# Models in spintronics (Part II)

OUTLINE :

**Spin-dependent transport in magnetic tunnel junctions**

-Introduction to tunnel effect

-magnetic tunnel junctions and tunnel MR

-Julliere model

-Slonczewski's model (free electron gas)

-Crystalline barrier: Spin-filtering according to symmetry of wave functions

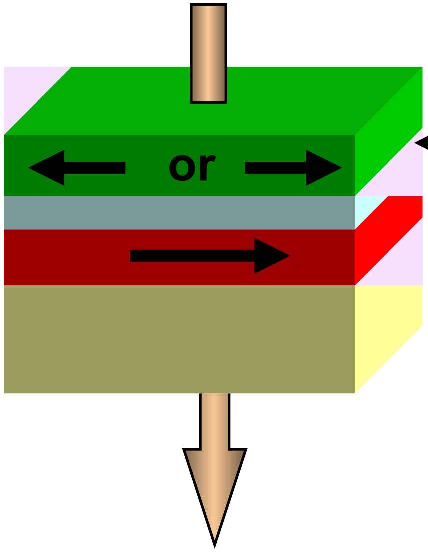
**Spin-transfer in non collinear magnetic configuration**

-spin-torque term and effective field term

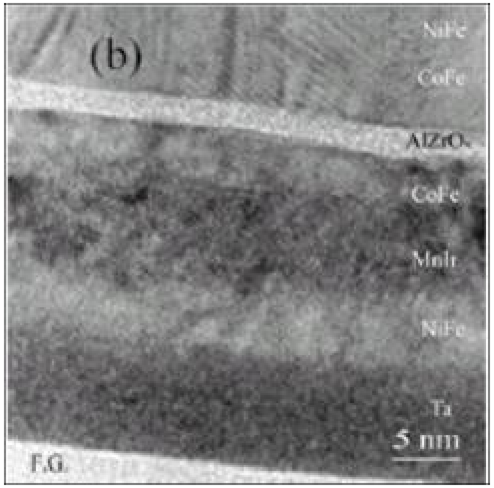
**Spin-injection in semiconductors**

# Magnetic tunnel junctions

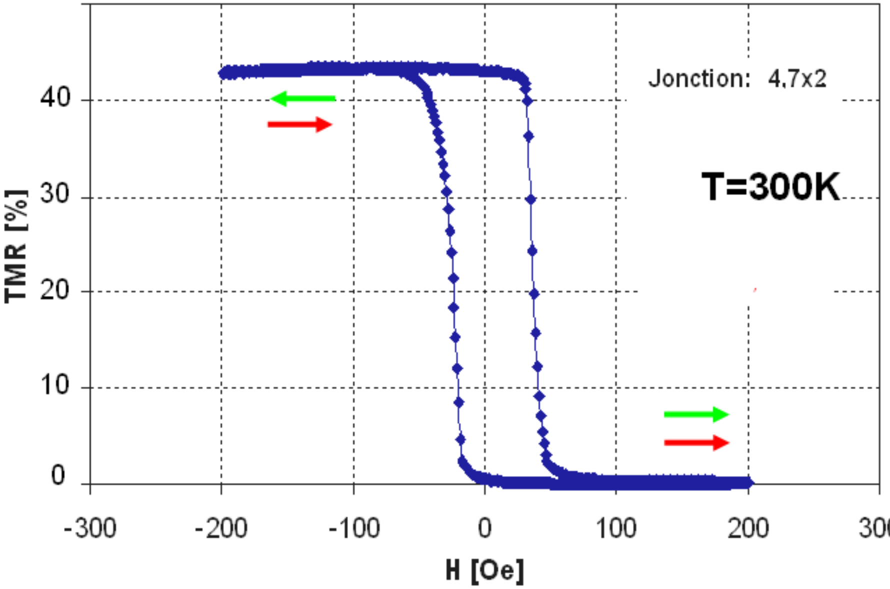
**Structure of a magnetic tunnel junction**




**Acts as a couple polarizer/analyzer with the spin of the electrons.**




$Al(Zr)O_x$




•First observation of TMR at low T in MTJ: Julliere (1975) (Fe/Ge/Co)

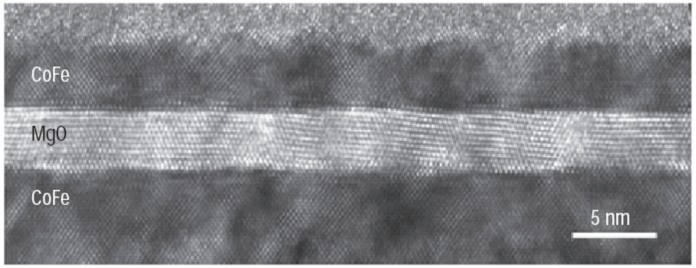
•TMR at 300K :

*Moodera et al, PRL (1995);*
*Myazaki et al, JMMM(1995).*
in $AlO_x$ based junctions

$\Delta R/R \sim 50\%$

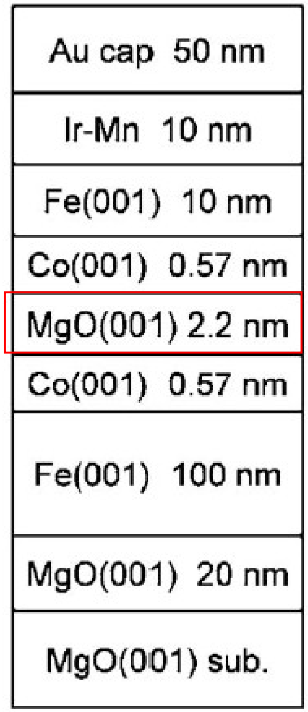
# Giant TMR of MgO tunnel barriers

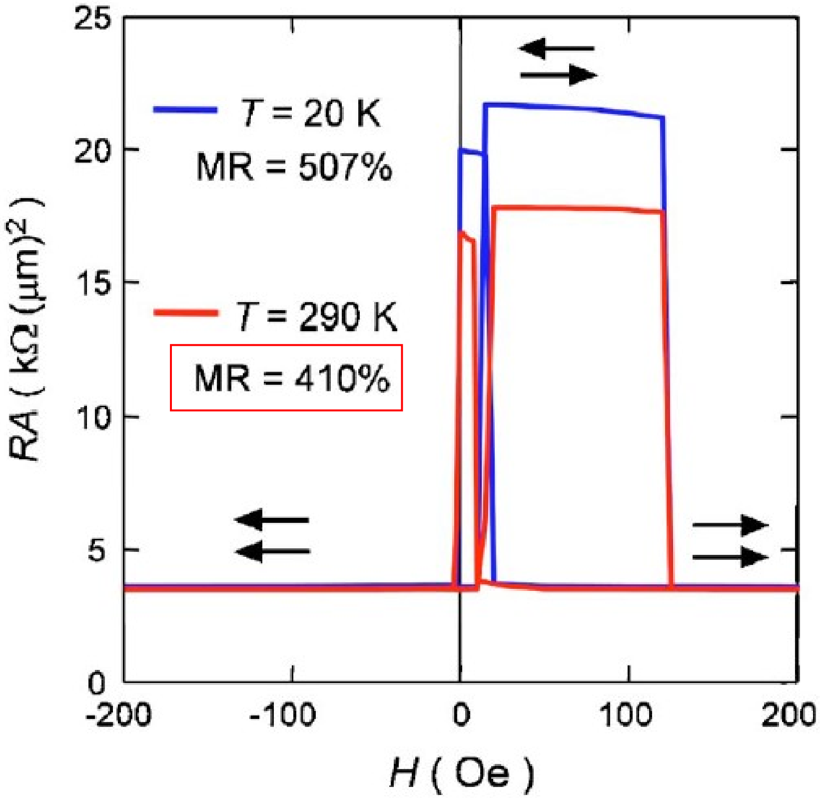
*S.S.P.Parkin et al, Nature Mat. (2004), nmat1256.*
*S.Yuasa et al, Nature Mat. (2004), nmat 1257.*




Very well textured MgO barriers grown by sputtering or MBE on bcc CoFe or Fe magnetic electrodes, or on amorphous CoFeB electrodes followed by annealing to recrystallize the electrode.

*Yuasa et al, APL89, 042505(2006)*

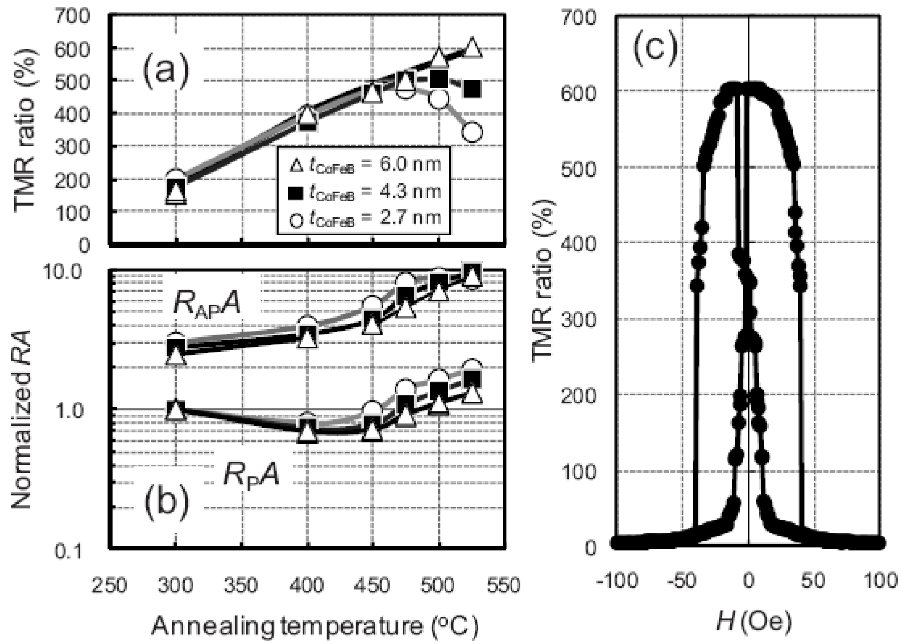


APPLIED PHYSICS LETTERS **93**, 082508 (2008)

# Tunnel magnetoresistance of 604% at 300 K by suppression of Ta diffusion in CoFeB/MgO/CoFeB pseudo-spin-valves annealed at high temperature

S. Ikeda,[1,a)] J. Hayakawa,[2] Y. Ashizawa,[3,b)] Y. M. Lee,[1,c)] K. Miura,[1,2] H. Hasegawa,[1,2] M. Tsunoda,[3] F. Matsukura,[1] and H. Ohno[1,d)]




Applied Physics Express **2** (2009) 083002

# Large Tunnel Magnetoresistance of 1056% at Room Temperature in MgO Based Double Barrier Magnetic Tunnel Junction

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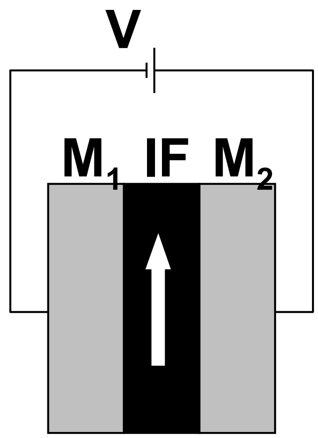
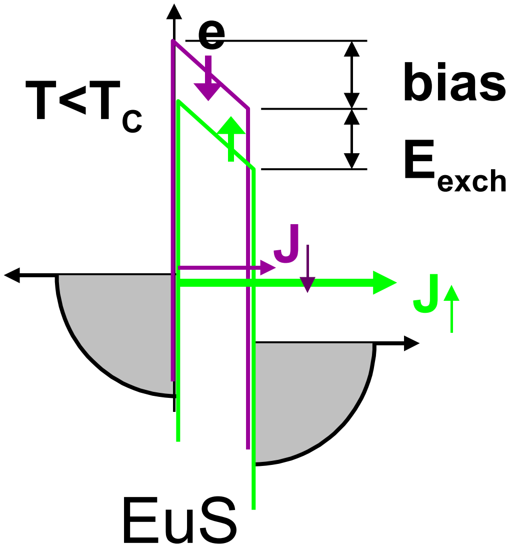
# Tunneling through magnetic insulators : spin filters

**Inject spin polarized electrons through spin-split insulator**

Barrier height h is spin-dependent
Tunnel current varies exponentially with $\sqrt{h}$




$$P = 1 - e^{-t(\alpha_{\uparrow} - \alpha_{\downarrow})} \quad \text{with} \quad \alpha_{\uparrow,\downarrow} = \sqrt{\frac{2mE_{\uparrow,\downarrow}}{\hbar^2}}$$




**$P_{injectée}$ ~ 90 % if M1, M2 normal metal**
**~ 130 % if M1 Gd (ferromagnetic)**

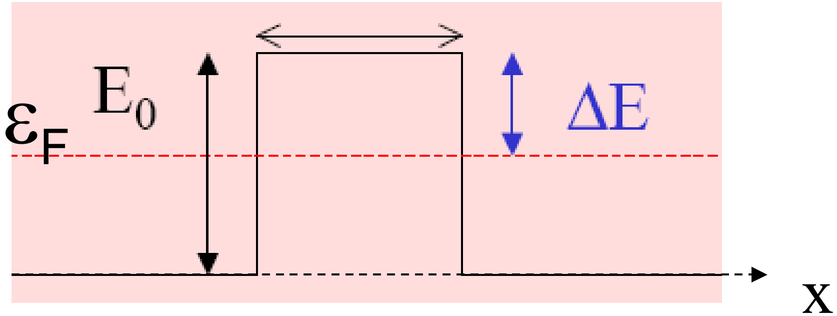
**…… but T = 4.2 K ($Tc_{EuS}$ ~ 16 K)**

**Also magnetic oxides ($Fe_3O_4$, $Fe_2CoO_4$…)**

*P. LeClair et al., Appl. Phys. Lett. 80, 625 (2002)*

# Tunnel effect

Quantum mechanical origin




A classical particle cannot enter the barrier zone if $\varepsilon_F < E_0$

In quantum mechanics, electrons obey Schrödinger equation (1D model):

