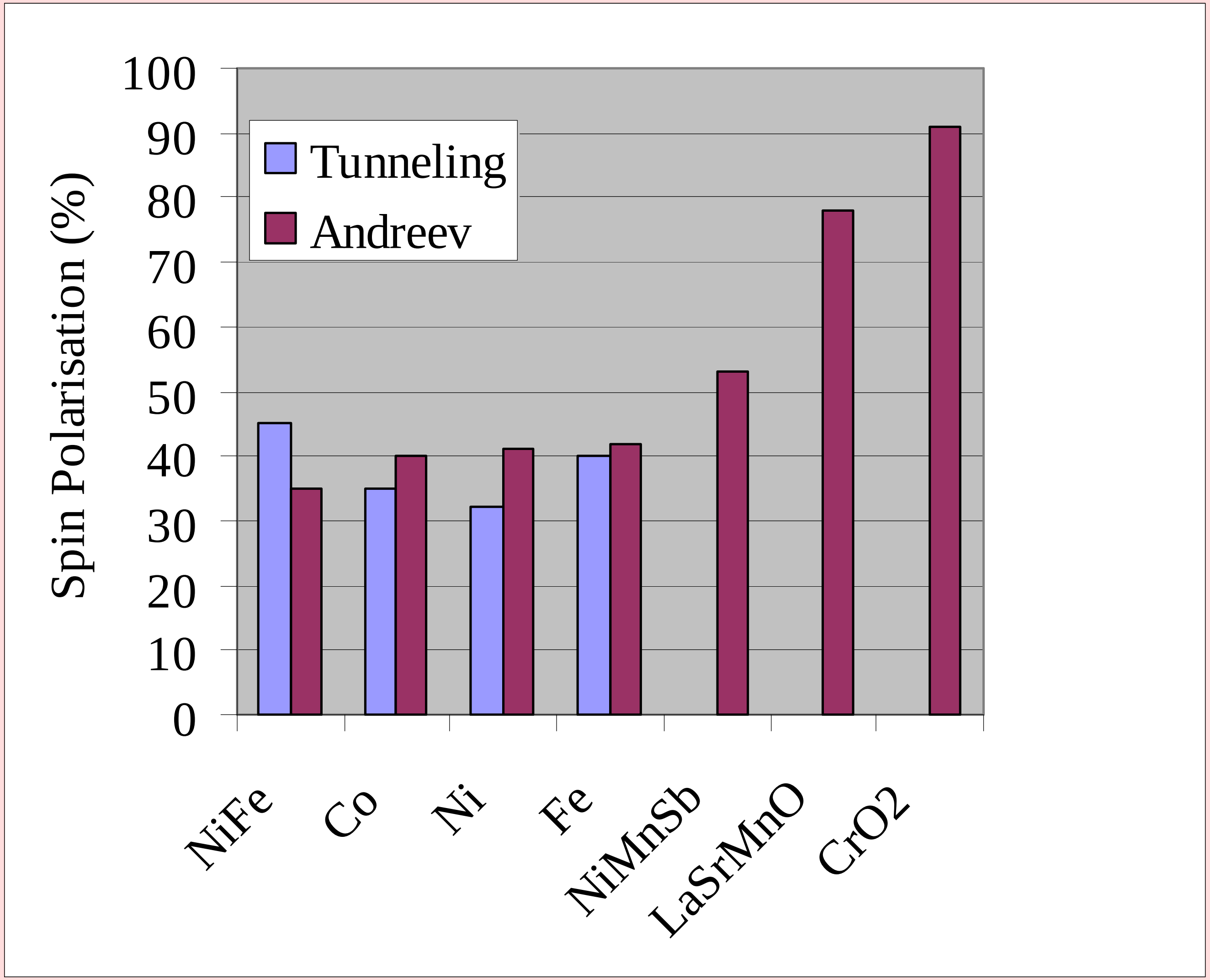


Normal metal : 1 electron arrives, 2 electrons enter


C
E
No state
available
eV
-eV
No Andreev
reflection
E
2Δ
N↑(E)
N↓(E)
N(E)
Metal (P=100%)
Superconductor