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

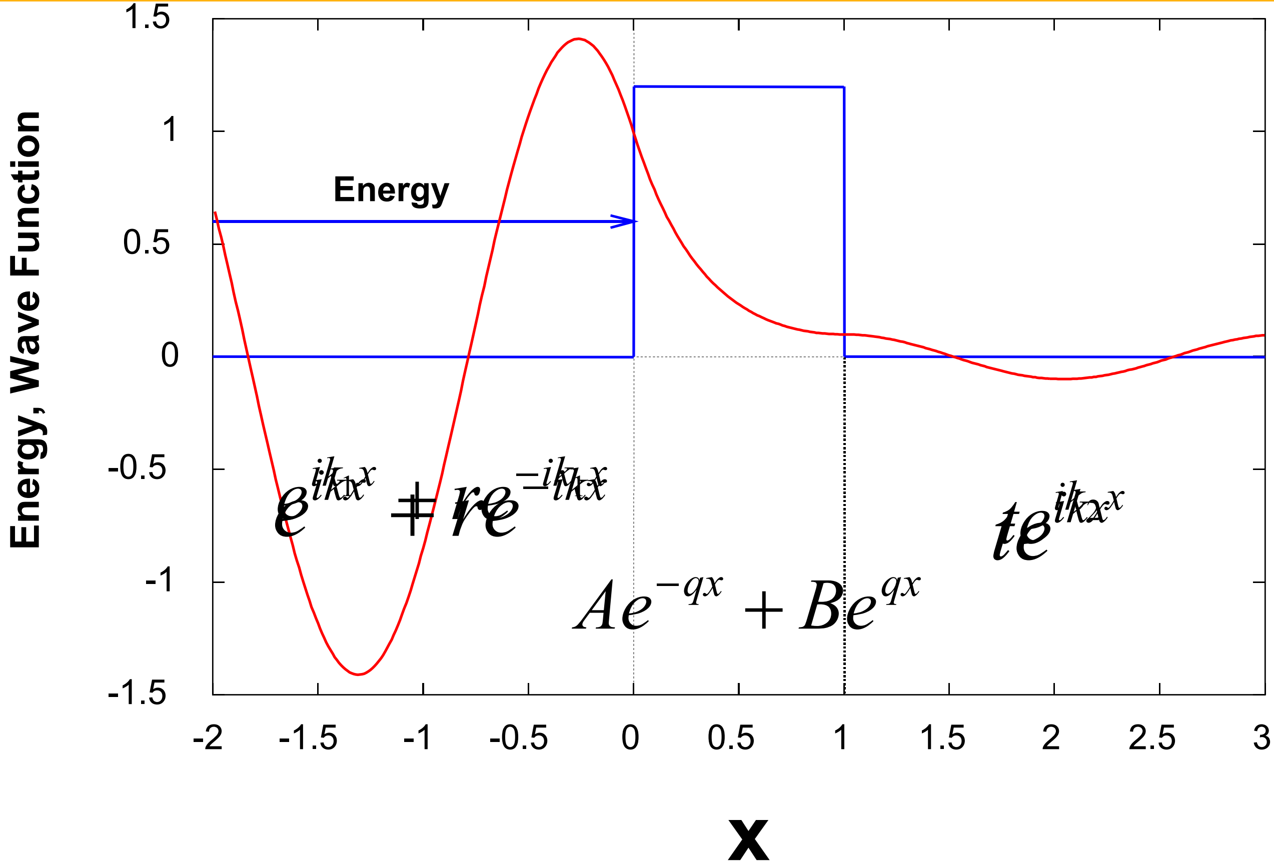
<u>Off the barrier</u> $$-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}|\psi\rangle = E|\psi\rangle \longrightarrow$$ Plane waves

$$|\psi\rangle = e^{ikx} \qquad k = \pm\sqrt{\frac{2mE}{\hbar^2}}$$

<u>In the barrier</u> $$-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}|\psi\rangle = (E - E_0)|\psi\rangle \longrightarrow$$ Evanescent waves

$$|\psi\rangle = e^{-qx} \qquad q = \pm\sqrt{\frac{2m\Delta E}{\hbar^2}}$$

# Tunneling through a simple rectangular barrier




Continuity of wave function and derivative through interfaces

$$\rightarrow \quad t = \frac{4qe^{-qa}\sqrt{k_1}}{(ik_1 - q)(ik_2 - q)}$$

# Transmission through a simple rectangular barrier

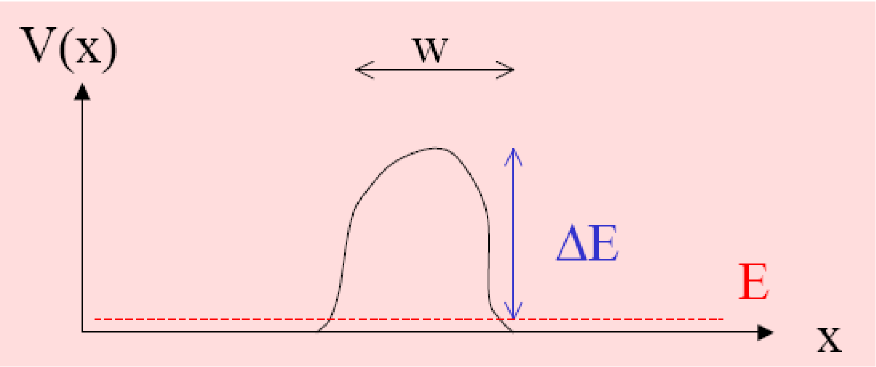
Probability of tunneling = t.t*

$$P = tt^* = \frac{16q^2 e^{-2qa} k_1}{\left(q^2 + k_1^2\right)\left(q^2 + k_2^2\right)}$$

Typically, ΔE~1eV, m~free electron
⇒1/q~0.2nm

Tunnel barrier must be at most a few nm thick to get reasonable tunneling rate through it

# Case of more general barrier




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

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

W.K.B approximation: $$|\psi\rangle = e^{\pm\int_0^x q(u)du}$$

What is neglected?: $$\frac{d\psi(x)}{dx} = \pm q(x)\psi(x)$$

$$\frac{d^2\psi(x)}{dx^2} = \pm\frac{dq(x)}{dx}\psi(x) \pm q(x)\frac{d\psi(x)}{dx}$$

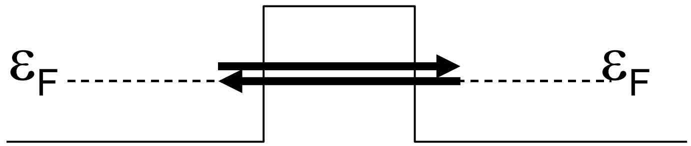
$$\frac{d^2\psi(x)}{dx^2} = \pm\frac{dq(x)}{dx}\psi(x) + q^2(x)\psi(x)$$

$$q(x) = \sqrt{\frac{2m(V(x)-E)}{\hbar^2}}$$

WKB OK if $q^2(x) >> \frac{dq}{dx}$ i.e. smoothly varying barrier

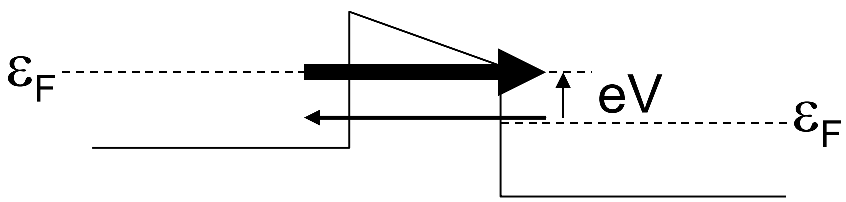
# How to calculate electrical current through barrier?

At zero bias voltage, same current from left to right and right to left.




$J_e\,(V=0)=0$

Need to apply a bias voltage, to create a dissymetry in tunneling current



## How to calculate electrical current through barrier? Cont'd

The probability for an electron to tunnel through the barrier is (WKB):

$$P(E) = tt^* = e^{-2\int_0^x q(u)\,du}$$

Nb of electrons tunneling per unit time:

Fermi-Dirac distribution

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

$$f_0(\vec{r},\vec{v}) = \frac{1}{\exp\left(\dfrac{\varepsilon - \varepsilon_F}{k_B T}\right) + 1}$$

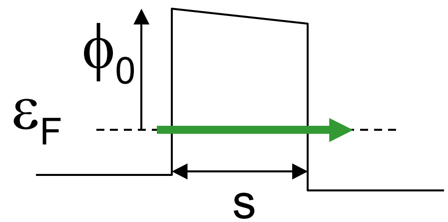
Electrical current:

$$J_e = e\left(\frac{dN_{1\to 2}}{dt} - \frac{dN_{2\to 1}}{dt}\right) = \frac{4e\pi m^2}{h^3} \int_0^E P(E_x)\,dE_x \int_0^\infty \left[f(E) - f(E + eV)\right] dE_{//}$$

# Approximate expressions of J(V) in free electron model

from Simons (1963)

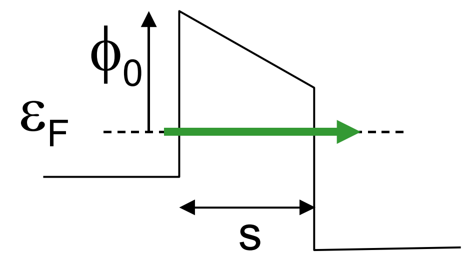
<u>For low bias</u>: still rectangular barrier




$$J = 3.16\ \ 10^{10} \sqrt{\phi_0}\, \frac{V}{s}\, e^{-1.02 s \sqrt{\phi_0}}$$

$\Rightarrow$ Linear J(V) at low bias

<u>For intermediate bias 0<V<</u>$\phi_0$: trapezoïdal barrier

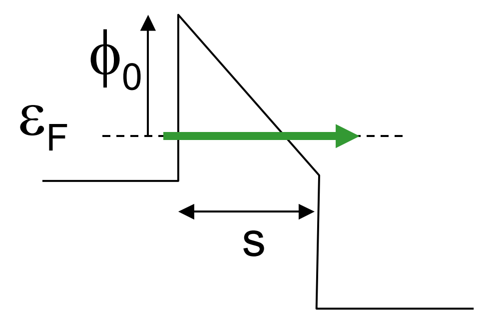



Conductance ↗ when V ↗

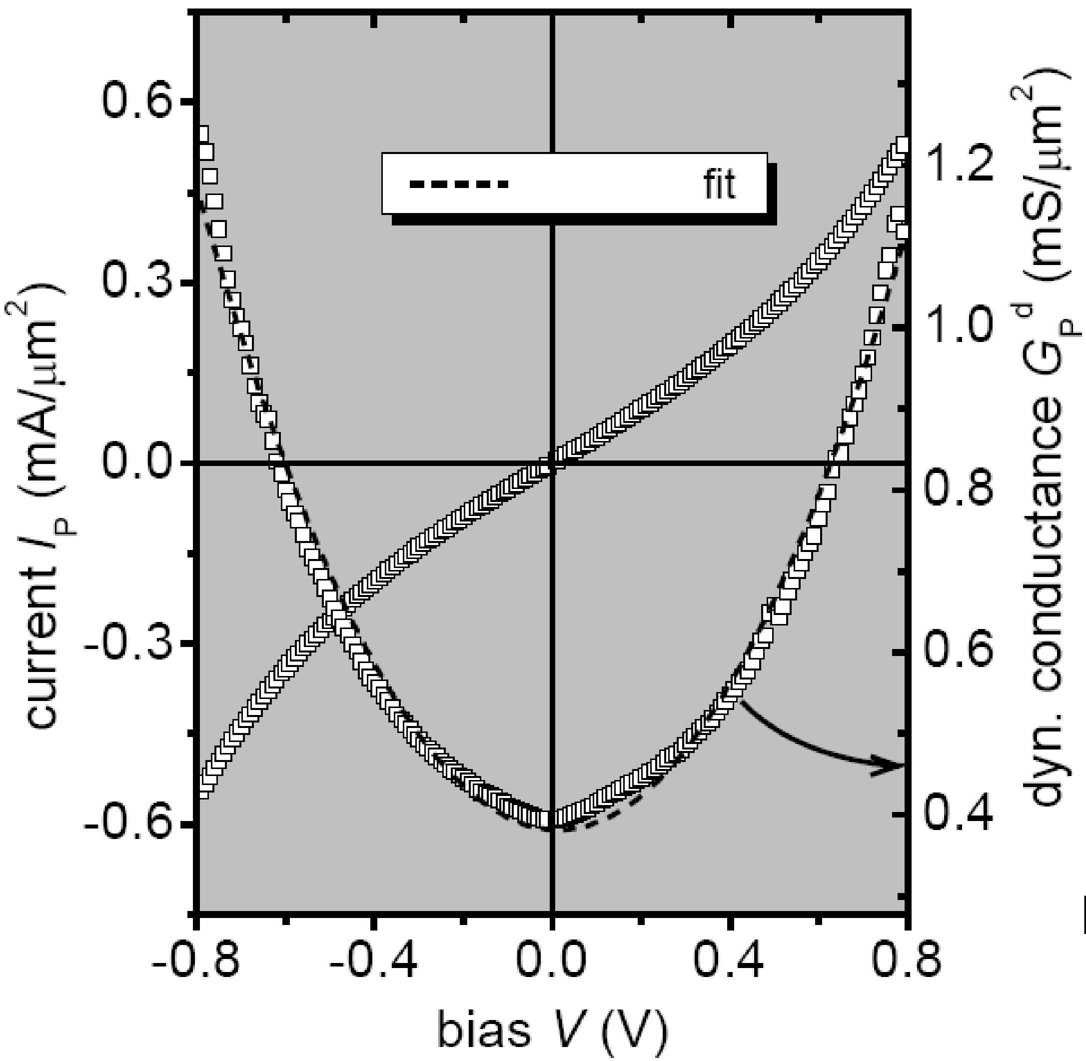
$$J = \frac{6.2\ 10^{10}}{s^2}\left[\left(\phi_0 - \frac{V}{2}\right)\exp\left(-1.025 s\left(\phi_0 - \frac{V}{2}\right)^{1/2}\right) - \left(\phi_0 + \frac{V}{2}\right)\exp\left(-1.025 s\left(\phi_0 + \frac{V}{2}\right)^{1/2}\right)\right]$$

<u>For large bias V></u>$\phi_0$: Fowler Nordheim

Injection in conduction band



# Exemple of experimental I(V) characteristics in tunnel junction




Tunnel barrier of MgO

**Barrier height:** $\varphi$**=1.04 eV**

**Barrier asymmetry:** $\Delta\varphi$**=0.20 eV**

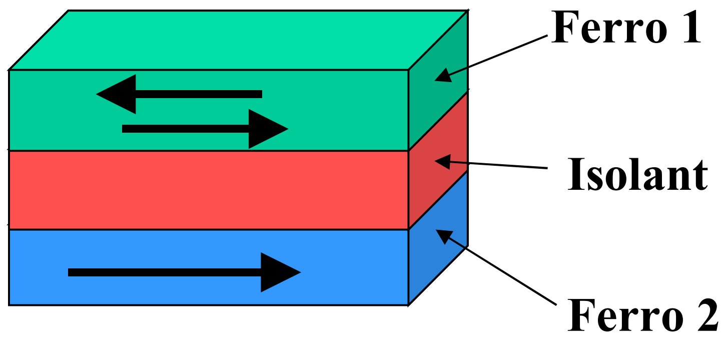
**Barrier thickness:** $d$**=1.6 nm**

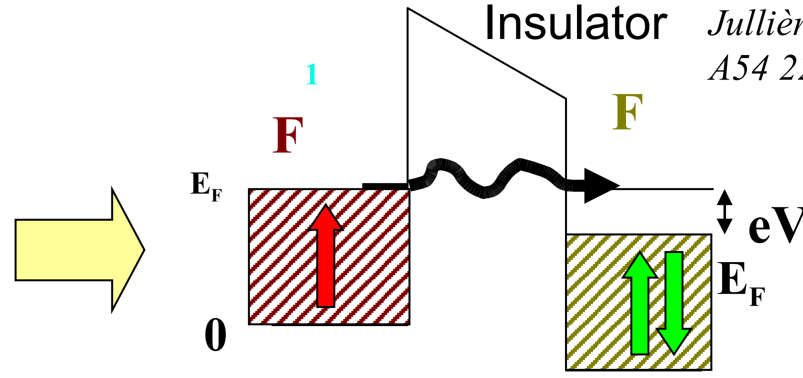
**Effective mass:** $m_{eff}/m_e = \alpha = 0.4$

Dynamic conductance=dI/dV

*T.Dimopoulos et al*

# Julliere model of TMR




*Jullière, Phys. Lett. A54 225 (1975)*

Fermi Golden rule: proba of tunneling $\quad P^{\sigma} \propto \left| \langle i|W|f \rangle \right|^2 D_f(E_F)$

Nb of electrons candidate for tunneling $\quad \propto D_i(E_F)$

$\Rightarrow$ tunneling current in each spin channel $\quad J^{\sigma} \propto D_1^{\sigma}(E_F) \times D_2^{\sigma}(E_F)$

<u>Parallel configuration</u>

$$J^{parallel} \propto D_1^{\uparrow} D_2^{\uparrow} + D_1^{\downarrow} D_2^{\downarrow}$$

<u>Antiparallel configuration</u>

$$J^{antiparallel} \propto D_1^{\uparrow} D_2^{\downarrow} + D_1^{\downarrow} D_2^{\uparrow}$$

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

$$TMR = \frac{\Delta R}{R_P} = \frac{2 P_1 P_2}{1 - P_1 P_2}$$

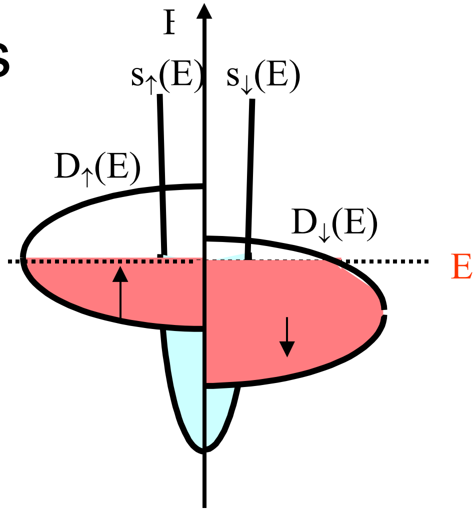
$$TMR = \frac{\Delta R}{R_{AP}} = \frac{2 P_1 P_2}{1 + P_1 P_2}$$

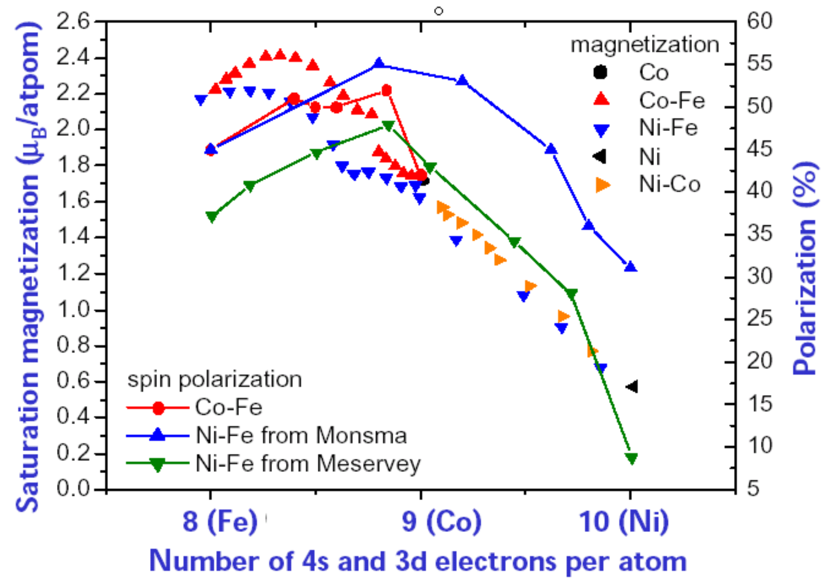
**P~50% in Fe, Co**

**ΔR/R~40 - 70% with alumina barriers**

# Spin polarization of 3d metals

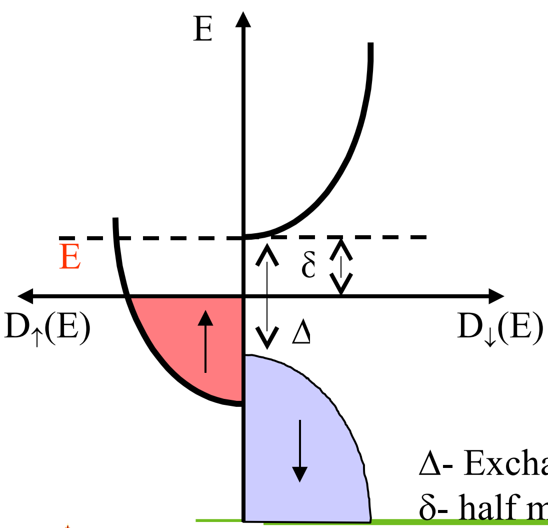
## Metals




Parkin et al

## Half metals




Half metals are 100% spin polarized !

Heussler alloys

$LaSrMnO_3$

$Fe_3O_4$

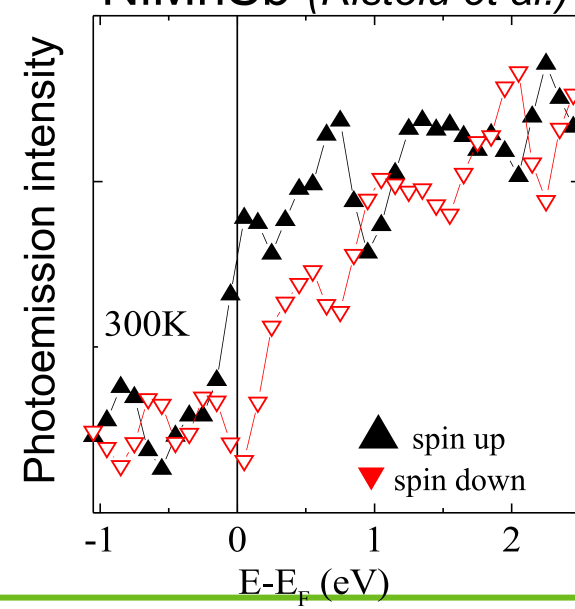
$CrO_2$

…

Δ- Exchange spliting

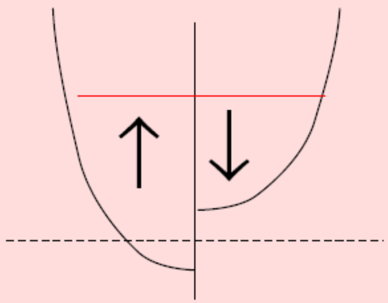
δ- half metallic gap

NiMnSb *(Ristoiu et al.)*



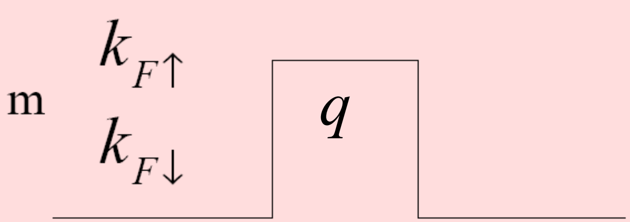
# Slonczewski's model (1989)

Ferromagnetic electrodes



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

Barrier in the model




Model of band structure derived from M.B.Stearns JMMM 5, 167 (1977).
Hybridization between s and d electrons.
« Itinerant free electrons » ie free electrons (parabolic bands) but with band splitting.

Schrödinger equation solved for both spin channels assuming continuity of $\psi$ and $\frac{d\psi}{dx}$ through the interfaces

For each spin channel:

$$J^{\sigma\sigma'} = \frac{16 q^2 e^{-2qa} k_\sigma k_{\sigma'}}{\left(q^2 + k_\sigma^2\right)\left(q^2 + k_{\sigma'}^2\right)}$$

σ, σ' refer to spin state in the left and right electrodes

# Slonczewski's model (1989) cont'd

Spin ↑ and spin ↓ channels conduct in parallel:

$$J_{Parallel} = J^{\uparrow\uparrow} + J^{\downarrow\downarrow} \quad \text{and} \quad J_{Antiparallel} = J^{\uparrow\downarrow} + J^{\downarrow\uparrow}$$

$$J_{Parallel} - J_{antiparallel} = 16q^2 e^{-2qa}\left[\frac{(k_\uparrow - k_\downarrow)(q^2 - k_\uparrow k_\downarrow)}{(q^2 + k_\uparrow^2)(q^2 + k_\downarrow^2)}\right]^2$$

Tunnel magnetoresistance:

$$\frac{\Delta G}{G_{Parallel}} = \frac{J_{Parallel} - J_{antiparallel}}{J_{parallel}} = \frac{2P^2}{1+P^2}$$

with

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

# Slonczewski's model (1989) cont'd

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

In Julliere's model, only the polarization within the magnetic electrodes influences the TMR. In slonczewski's model, the barrier height also plays a role.

Case of high barrier: $q >> k_{F\uparrow}, k_{F\downarrow}$ ➡ $P \approx \frac{k_{F\uparrow} - k_{F\downarrow}}{k_{F\uparrow} + k_{F\downarrow}}$

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

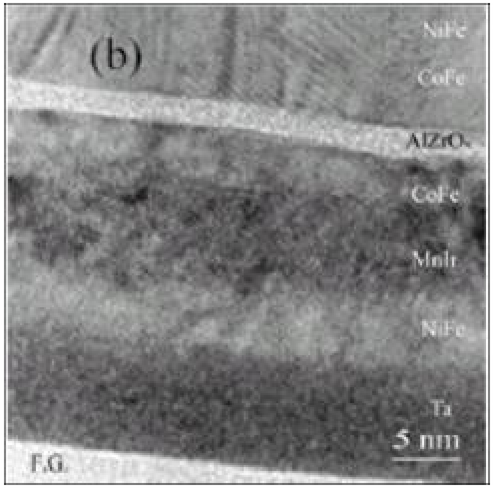
➡ $P \approx \frac{D_\uparrow - D_\downarrow}{D_\uparrow + D_\downarrow}$ Back to Julliere formula $\frac{\Delta R}{R_{Antiparallel}} = \frac{\Delta G}{G_{Parallel}} = \frac{2P^2}{1+P^2}$

# Utility of Julliere/Slonczewski Models

•AlOx tunnel barriers are amorphous. In amorphous materials, all electronic effects related to crystal symmetry are smeared out. Evanescent waves in alumina have “free like” character. Free electrons model work OK in this case.

•These models semi-quantitatively account for the relationship between bulk polarization of the electrodes and TMR in alumina based MTJ

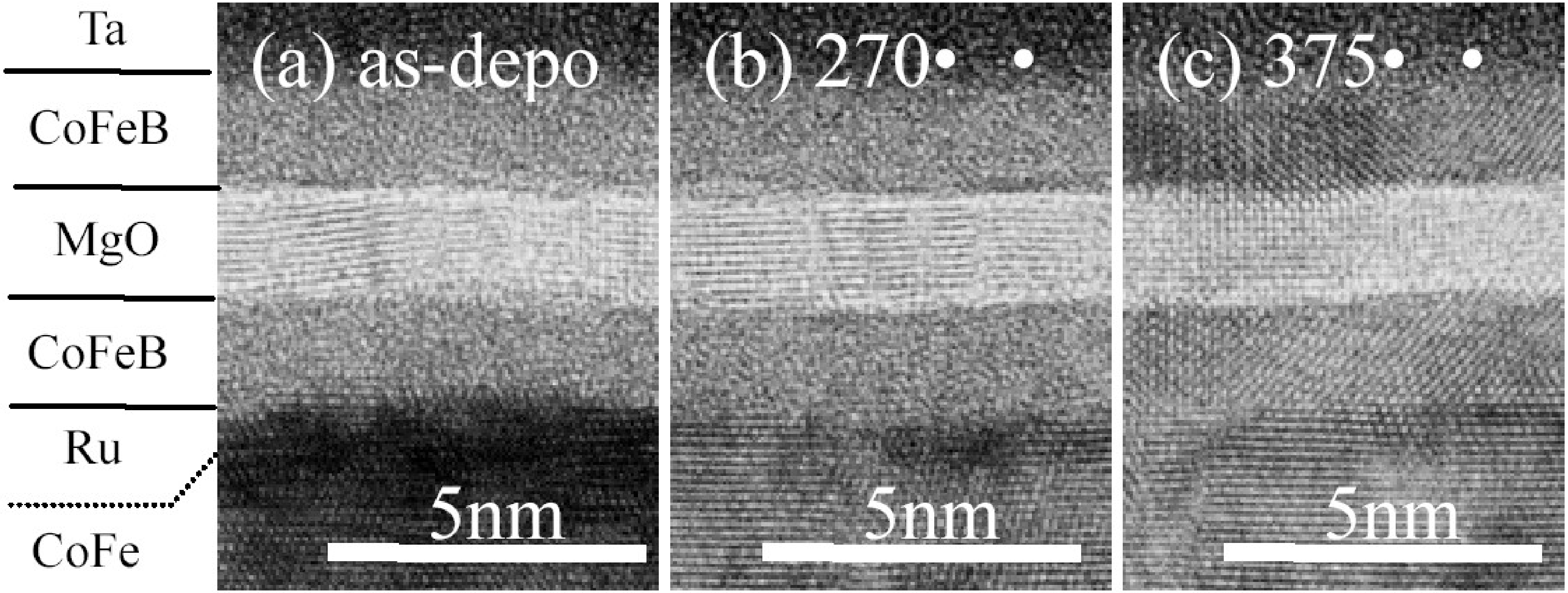
•However, they fail with crystalline barriers. Additional band structures effect in the electrodes and barrier must be taken into account



# Magnetic tunnel junctions based on MgO tunnel barriers

•As-deposited, CoFeB amorphous, MgO polycristalline
•Upon annealing, recrystallization of CoFeB from the MgO interfaces and improvement in MgO crystallinity with (100) bcc texture

Fig.4 J. Hayakawa et al. Jap. J. Appl. Physics 2005




Also, Yuasa et al. Applied Physics Letters, 2005

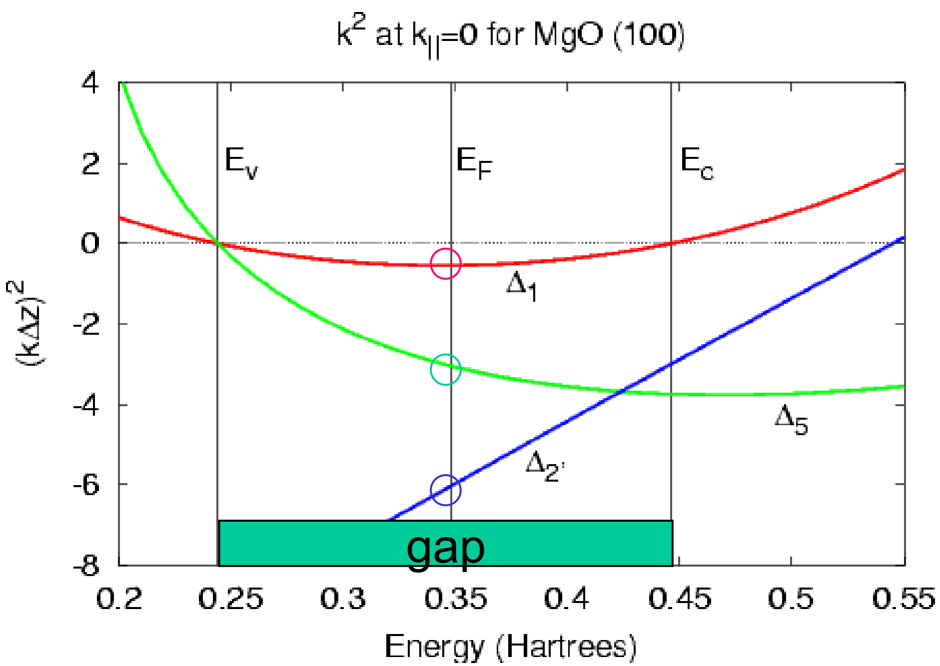
# Tunneling through crystalline MgO barriers (cont'd)

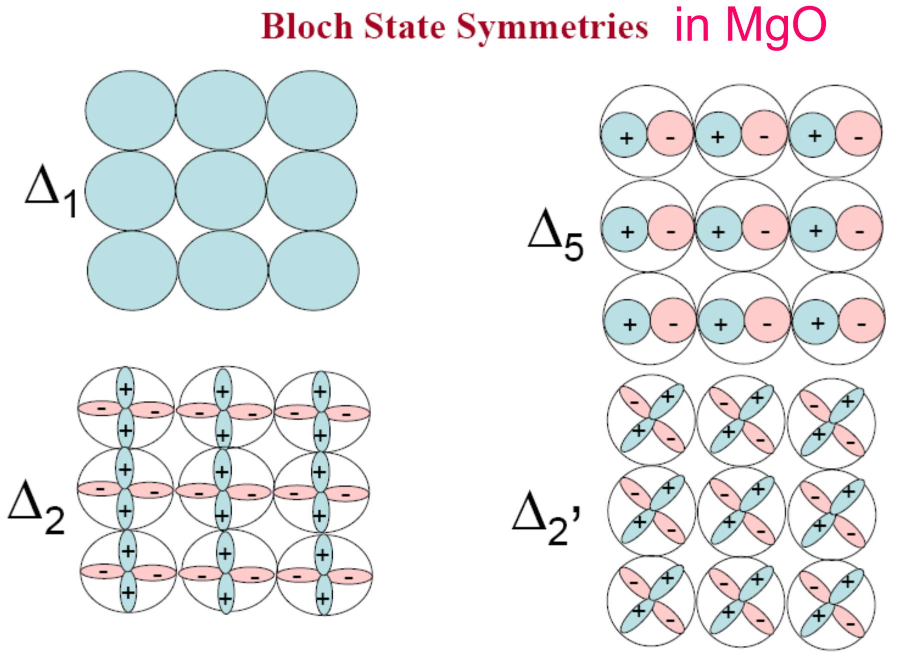
MgO barriers crystalline (bcc):

•Evanescent waves have symmetries respecting the crystal symmetry.