No conductance at small bias

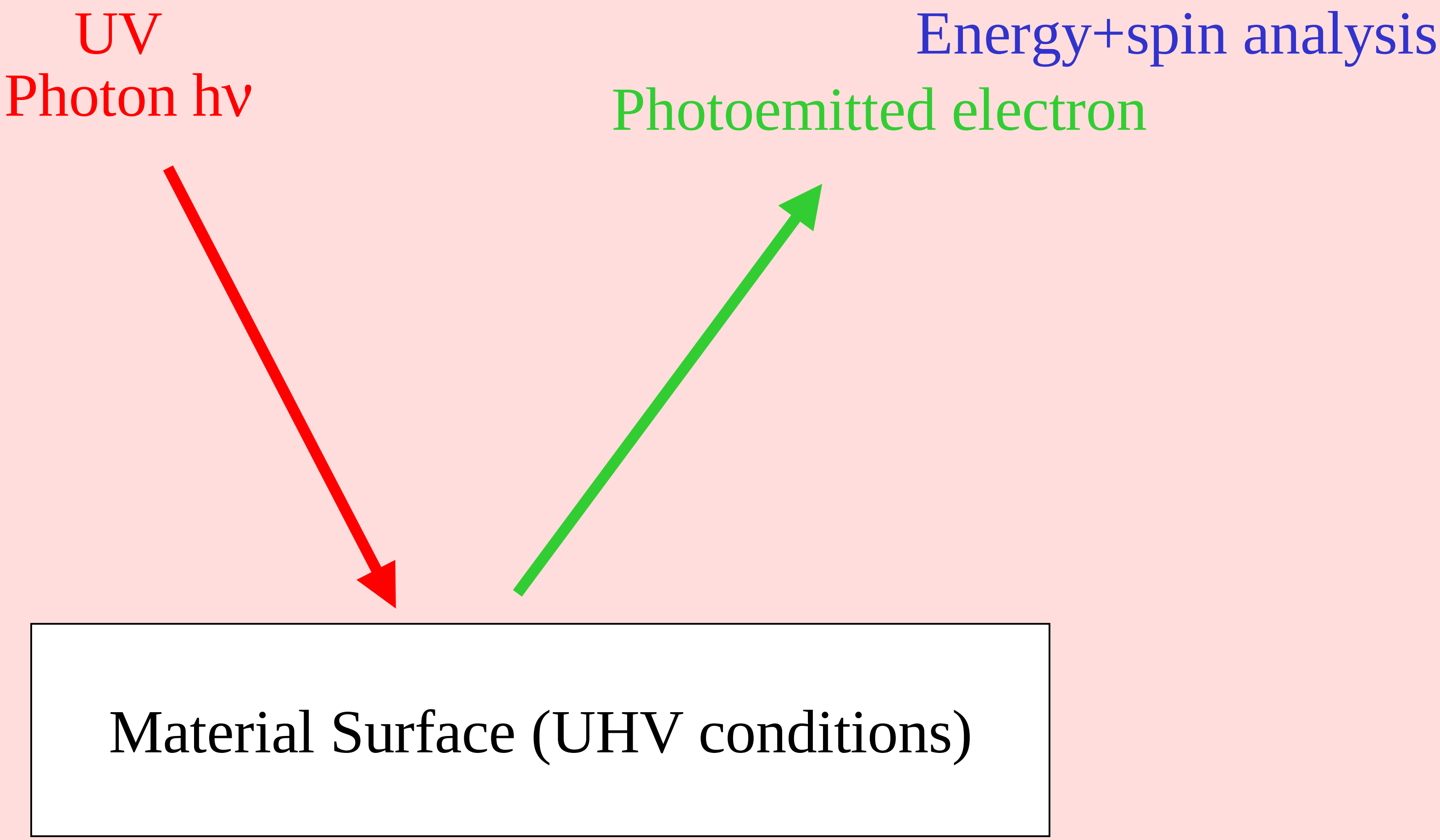


Soulen et al. 1999

But it only works at 1 Kelvin !

Andreev Reflexion does not give the sign of P

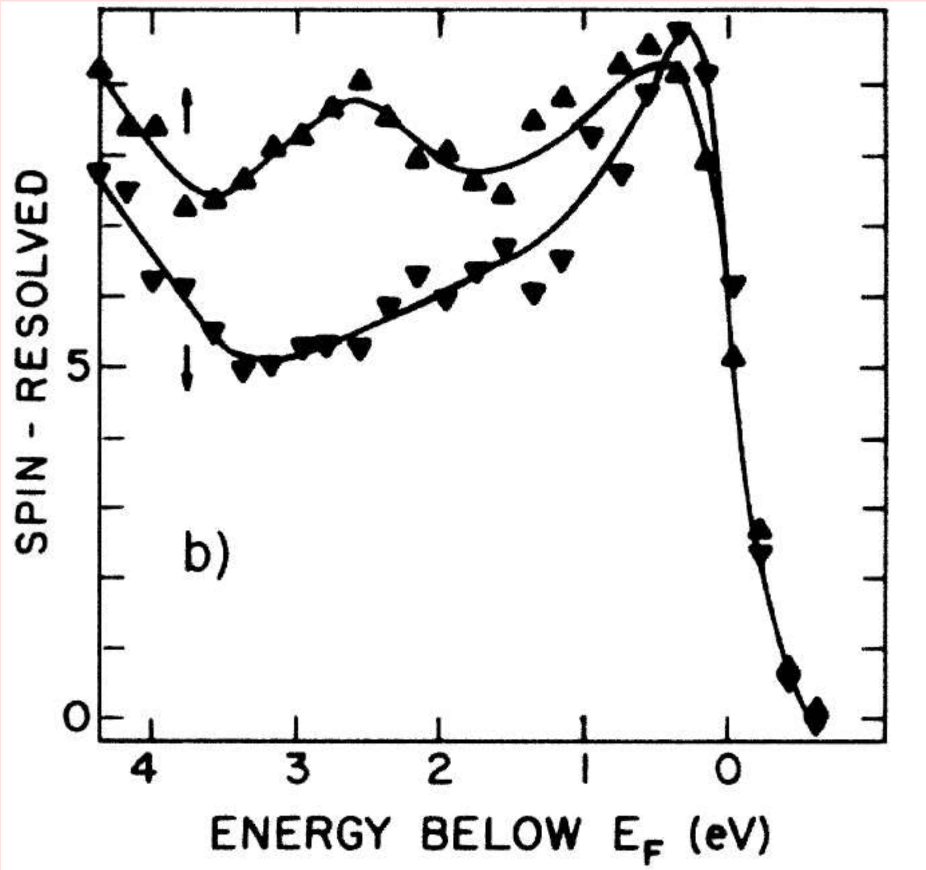
To analyse the conduction electrons : spin resolved photoemission