•The evanescent wave vectors strongly depends on the wave function symmetry

Ab initio calculation from Butler et al.:



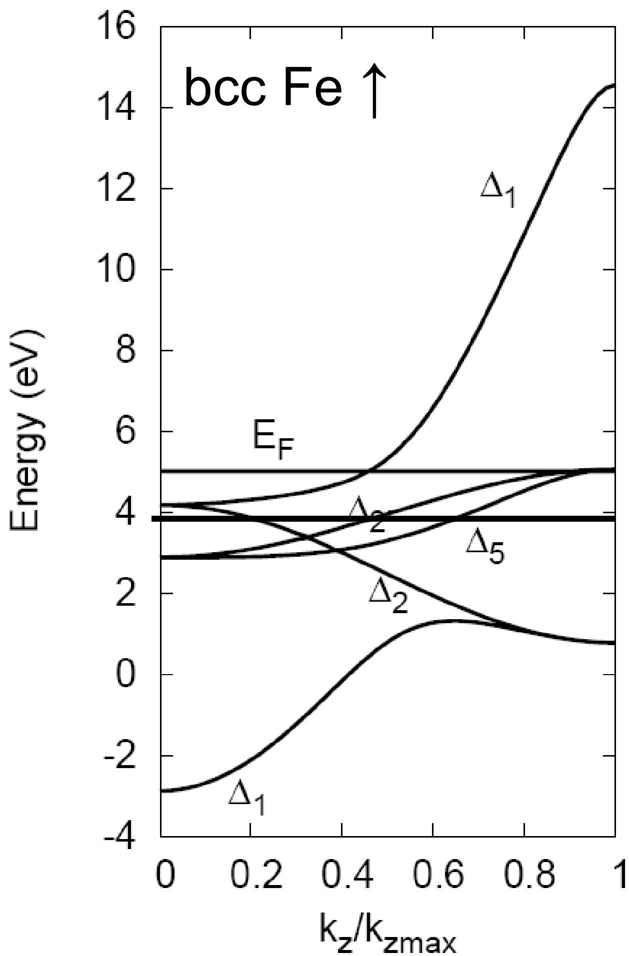



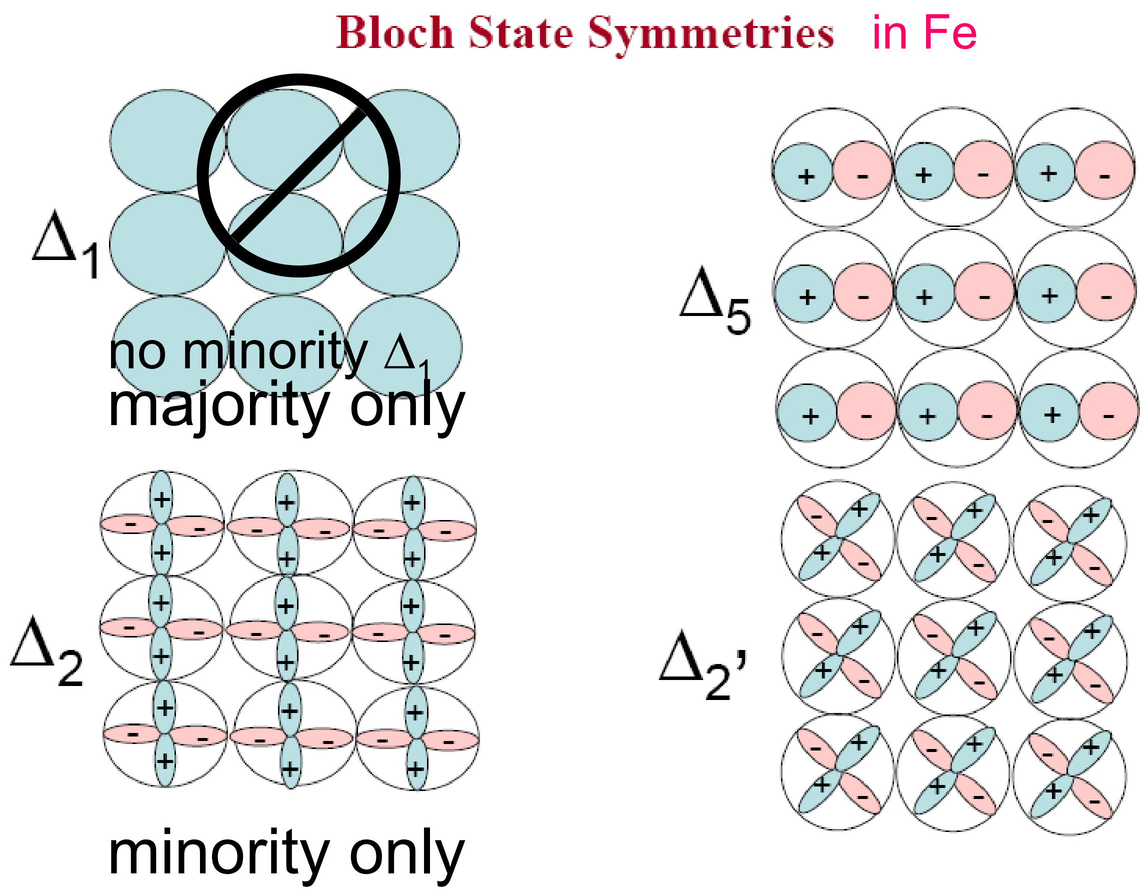

Decay rate of $\Delta 1$ much smaller than decay rate of $\Delta 5$ or $\Delta 2'$.

If the occupation of these various symmetries is spin-dependent, this provides a new mechanism for spin-filtering

# Tunneling through crystalline MgO barriers (cont'd)

For bcc Fe, at $E_F$ in (001), the $\Delta_1$ symmetry Bloch state is only present for majority.

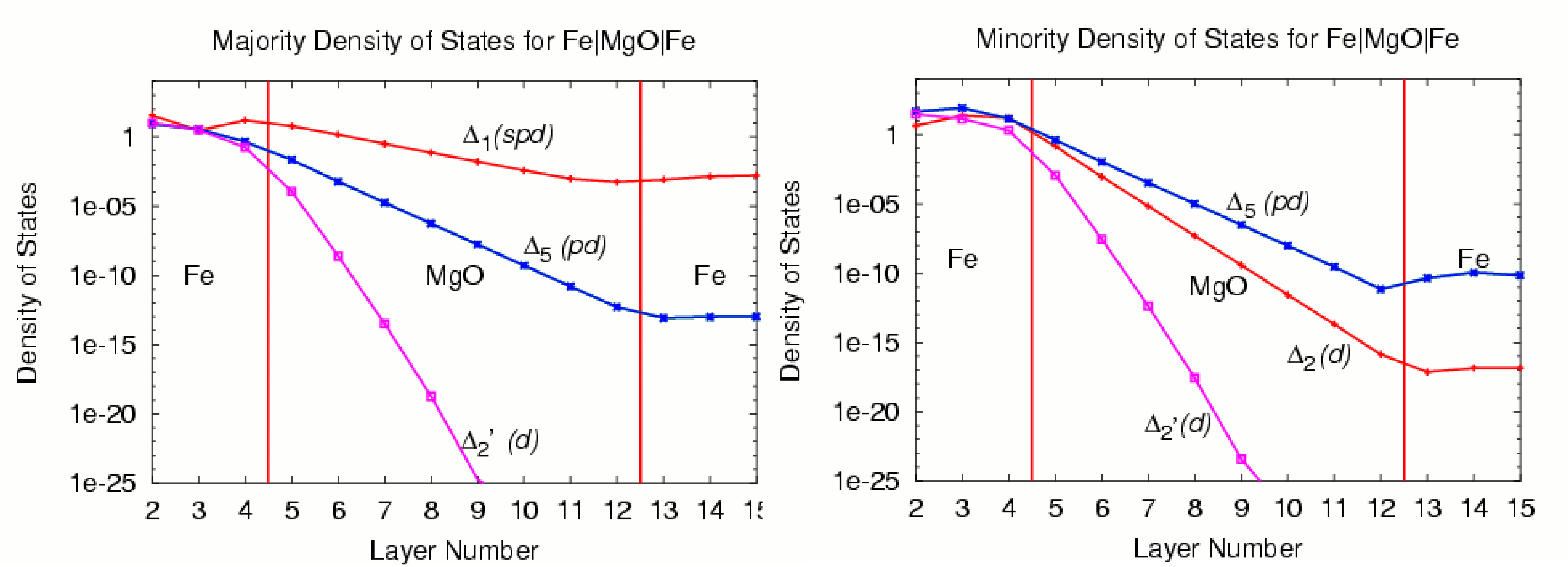



*W.Butler, Alabama Univ*

# Tunneling through crystalline MgO barriers (cont'd)

"Tunneling DOS" for k|| = 0 depends strongly on symmetry of Bloch states in Fe.

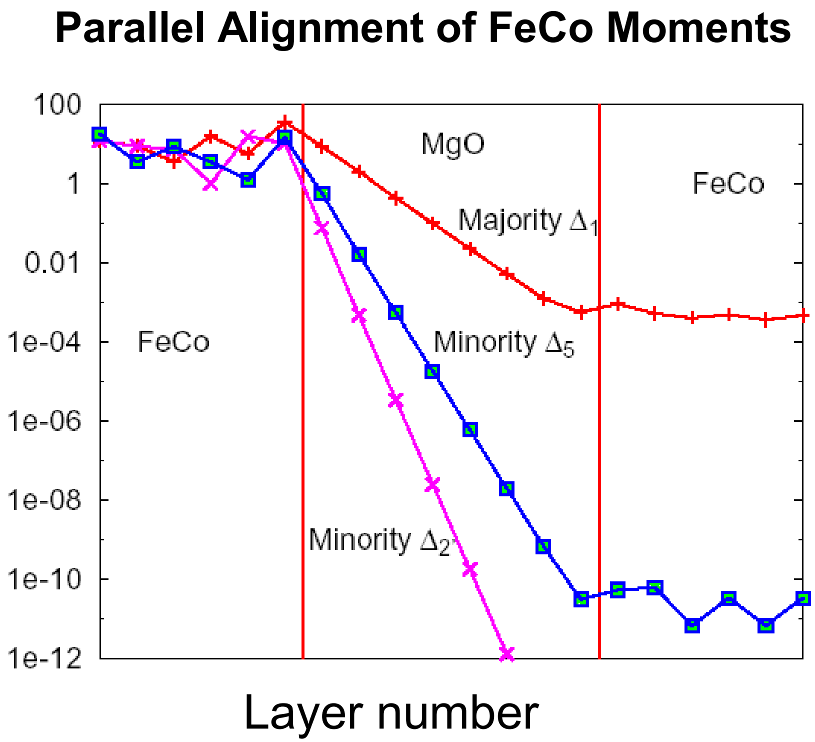


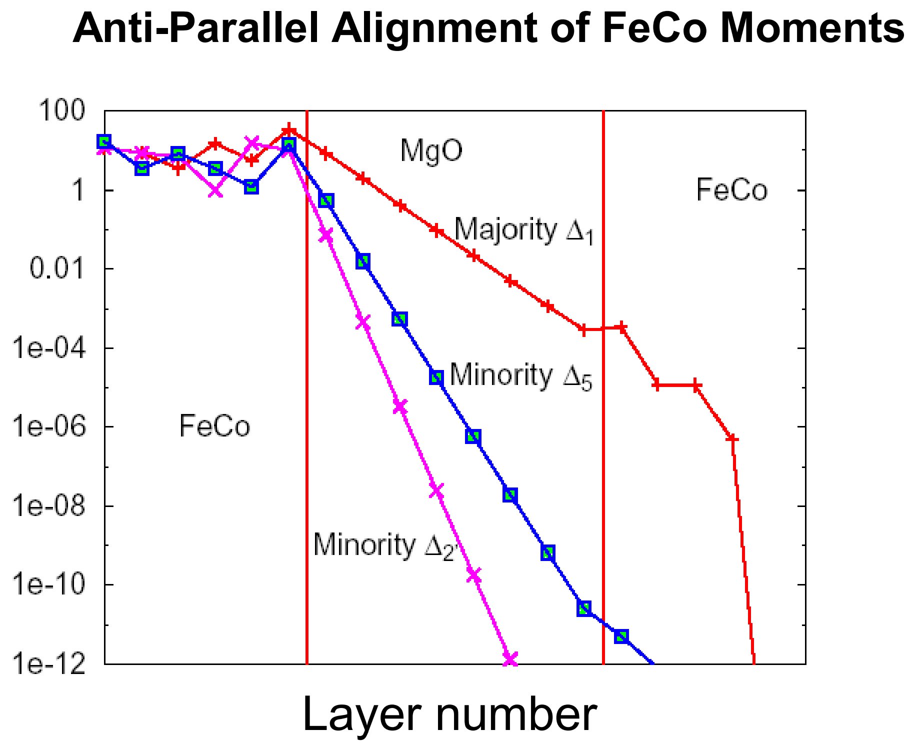

- Figures show the density of states (DOS) for electrons incident from the left in a particular Bloch state for each atomic layer.
- One particular majority band ($\Delta_1$) readily enters the MgO and decays slowly inside the MgO.

*W.Butler, Alabama Univ*

# Tunneling through crystalline MgO barriers (cont'd)

Majority bcc FeCo has only one band at the Fermi energy, a $\Delta 1$ band. There is no $\Delta 5$ band at Fermi energy – consequence even larger TMR!




•Density of states on each atomic layer at *k*|| = 0 for FeCo/MgO/FeCo tunnel junction (boundary condition is – single Bloch state incident from left).

Zhang and Butler *PRB* **70**, 172407 (2004).

*W.Butler, Alabama Univ*

Co|MgO|Co and CoFe|MgO|CoFe are predicted to show extremely high TMR for well ordered interfaces.

| Spin alignment | up-up | down-down | up-down or down=up | $G_P/G_{AP}$ |
|---|---|---|---|---|
| Fe\|MgO\|Fe | 2.55 x$10^9$ | 7.08 x$10^7$ | 2.41 x$10^7$ | 54.3 |
| Co\|MgO\|Co | 8.62 x$10^8$ | 7.51 x$10^7$ | 3.60 x$10^6$ | 147.2 |
| FeCo\|MgO\|FeCo | 1.19 x$10^9$ | 2.55 x$10^6$ | 1.74 x$10^6$ | 353.5 |

The conductances above were calculated by integrating over the entire Fermi surface. They assumed 8 layers of MgO.

*W.Butler, Alabama Univ*

# Summary on magnetic tunnel junctions

Tunneling: a quantum effect

TMR amplitude not only due to spin-polarization in the ferromagnetic electrodes but also to characteristics of the barrier.

Influence of the barrier height

Spin-dependent hybridization effects may take place at Ferro/oxide interface

With crystalline barrier, spin-filtering effect according to symmetry of wave function. Very large TMR amplitude obtained with MgO barriers.

# Models in spintronics (Part II)

OUTLINE :

## Spin-dependent transport in magnetic tunnel junctions

-Introduction to tunnel effect

-magnetic tunnel junctions and tunnel MR

-Julliere model

-Slonczewski's model (free electron gas)

-Crystalline barrier: Spin-filtering according to symmetry of wave functions

## Spin-transfer in non collinear magnetic configuration

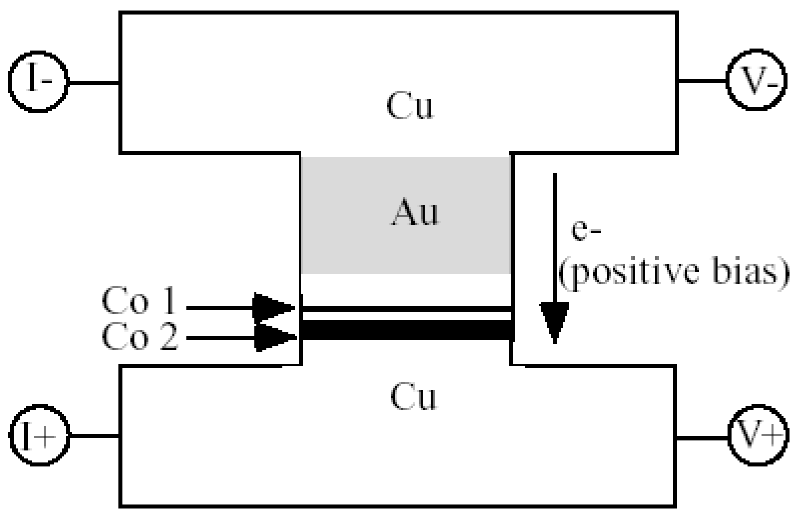
-spin-torque term and effective field term

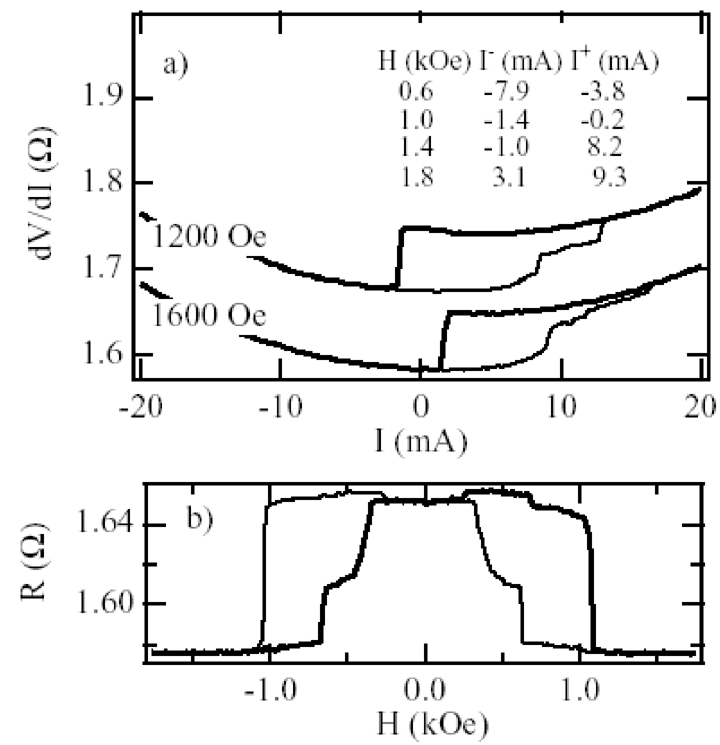
## Spin-injection in semiconductors

# Spin transfer effect in CPP geometry

Possibility to generate magnetic excitations or flip the magnetization in a magnetic thin film by a spin polarized current predicted by Slonczewski (JMMM.159, L1(1996)) and Berger (Phys.Rev.B54, 9359 (1996)).

First experimental observation of <u>magnetic excitations due to spin polarized current</u>: M.Tsoi et al, Phys.Rev.Lett.80, 4281 (1998) and of <u>current induced switching</u> : Katine et al, Phys.Rev.Lett.84, 3149 (2000) on Co/Cu/Co sandwiches ($J_c$ ~2-4.10  A/cm$^2$)



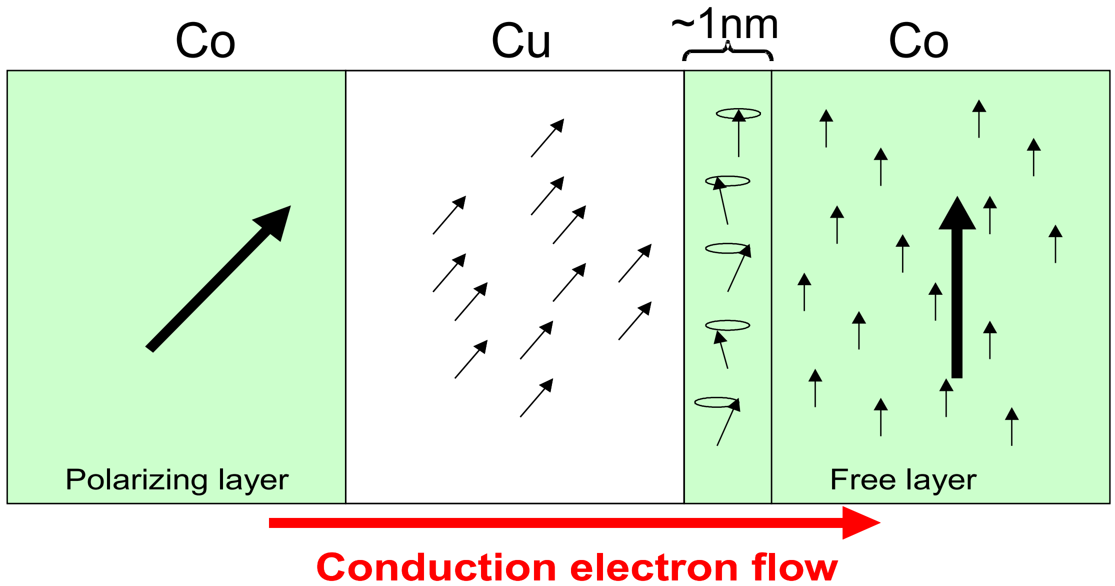



# Physical origin of Spin transfer

**GMR, TMR**:
Acting on electrical current via the magnetization orientation

**Spin transfer is the reciprocal effect**:
Acting on the magnetization via the spin polarized current

**Diffusive picture**:




*M.D.Stiles et al, Phys.Rev.B.66, 014407 (2002)*

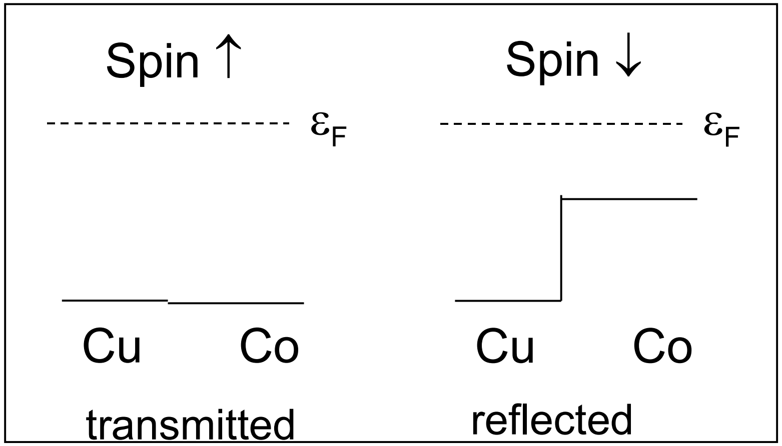
Reorientation of the direction of polarization of current via incoherent precession/relaxation of the electron spin around the local exchange field

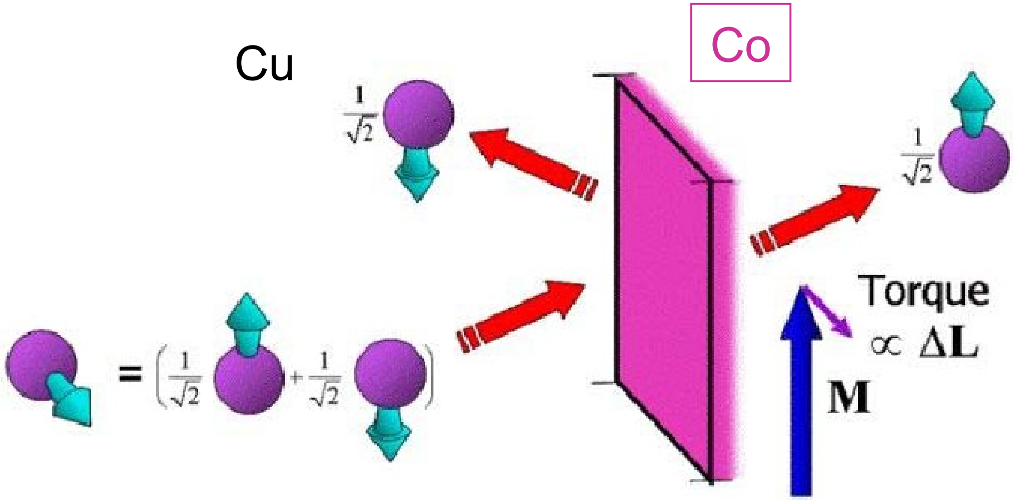
$\Rightarrow$ **Torque on the F magnetization**

# Physical origin of Spin transfer (cont'd)

**Ballistic QM picture:**

Schematic band structure of Cu/Co :




Reorientation of the direction of polarization of the spin current as the spin polarized electrons penetrate in the magnetic layer :

⇒ **Torque on F magnetization**

# Physical origin of Spin transfer (sd model)

Consider two populations of electrons:
-1)s conduction electrons (spin-polarized)
-2) d more localized electrons responsible for magnetization

The spin-polarized conduction electrons and localized d electrons interact by exchange interactions

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Pauli matrices vector

Hamiltonien of propagating s electrons: $$H = \frac{p^2}{2m} + U(r) - J_{sd}(\vec{\boldsymbol{\sigma}}.\mathbf{S_d})$$

Kinetic   Potential   Unit vector//M

Exchange sd

In non-colinear geometry, exchange of angular momentum takes place between the two populations of electrons but total angular moment is conserved.

$$\text{Torque on } \mathbf{S}_d \text{ due to s electrons} = \frac{J_{sd}}{\hbar} \mathbf{S_d} \times \mathbf{s}(r,t)$$

**s**=local spin-density of s electrons

# Physical origin of Spin transfer (sd model) (cont'd)

Electron wave-function $\psi(r,t)\ \begin{cases}\psi^{\uparrow}(r,t)\\ \psi^{\downarrow}(r,t)\end{cases}$

Local spin density at r and t : $\mathbf{s}(r,t)=\psi^{*}(r,t)\frac{\hbar}{2}\vec{\boldsymbol{\sigma}}\psi(r,t)$

Temporal variation of local spin density: $\frac{d}{dt}\mathbf{s}(r,t)=\frac{\hbar}{2}\left[\frac{d}{dt}\psi^{*}\vec{\boldsymbol{\sigma}}\psi+\psi^{*}\vec{\boldsymbol{\sigma}}\frac{d}{dt}\psi\right]$ (1)

Schrödinger equation : $\frac{d}{dt}\psi(r,t)=-\frac{i}{\hbar}H\psi(r,t)$ (2)

Substitution (2) in (1) : $\frac{d}{dt}\mathbf{s}(r,t)=\frac{1}{2i}\left[\psi^{*}\vec{\boldsymbol{\sigma}}H\psi+(H\psi)^{*}\vec{\boldsymbol{\sigma}}\psi\right]$

$\ldots\Rightarrow$ $\frac{d}{dt}\mathbf{s}(r,t)=-\nabla\mathbf{J}_{\mathbf{s}}(r,t)+\frac{J_{sd}}{\hbar}\mathbf{S}_{\mathbf{d}}\times\mathbf{s}(r,t)$

Precession of s spin density around $S_d$

$\mathbf{J}_{\mathbf{s}}$ Is the spin density current
3x3 tensor
Spin space x real space

$$\mathbf{J}_{\mathbf{s}}=-\frac{\hbar^{2}}{2m}\mathrm{Im}\left[\psi^{*}(r,t)\vec{\boldsymbol{\sigma}}\otimes\nabla_{\mathbf{r}}\psi(r,t)\right]$$

# Physical origin of Spin transfer (sd model) (cont'd)

In steady state (ballistic systems):

$$\text{Spin - transfer torque} = \left.\frac{\partial \mathbf{S_d}}{\partial t}\right|_{transfer} = \nabla \mathbf{J_s}(r,t) = \frac{J_{sd}}{\hbar}\mathbf{S_d} \times \mathbf{s}(r,t)$$

**The exchange interaction between spin-polarized s electrons and more localized d electrons is responsible for spin-torque. This interaction yields a precessional motion of spin-density of s electrons around the local magnetization. In ballistic regime, the spin-transfer torque is also equal to the divergence of spin-current**

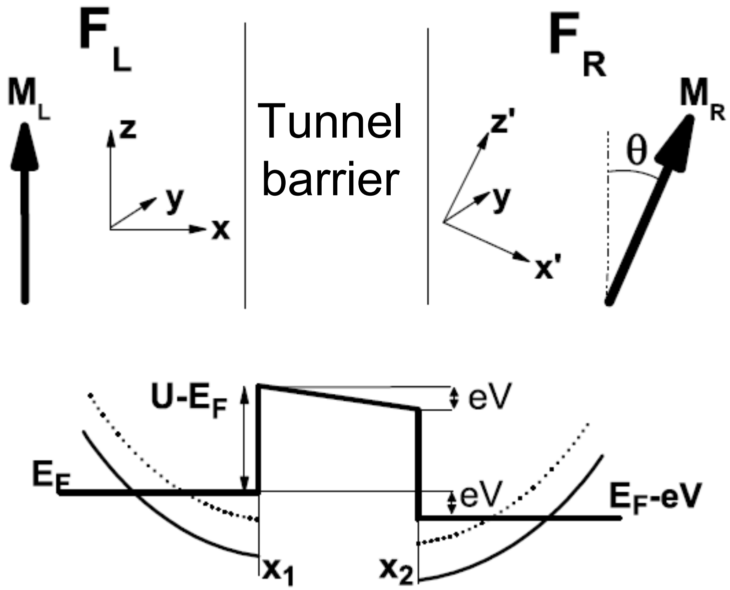
In diffusive systems: $$\left.\frac{\partial \mathbf{S_d}}{\partial t}\right|_{transfer} = \nabla \mathbf{J_s}(r,t) + \frac{\mathbf{s}}{\tau_{SF}} = \frac{J_{sd}}{\hbar}\mathbf{S_d} \times \mathbf{s}(r,t)$$

Takes into account the spin-memory loss by scattering with spin lifetime $\tau_{SF}$

LLG equation for magnetization dynamics with spin-transfer torque:

$$\frac{\partial \mathbf{S_d}}{\partial t} = -\gamma\, \mathbf{S_d} \times \left(\mathbf{H_{eff}} + \frac{J_{sd}}{\hbar \mu_B}\mathbf{m}\right) + \alpha\, \mathbf{S_d} \times \frac{\partial \mathbf{S_d}}{\partial t}$$

# Physical origin of Spin transfer (sd model) (cont'd)




$$\mathbf{T} = \frac{J_{sd}}{\mu_B} \mathbf{M}_L \times \mathbf{m}$$

$$\mathbf{T} = \frac{J_{sd}}{\mu_B} \left[ \underbrace{m_x \mathbf{M}_L \times \mathbf{M}_R}_{} - \underbrace{m_y \mathbf{M}_L \times \left( \mathbf{M}_L \times \mathbf{M}_R \right)}_{} \right]$$

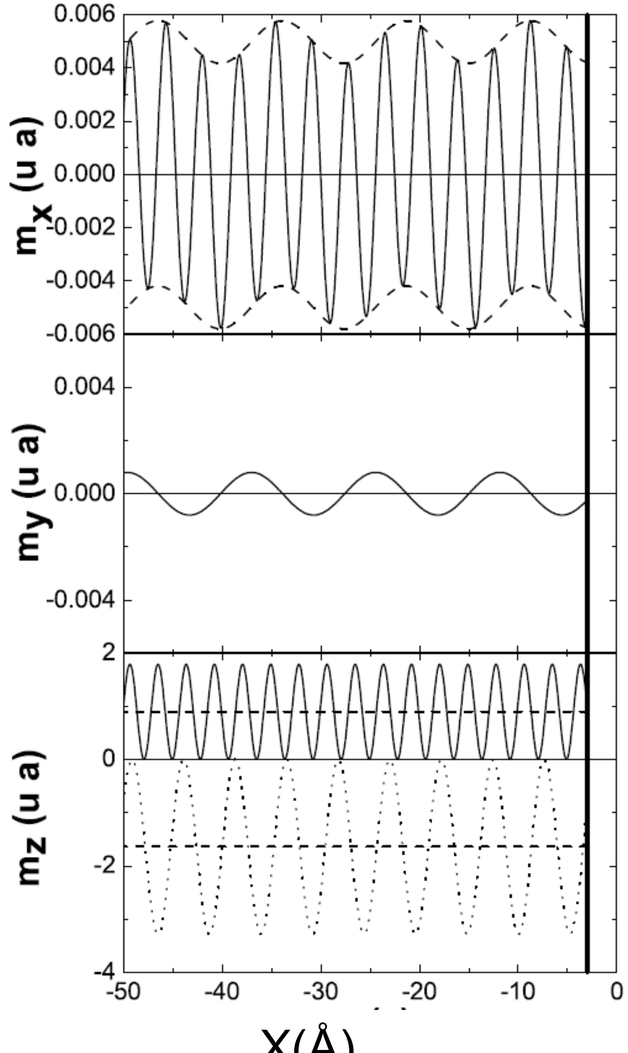
Perpendicular torque or interlayer exchange coupling (IEC)

In-plane torque or Slonczewski torque

$m_x$, $m_y$ can be fully calculated by solving Schrodinger equation in non-colinear geometry