Photon penetration length = 0.5 nm
Very clean surface, UHV prepared surface

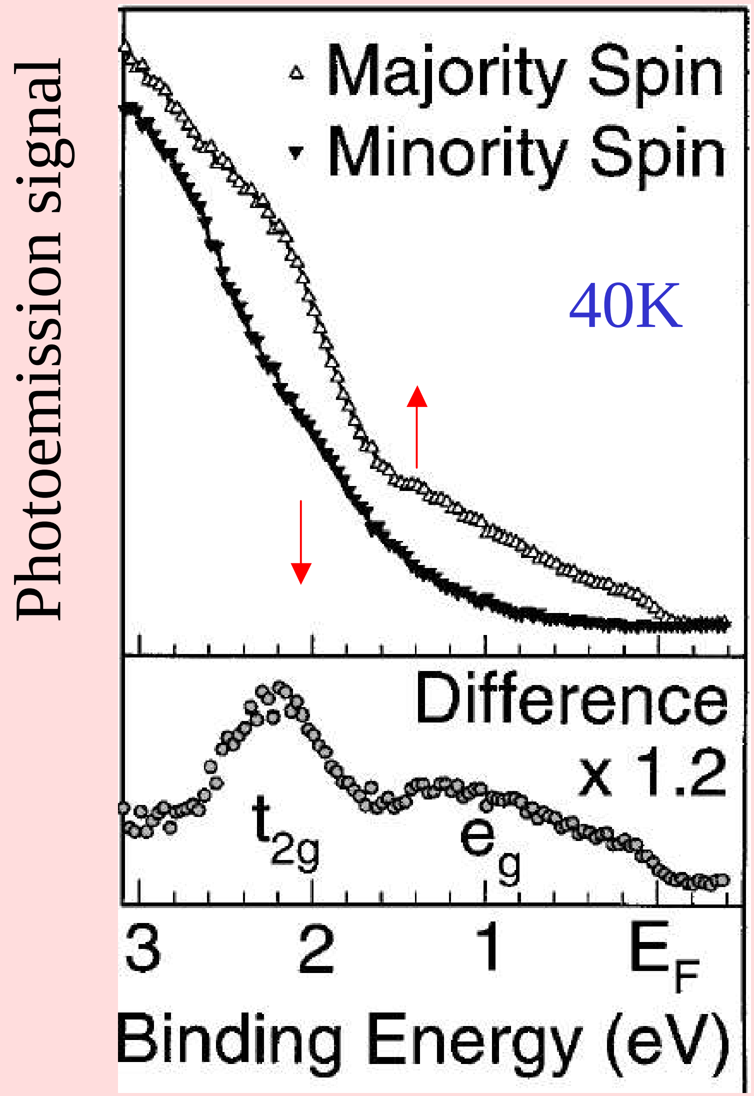
Spin-resolved photoemission

Example : Epitaxial Fe on Ag



Jonker et al. PRL57 (1986)

$La_{0.7}Sr_{0.3}MnO_3$ film



Photon hν = 40eV

Park et al. PRL 81 (1998)

Polarisation at 0K for Ni, Co and Fe is known

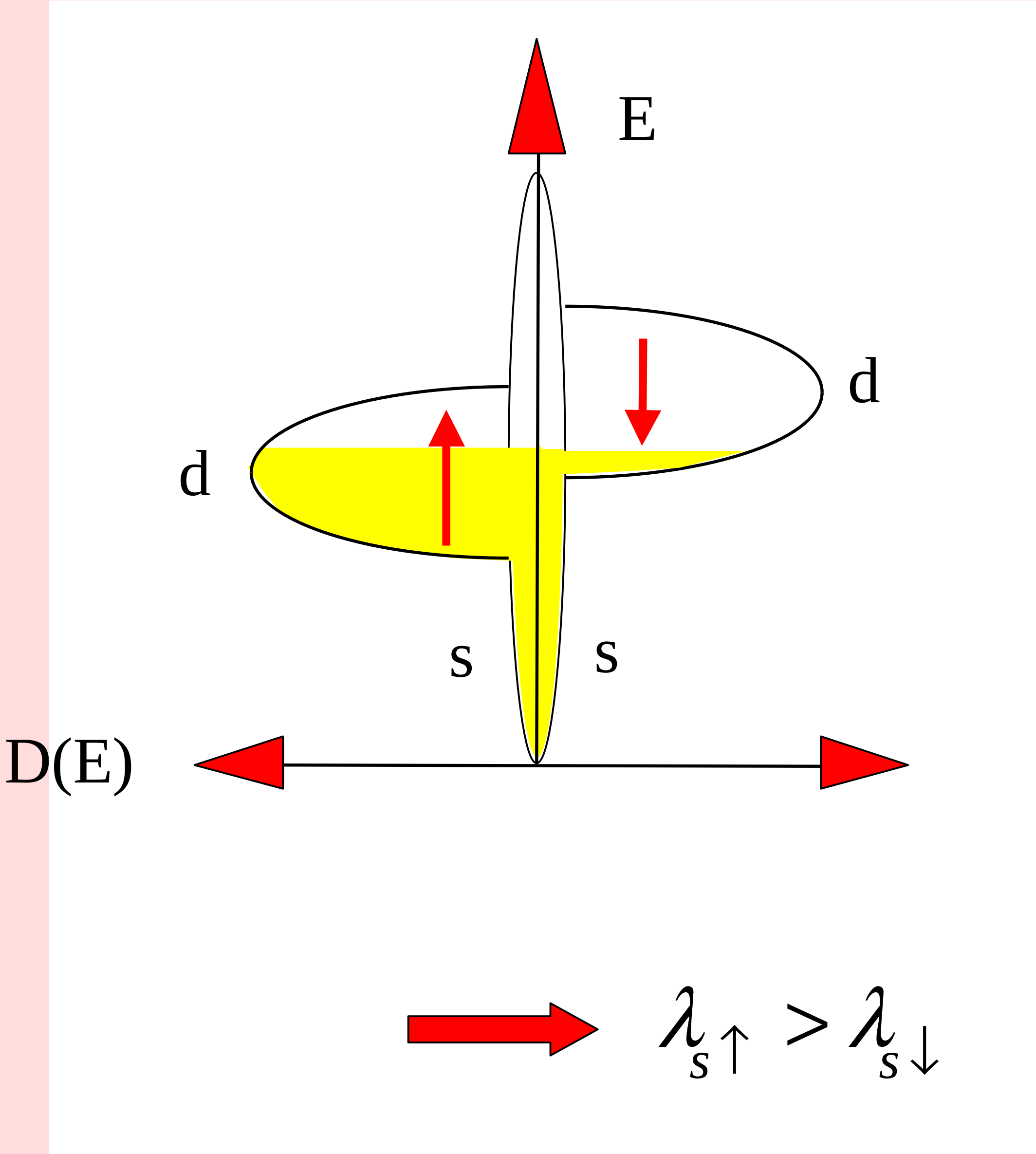
Its temperature dependence is still unclear

Surface polarisation still a mystery

(enough to keep you busy after Brasov school)

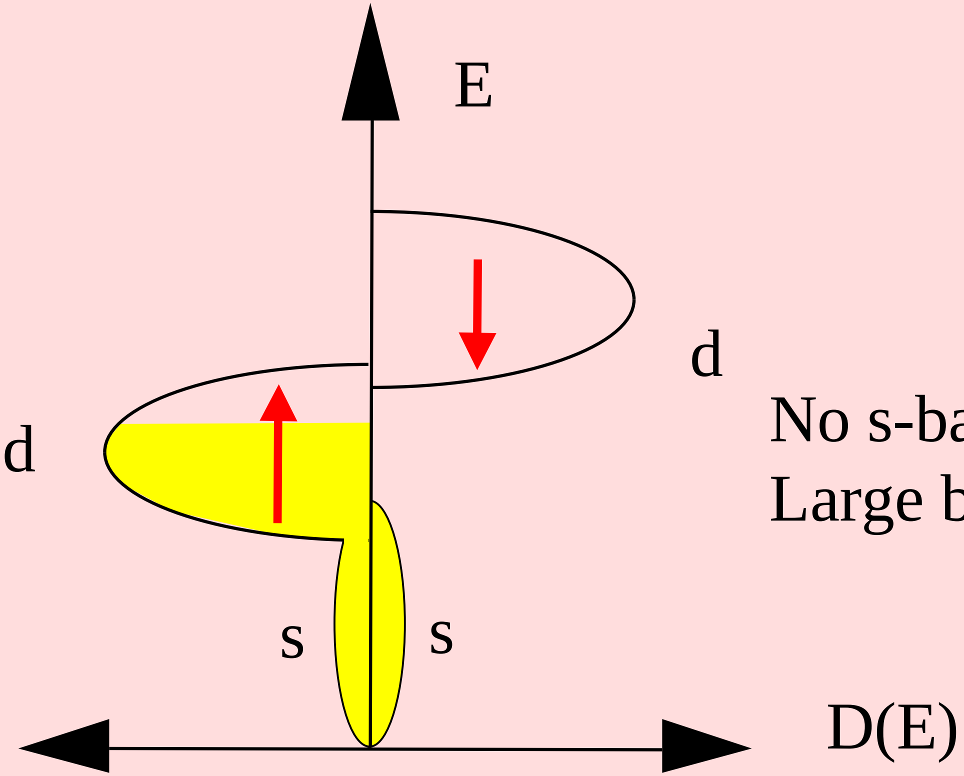
What about the other magnetic metals ?