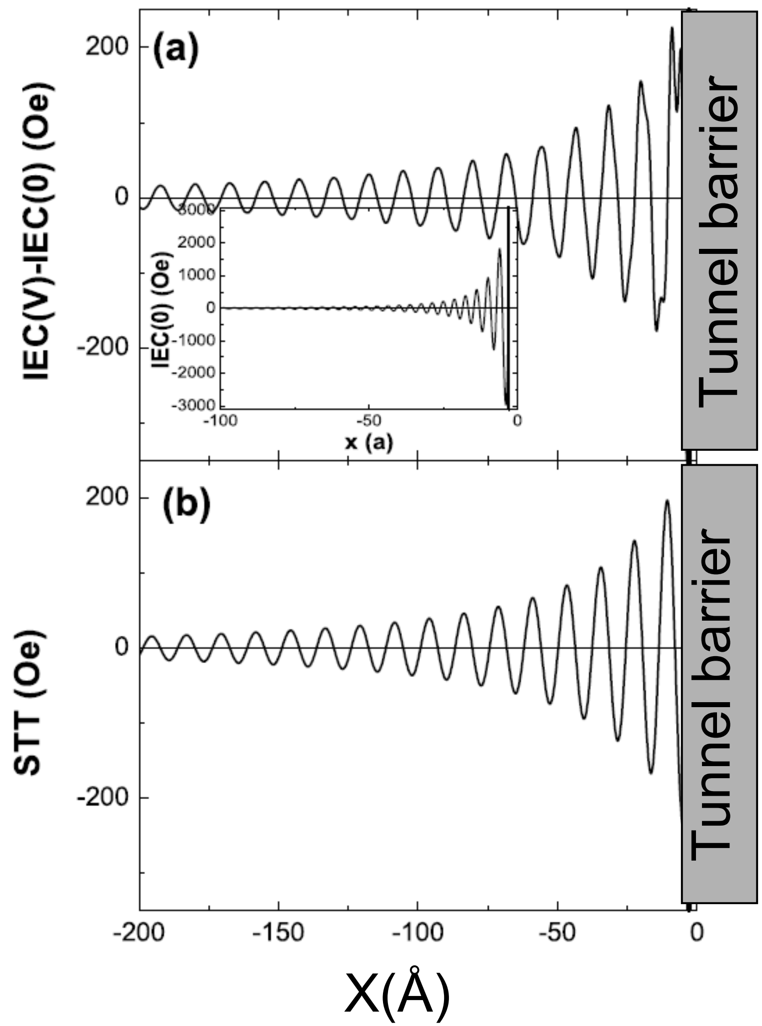
# Physical origin of Spin transfer (sd model) (cont'd)

Out-of equilibrium magnetization due to tunneling electrons with normal incidence on the barrier




Coherent oscillations due to spin precession

Resulting local in-plane and perpendicular torque




Damped oscillations due to averaging on incidence

## Two terms in spin-transfer: perpendicular + in-plane torques

$$\frac{dM}{dt} = -\gamma M \times \left(H_{eff} + bI.M_p\right) + \gamma aI.M \times \left(M \times M_p\right) + \alpha M \times \frac{dM}{dt}$$

Effective field term (conserves energy)

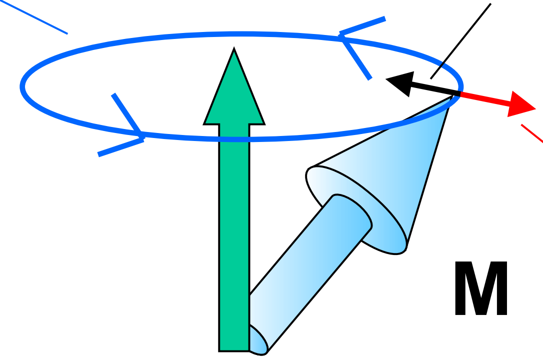
Spin-torque term: ~damping (or antidamping) term

Gilbert Damping term

( Modified LLG)

Not conservative

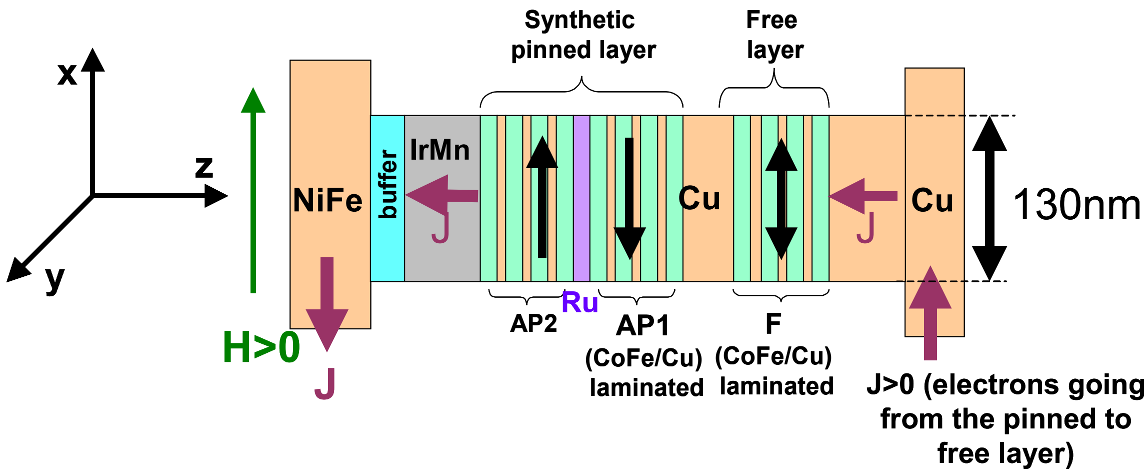
a and b are coefficients proportional to the spin polarization of the current




Effective term seems weak in metallic pillars (~10% of spin-torque term) but more important in MTJ (~30 to 50% of ST term)

# Current induced switching: experiments

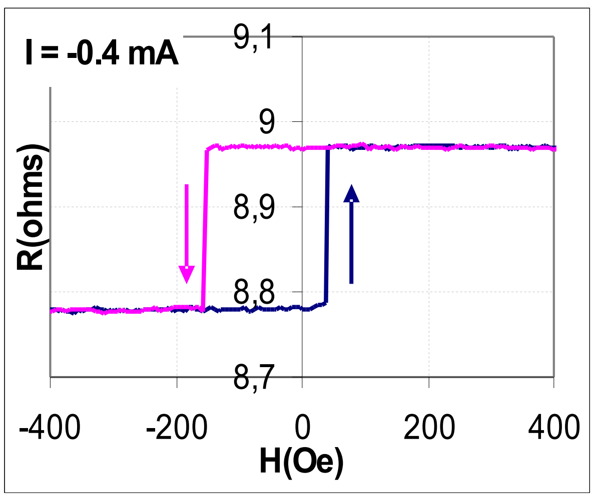
Experiments conducted on nanopillars (d<150nm) to minimize Oersted field effect



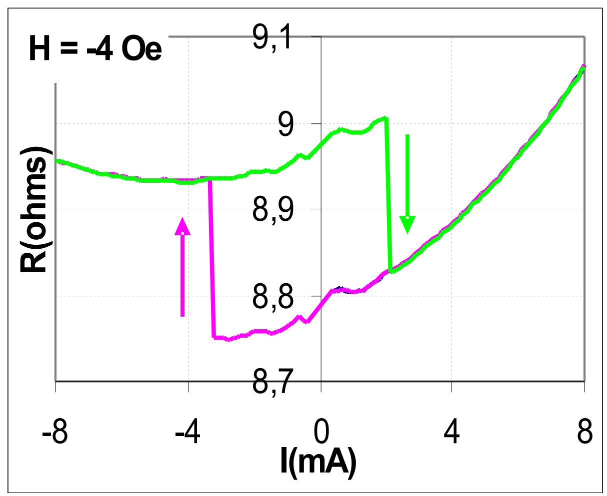

Samples from Headway

H>0 favors AP
J>0 favors P

## Field scan



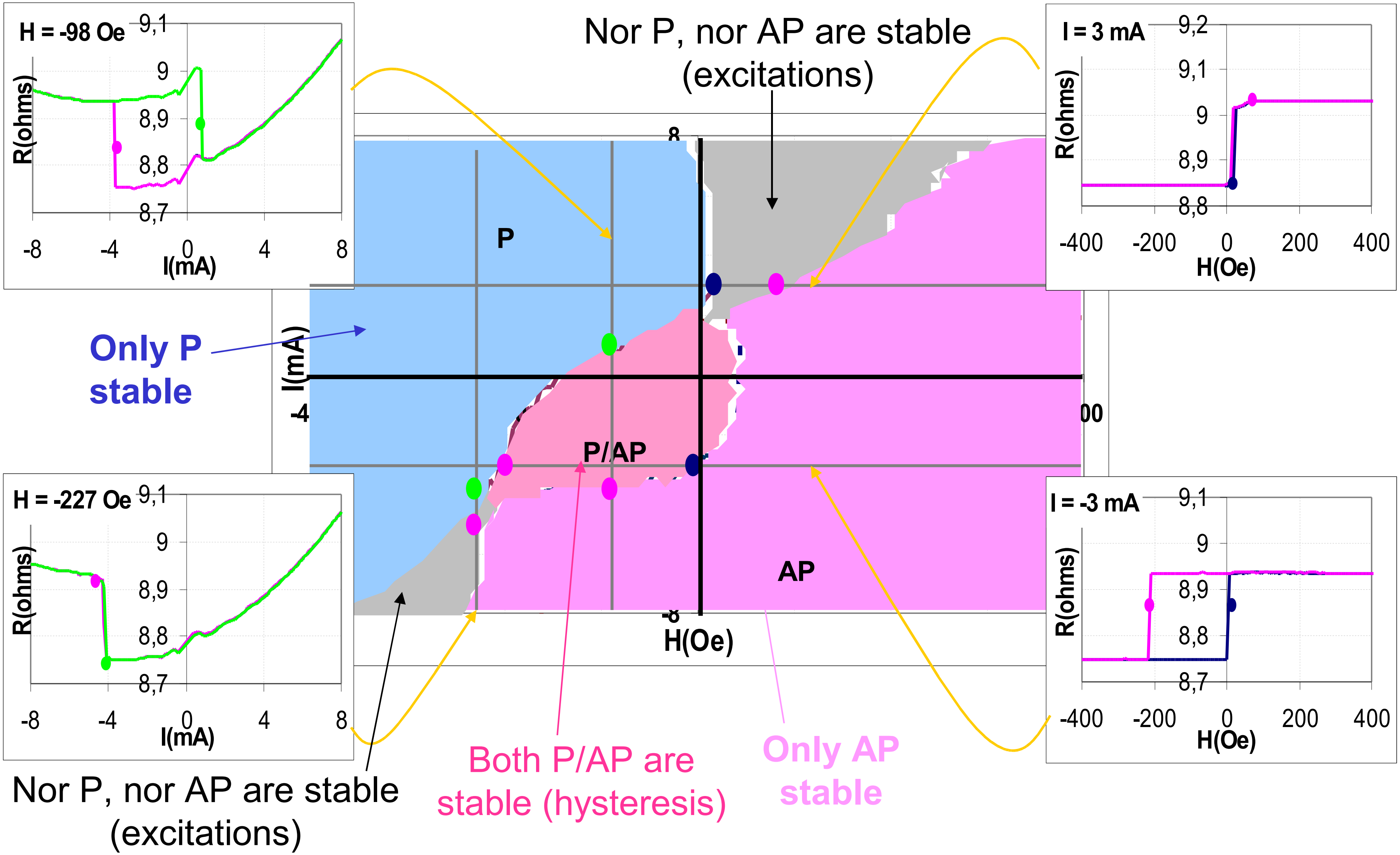

## Current scan



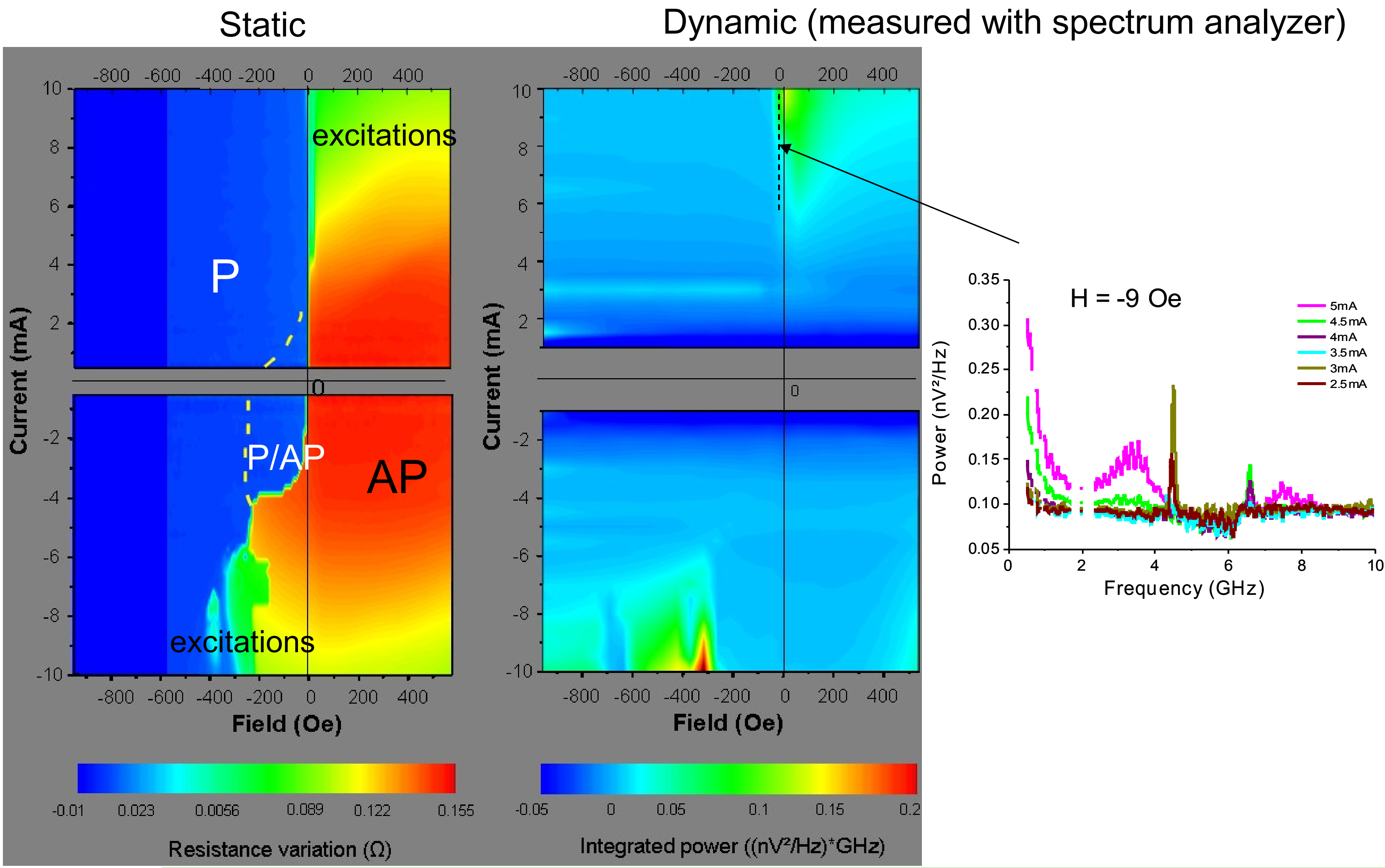

(jc = 1.18*10 A/cm²

(jc = 1.95*10 A/cm²

# Current induced switching: Stability phase diagram



# Steady states excitations when field and spin-transfer torque have opposite influence



# Charge current and spin current in complex geometry

## In diffusive limit:

**Charge current :** $\mathbf{J_e} = 2\sigma\nabla\varphi - \dfrac{2\beta\sigma}{\nu}(\mathbf{M},\nabla\mathbf{m})$

**Spin current :** $\mathbf{J}_m = 2\sigma\beta(\mathbf{M}\nabla\varphi) - \dfrac{2\sigma}{\nu}\nabla\mathbf{m}$

$$div\mathbf{J_e} = 0$$

$$div\mathbf{J_m} + \frac{2\sigma}{\nu\, l_J^2}(1-\beta^2)(\mathbf{M}\times\mathbf{m}) + \frac{2\sigma}{\nu\, l_{sf}^2}(1-\beta^2)\mathbf{m} = 0$$

Diffusion of charge (with conservation of charge)

Diffusion of spin (without spin conservation due to spin-torque and spin-relaxation

4 Unknowns: | $\varphi \quad m_x \quad m_y \quad m_z$

4 Equations: 1 diffusion of e + 3 diffusion of m

lSF=spin-diffusion length
lJ=spin-reorientation length

**Spin-torque :**

$$\mathbf{T} = \frac{2\sigma}{\nu\, l_J^2}(1-\beta^2)(\mathbf{M}\times\mathbf{m})$$

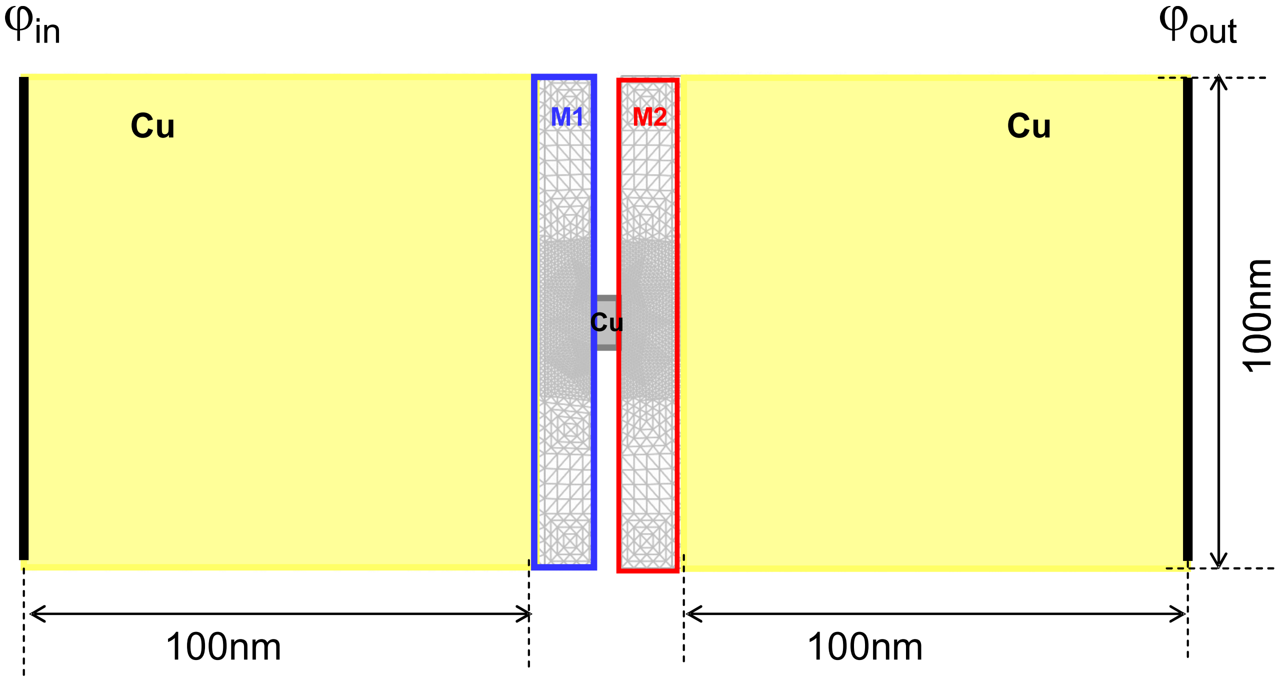
Torque exerted by the local spin-accumulation on the local magnetization because of their exchange interaction

Contains both Slonczewski (in-plane) and field-like (perpendicular) torque components

S.Zhang, et al, PRL 88, 236601 (2002); M.D. Stiles, A. Zangwill, J. Appl. Phys. 91 (2002) 6812; M.D. Stiles and A. Zangwill, Phys. Rev. B 66, 014407, 2002; A. Shpiro, P.M. Levy, S. Zhang, Phys. Rev. B 67 (2003) 104430

# Finite element approach for solving transport equations

Approach built around a finite element solver.
Calculation of the solutions of charge and spin-diffusion equations in FEM approximation



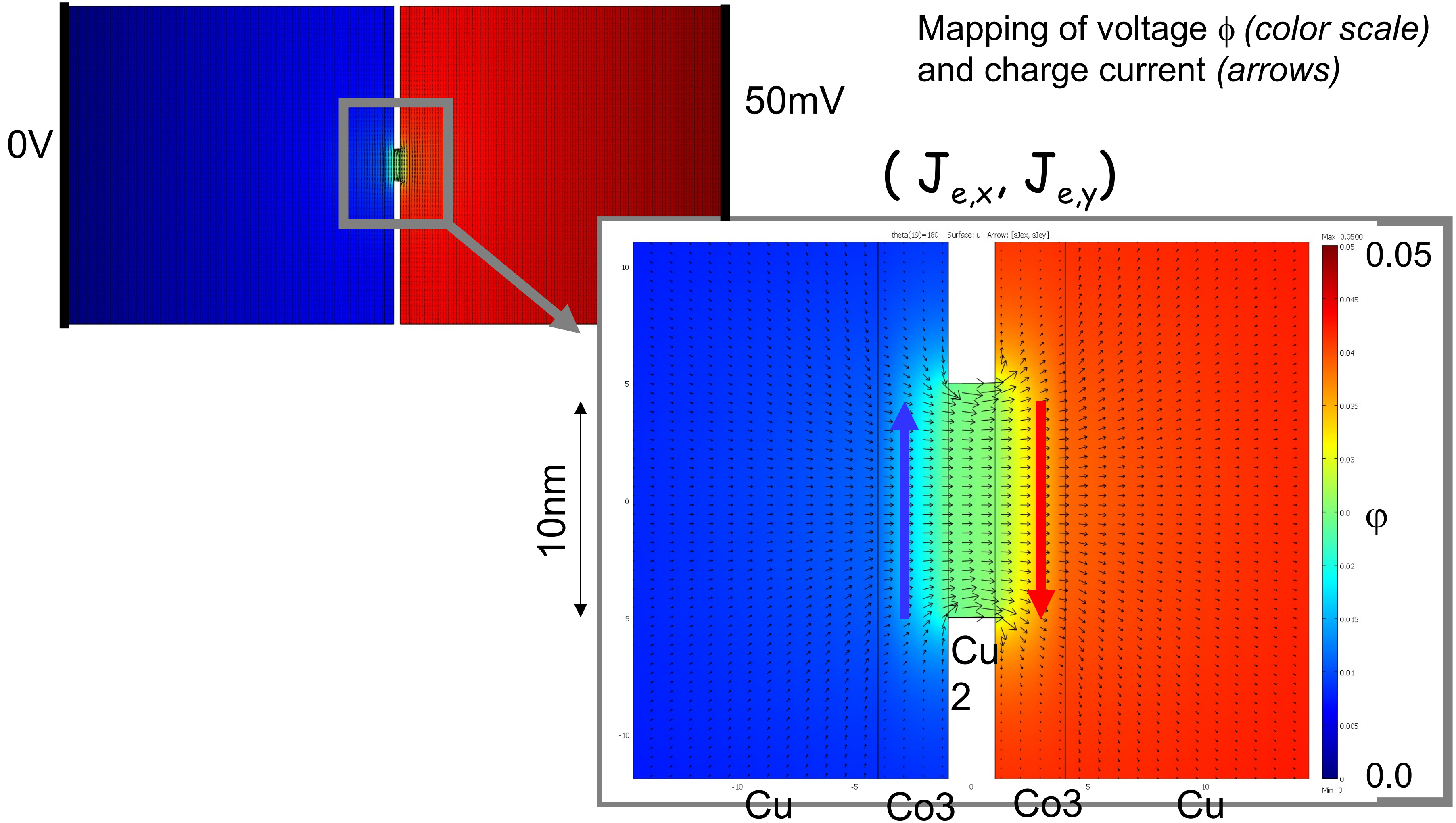

Typically
20 000 nodes

2D or 3D possible but 3D requires large computer memory

# 2D CPP structure with nanoconstriction

Cu 100nm /Co 3nm/Cu 2nm/Co 3nm/Cu 100nm

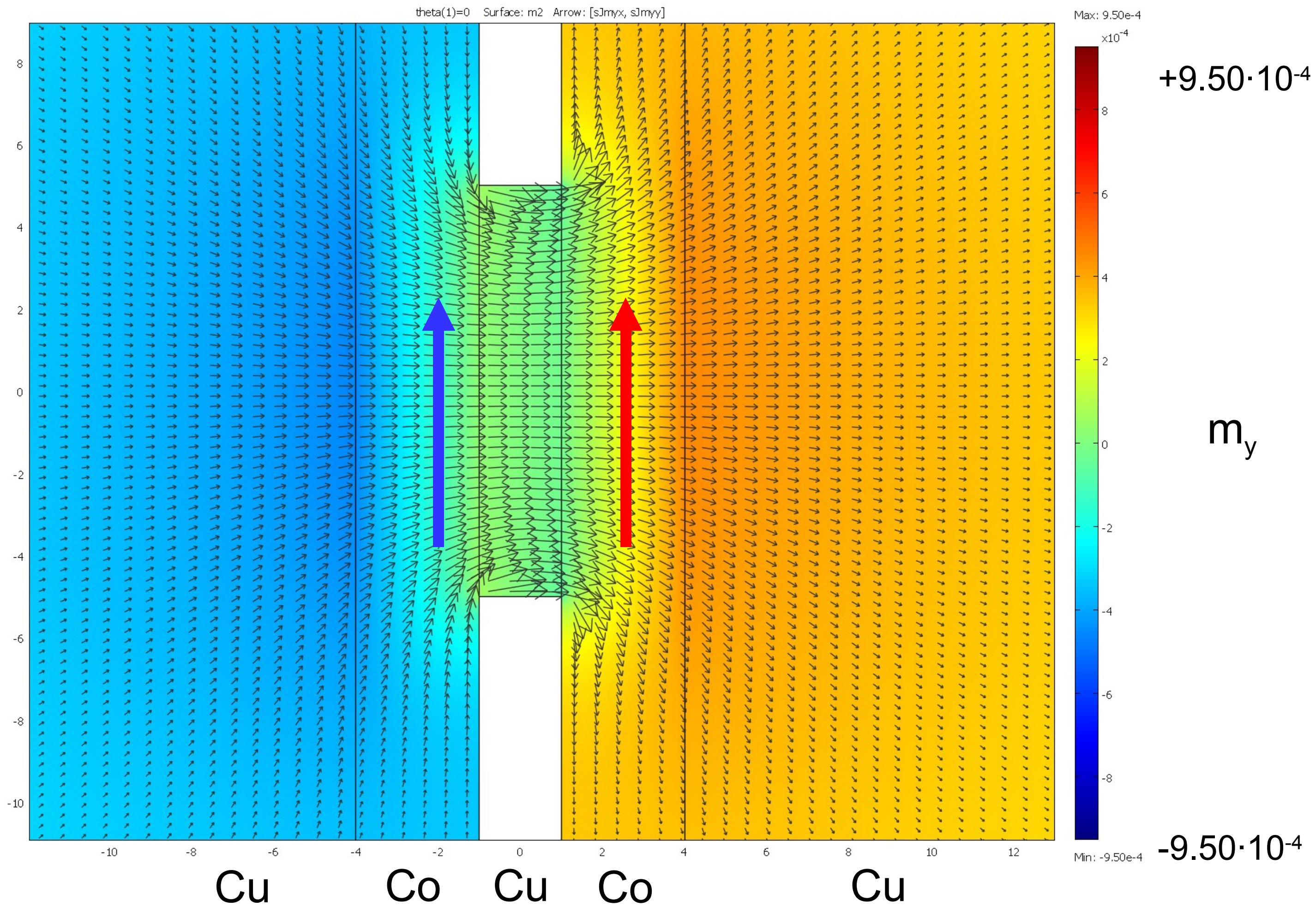
Mapping of voltage ϕ *(color scale)* and charge current *(arrows)*



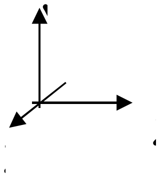
# 2D CPP structure with nanoconstriction