V-Half Metallic Ferromagnets



Ferromagnetic band structure

Half metallic ferromagnets



No s-band at Fermi level
Large band splitting

- Fully spin polarised conduction band
- Gap = not usual metals = less metallic than metals

Predicted HMF

1984 : *ab initio* calculcations (De Groot et al.)

NiMnSb (T_c=720 K), PtMnSb (T_c=575 K)

CrO_2

$La_{0.7}Sr_{0.3}MnO_3$

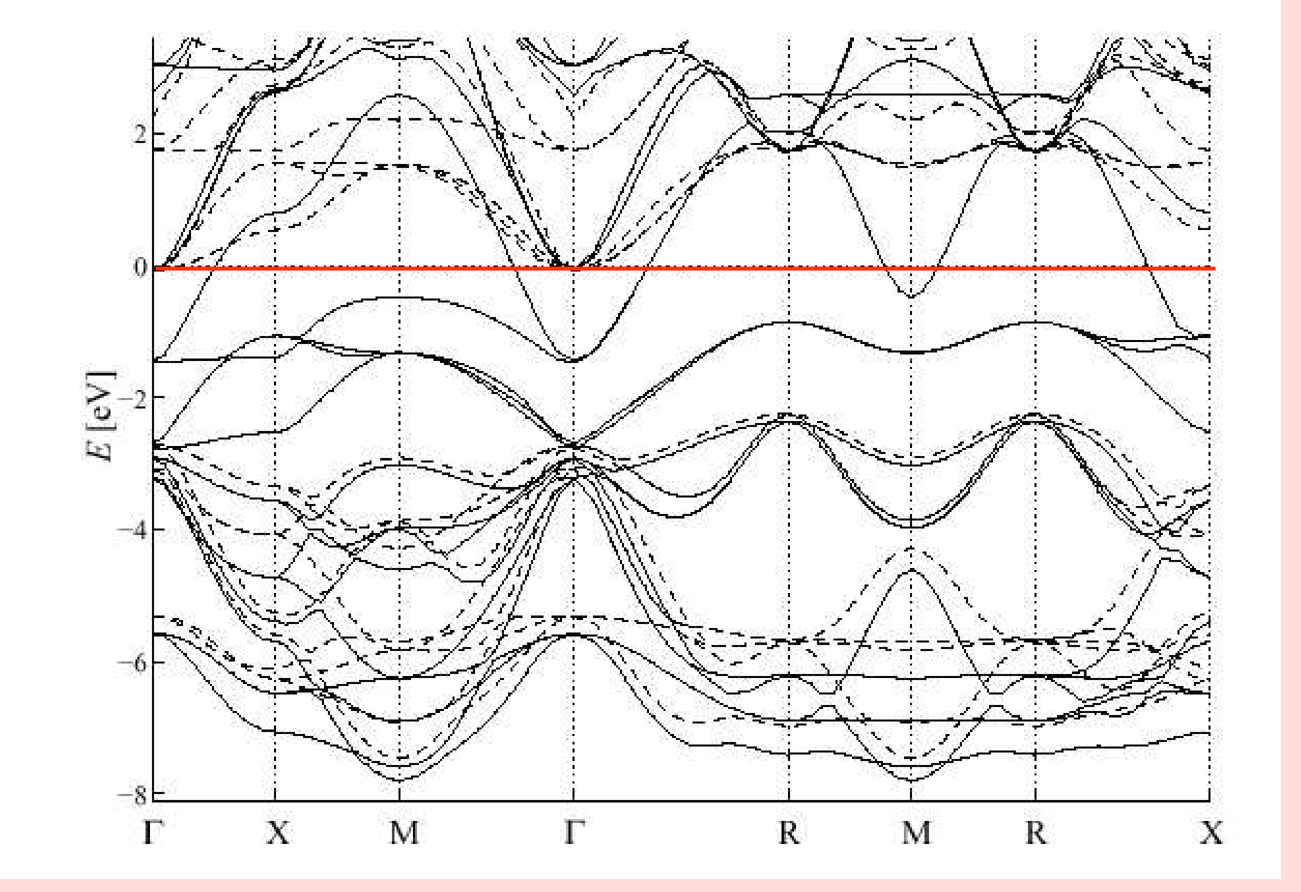
Fe_3O_4

$Fe_xCo_{1-x}S_2$ ………….

magnetic semiconductors ?

Compound	Curie temperature	Magnetisation $\mu_o M_s$	Crystallographic structure
$La_{0.7}Sr_{0.3}MnO_3$	350 K	0.74 T 3.7 μ_B/Mn	Perovskite
NiMnSb	728 K	0.89 T 4 μ_B/Mn	Semi Heusler
CrO_2	396 K	0.81T 2 μ_B/Cr	Rutile
Fe_3O_4	860 K	0.63 T 4 μ_B/F.U.	Inverse Spinel
PtMnSb	572 K	0.9 T 4 μ_B/Mn	Semi Heusler
Sr_2FeMoO_6	415 K	0.73 T 4 μ_B/F.U.	Double perovskite

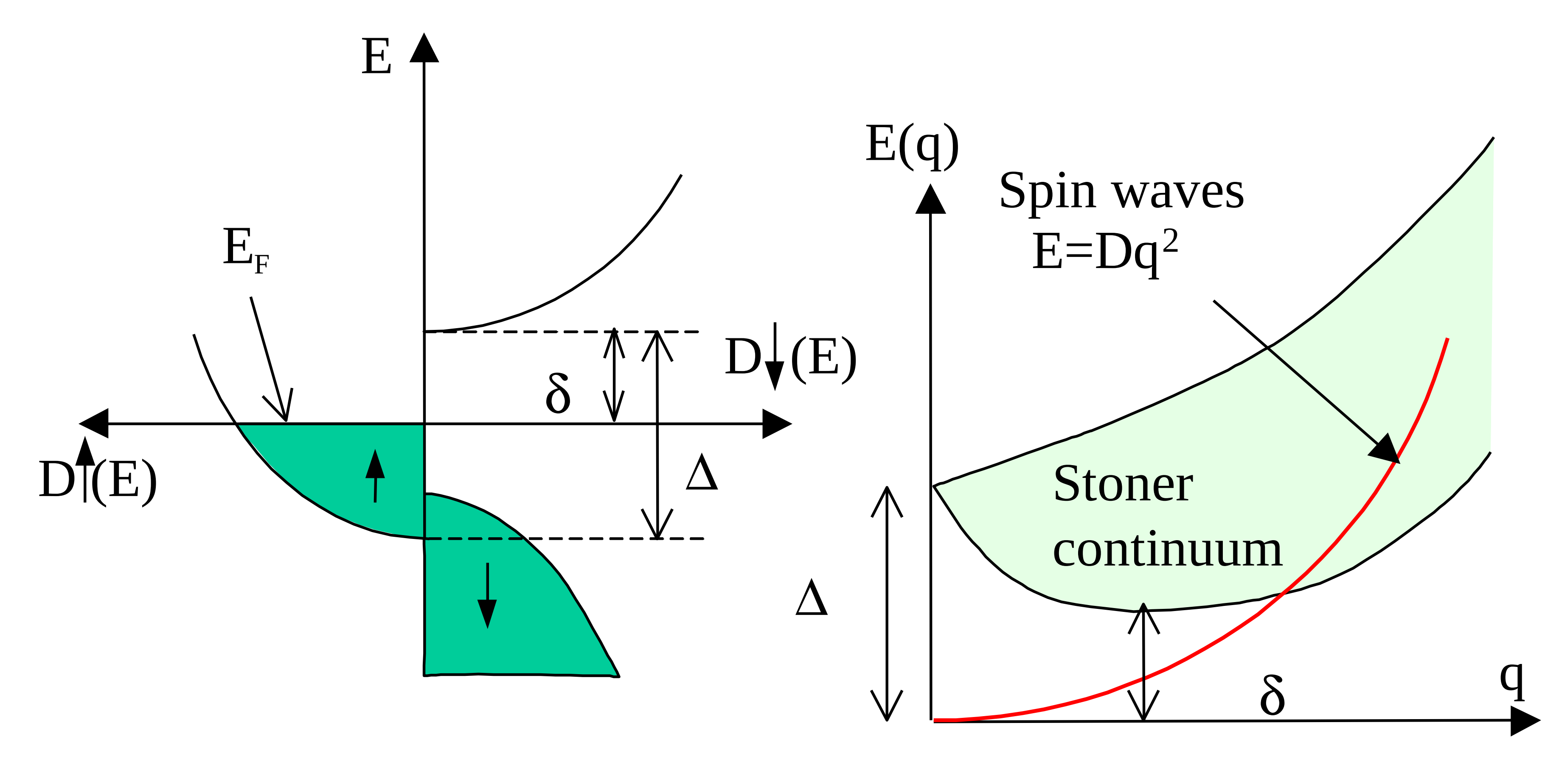
Predicted Half metallic character of $La_{0.7}Sr_{0.3}MnO_3$



Zero K picture

Spin-polarized band structure of $La_{0:7}Sr_{0:3}MnO_3$. The majority bands are shown as solid lines, and the minority as dashed lines

Livesay et al. J. Phys.: Condens. Matter **11** (1999) L279–L285



Electronic excitations in a HMF

Still exist at T>0

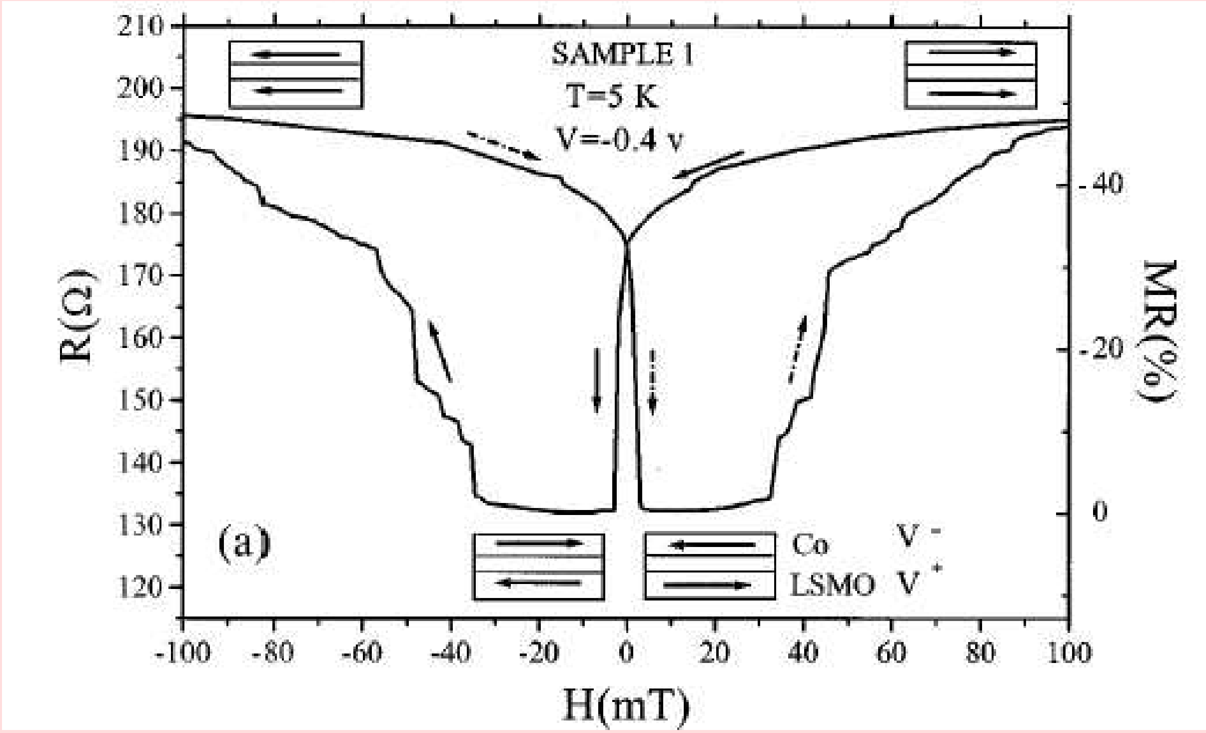
HMF are a very interesting class of materials

Useful to study HMF state

- Are they really 100% polarised ?
- Up to T_c ?
- Is the surface polarised ?

Useful to study other materials

- Source of d-like electrons
- Highly spin polarised source



DeTeresa et al. PRL 82(1999)

Inverse TMR

Cobalt : positive P (previous studies)
LaSrMnO : positive P (no down bands)

and negative TMR !

d electrons tunnel

Conclusions :

Tunnel is old but TMR is quite a recent field

Spin-dependent transport properties are not fully understood

HMF is still a mystery

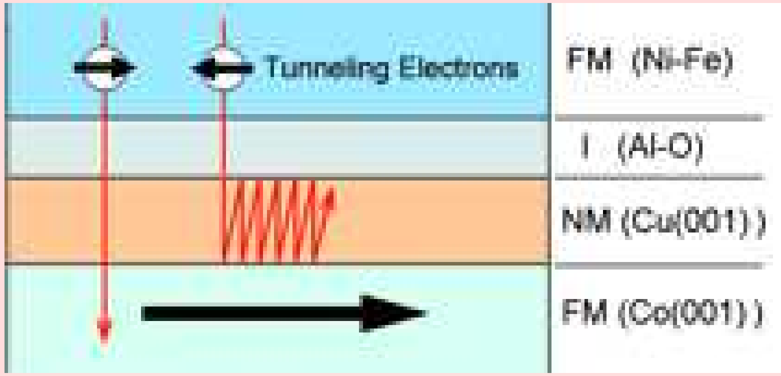
A lot of material science is necessary to control the structures

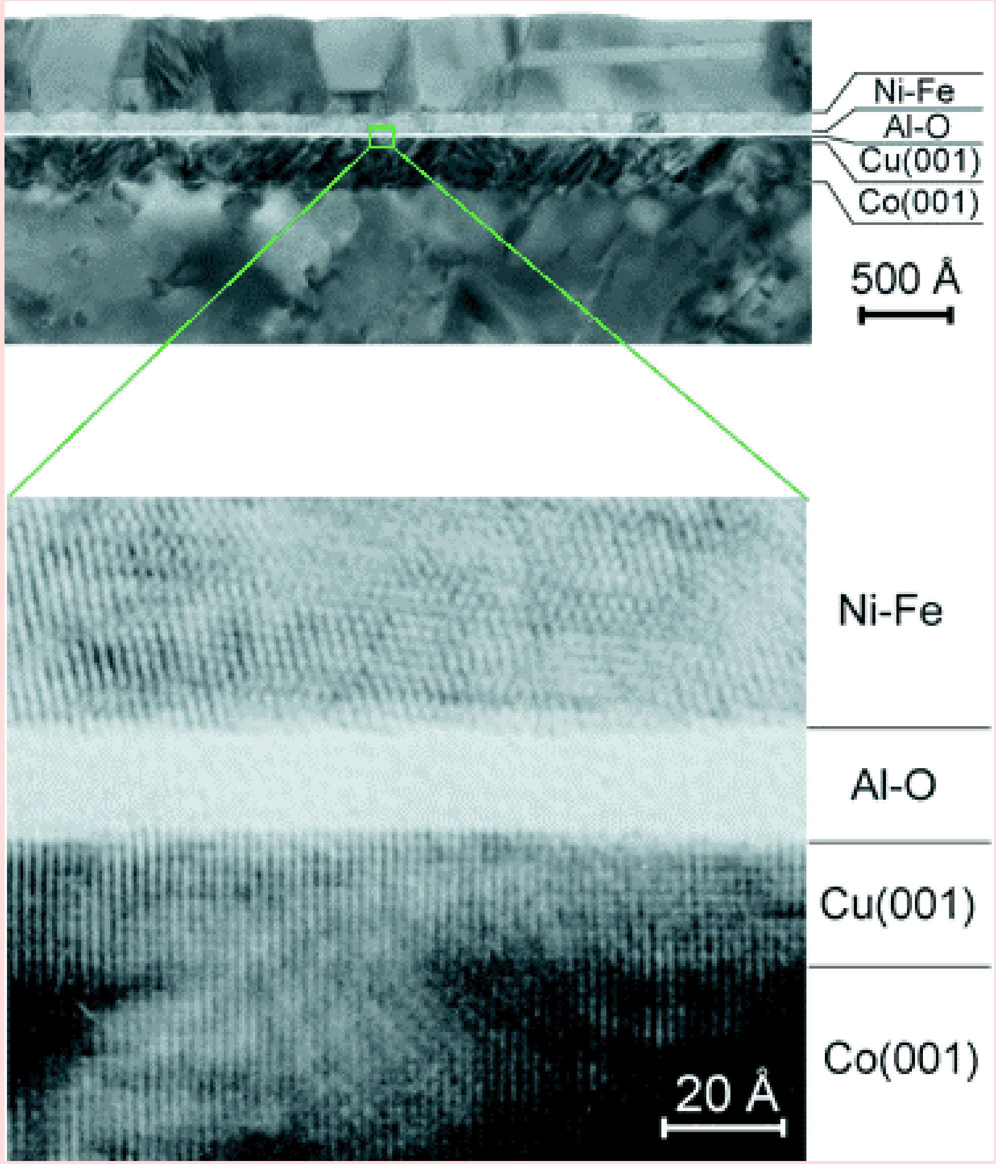
Only a few materials and structures have been controled

Bringing together magnetism and electronics is a fruitful playground ...

FIN

Improved structures : resonant junctions





Ivo Sturm
Manouk Rijpstra

Epitaxial junctions

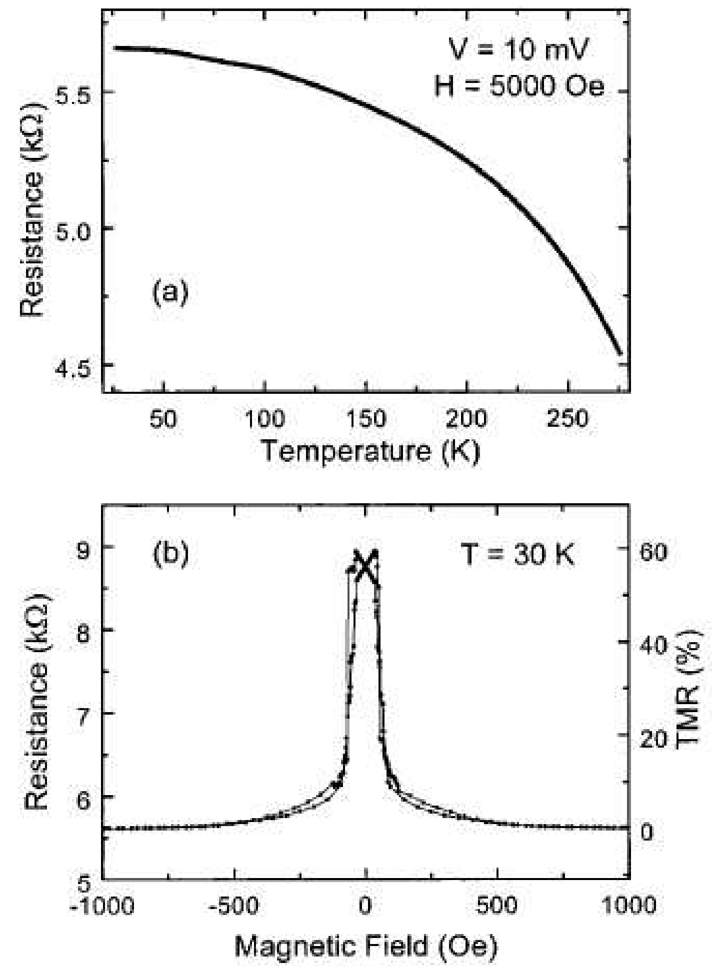


FIG. 2. Transport studies for a Fe(001)/MgO 20 Å(001)/FeCo(001) tunnel junction of diameter 10 μm: (a) resistance vs temperature at $V = 10$ mV and $H_{app} = 5000$ Oe; (b) resistance and TMR vs magnetic field at $V = 10$ mV and $T = 30$ K.

Bowen et al. APL 2001