## y-spin-accumulation and y-spin-current $(J_{m,yx}, J_{m,yy})$

**Parallel** state

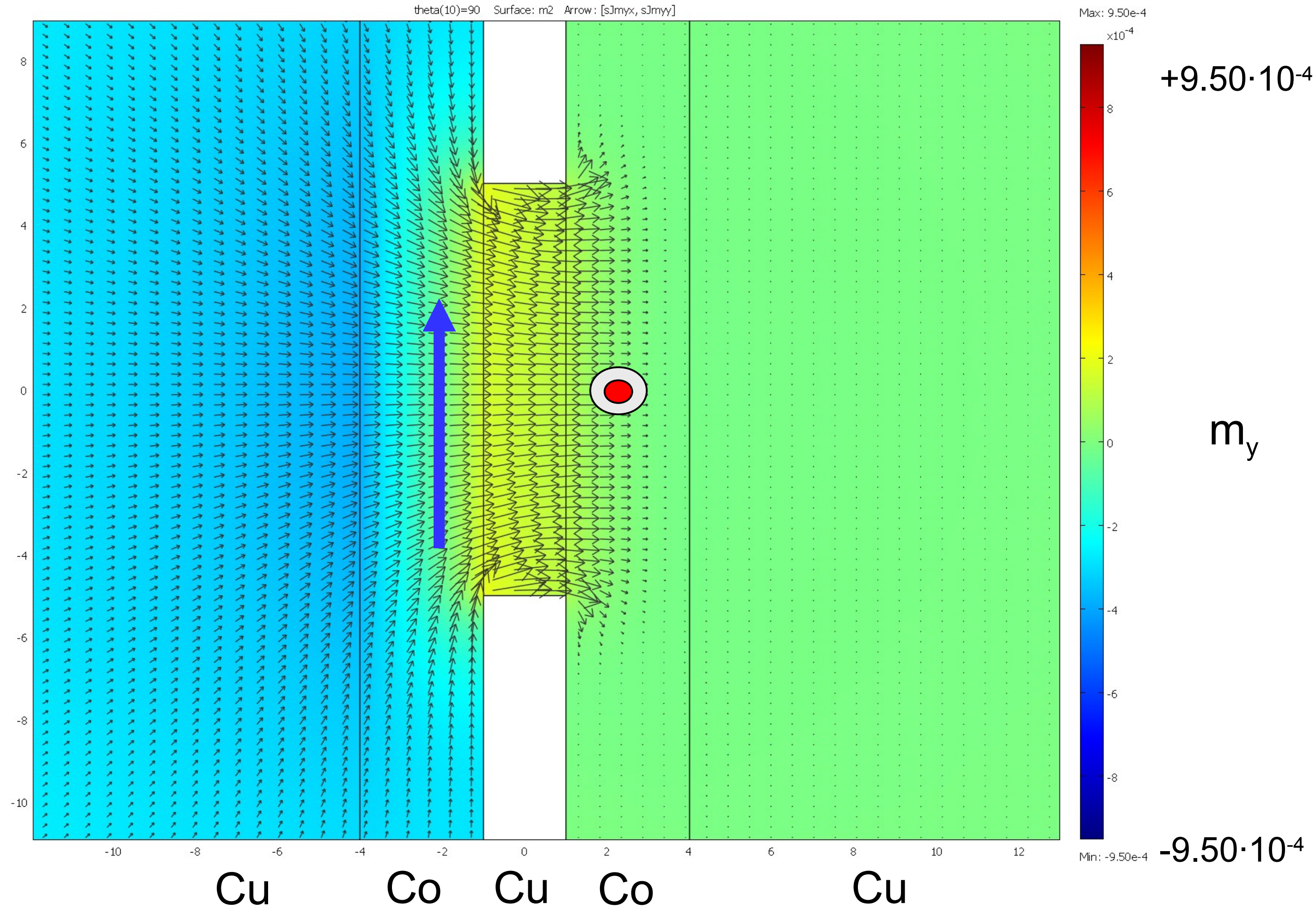


# 2D CPP structure with nanoconstriction



## y-spin-accumulation and y-spin-current $(J_{m,yx}, J_{m,yy})$

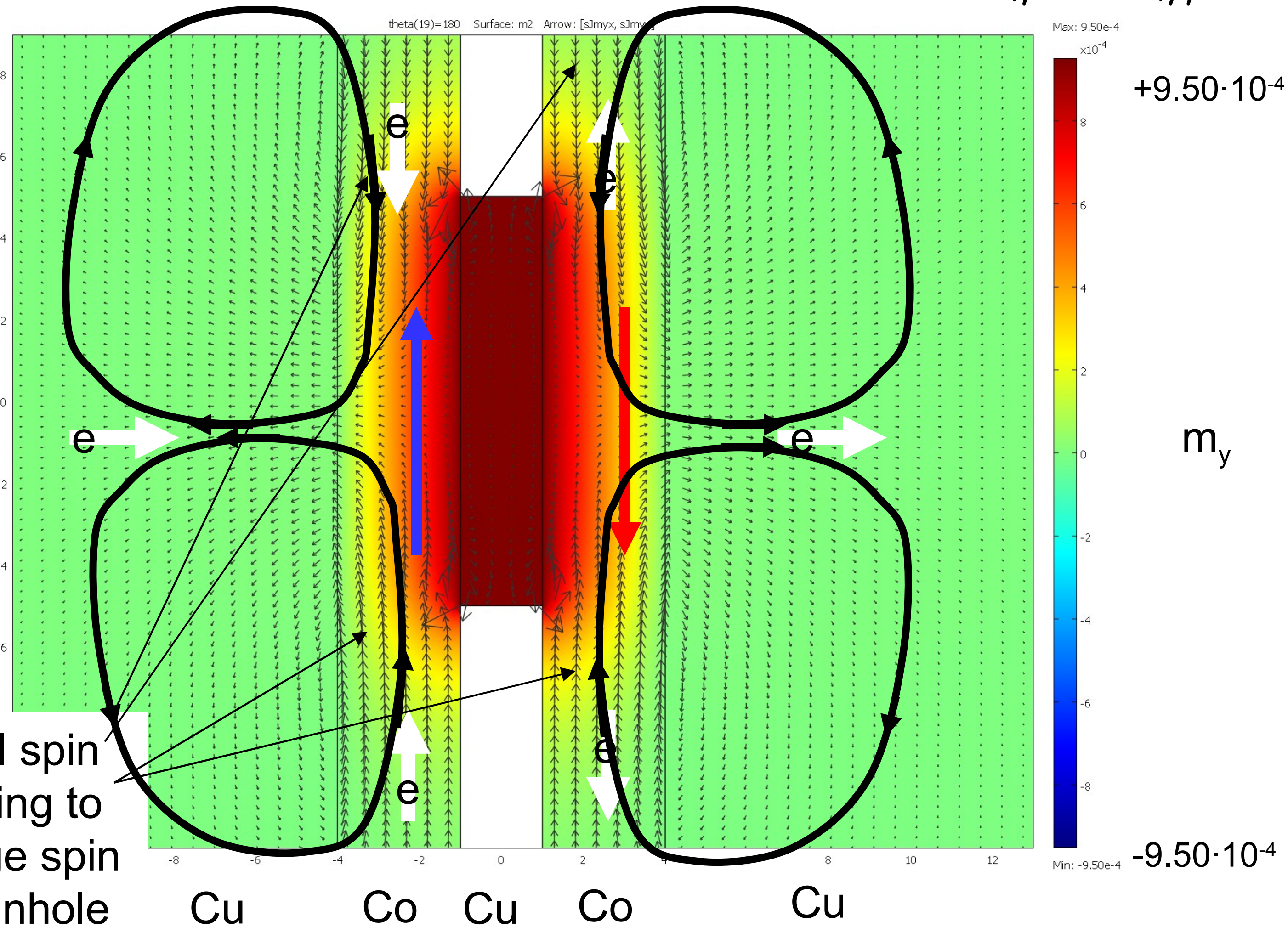
**Perpendicular** state



# 2D CPP structure with nanoconstriction

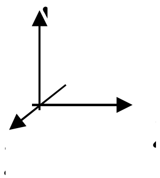
y-spin-accumulation and y-spin-current $(J_{m,yx}, J_{m,yy})$

**Antiparallel** state

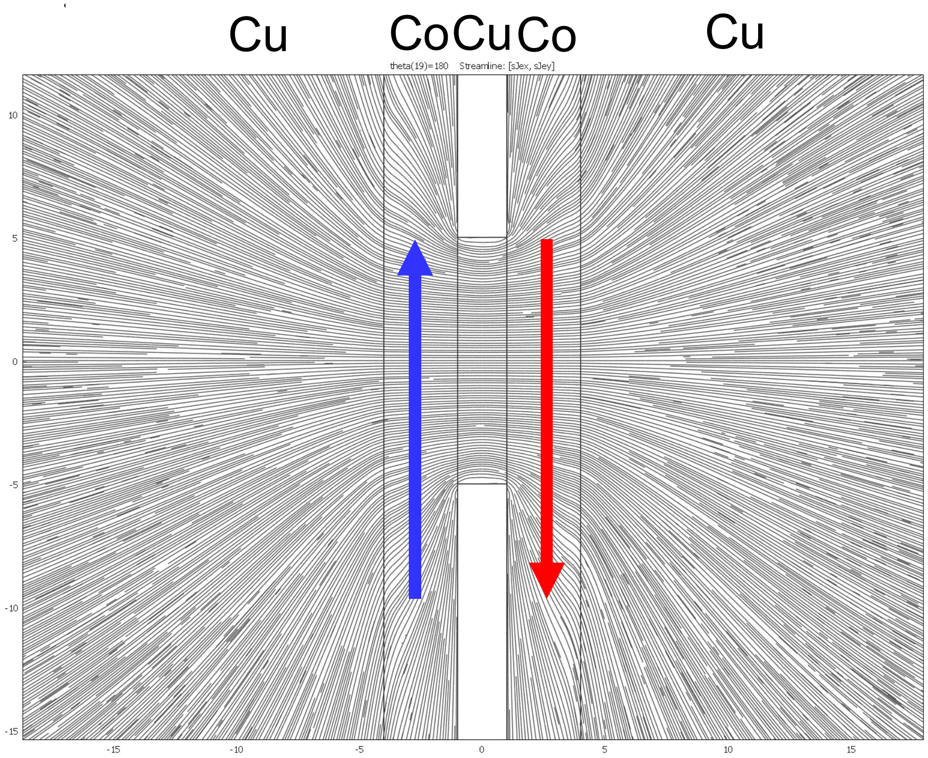



Very strong lateral spin ↑ current converging to pinhole⇒very large spin accumulation in pinhole

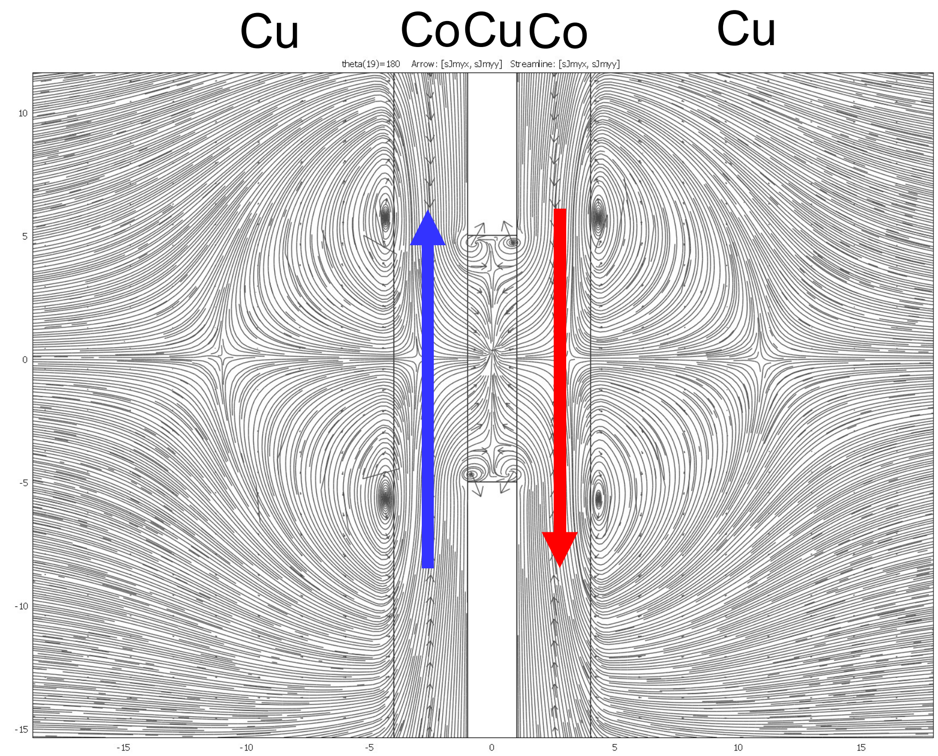
# Charge and y-spin currents in AP configuration



## Antiparallel state




Streamline –charge current




Streamline –spin current

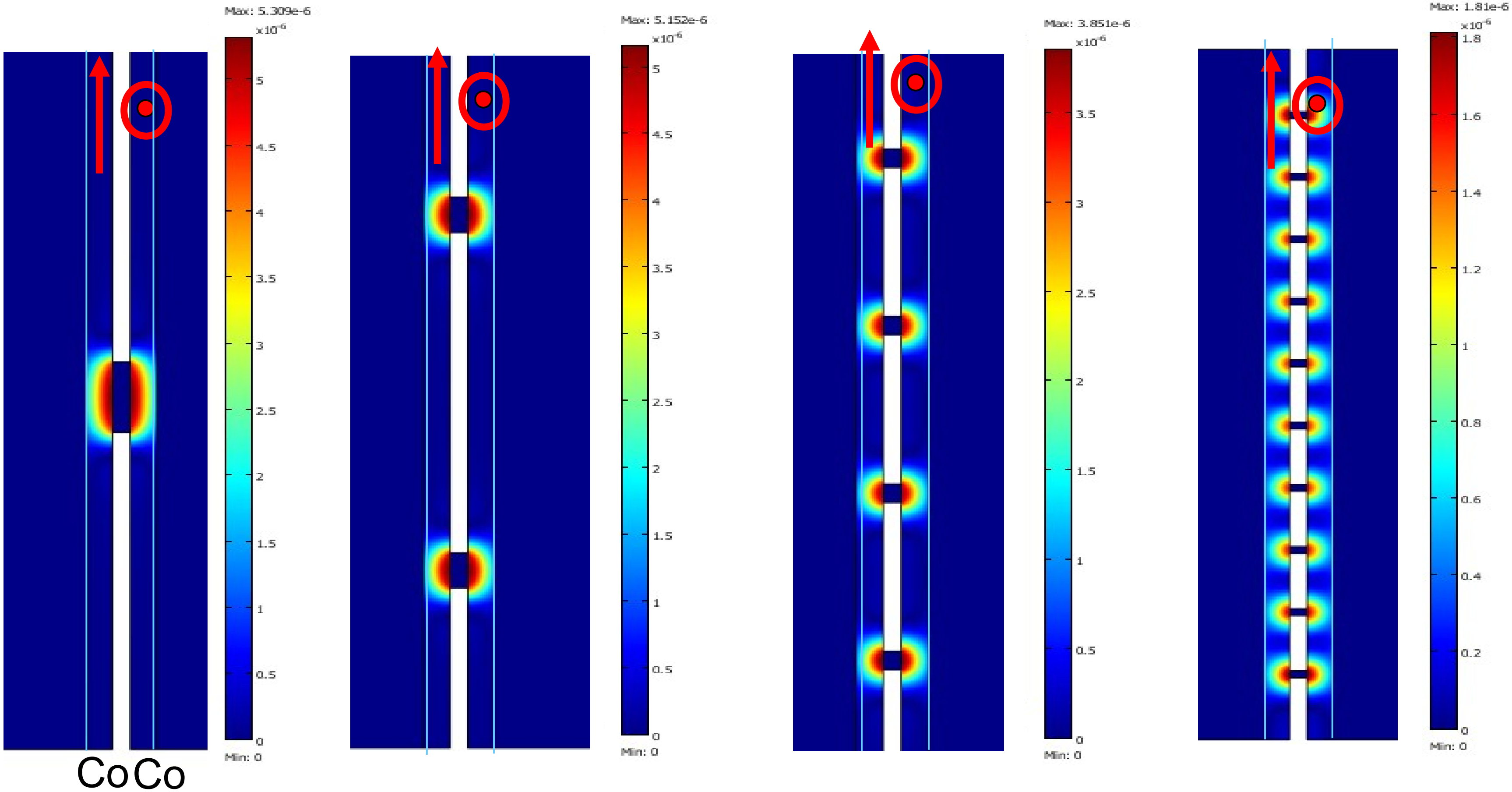
$(J_{m,yx}, J_{m,yy})$

**Striking apparition of vortices spin-current close to the antiparallel state**

SF

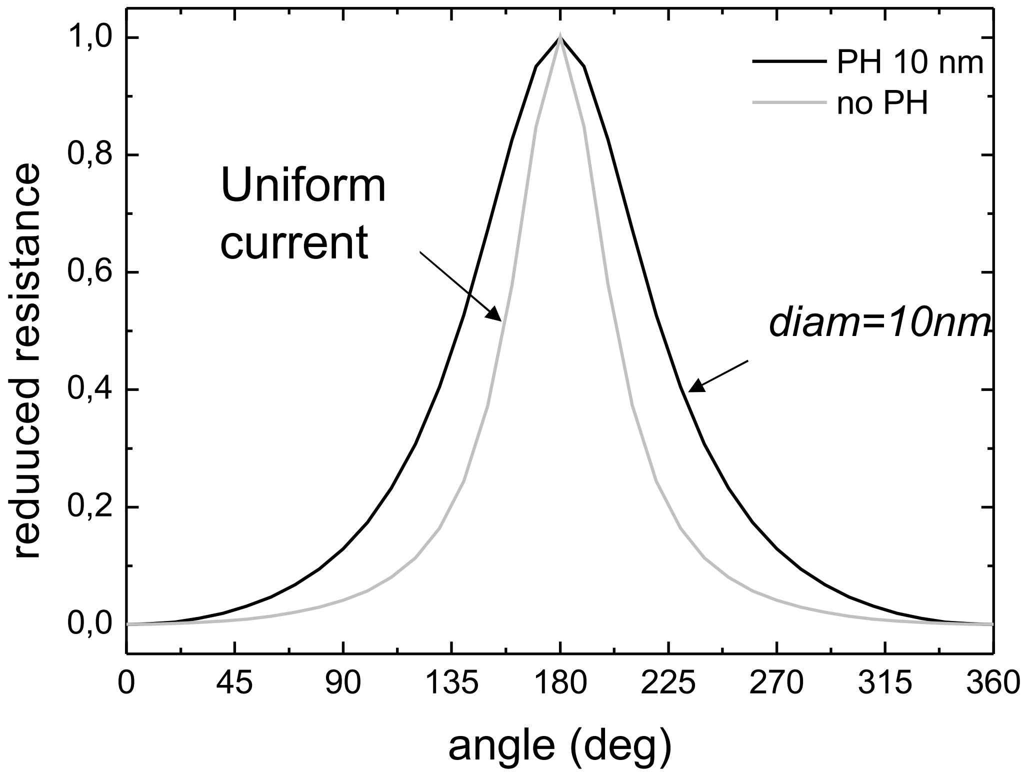
# Multiple nanoconstrictions (spin-torque amplitude)

Color scale=in-plane spin-torque amplitude for 90° configuration




Spin-torque exerted locally at the exit of pinholes. Aside from the pinhole, quiet magnetization which can quench the magnetic excitations generated by the spin-torque. There is an optimum pinhole density.

# Angular variation of CPP-GMR with nanoconstriction



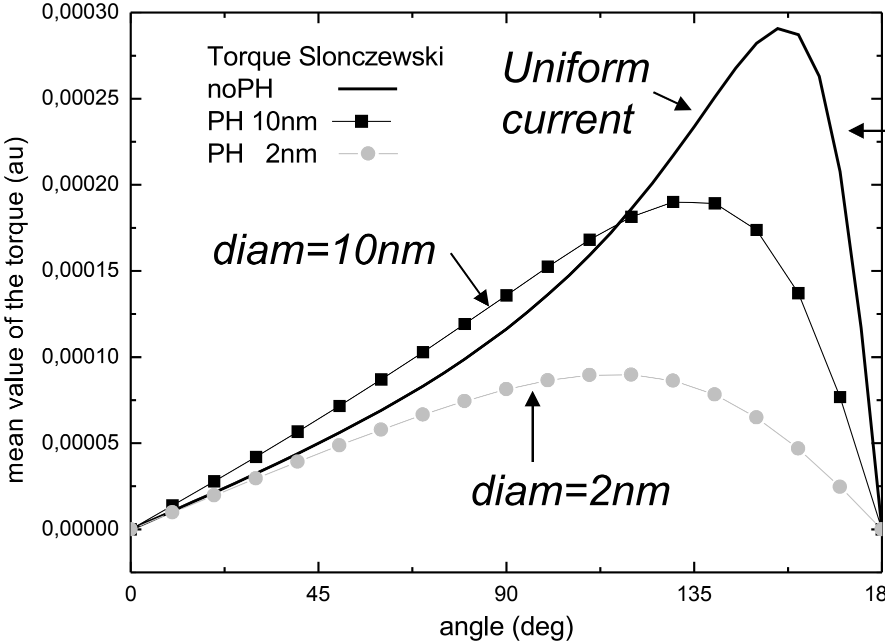

| | $\chi$ |
|---|---|
| No PH | 20.5 |
| PH 10nm | 5.5 |

$$r = \frac{1-\cos^2\theta}{1+\chi\cos^2\theta}$$

JC Slonczewski JMMM 247, 324 (2002)

No particular features observed on angular variation of CPP-GMR associated with smooth/turbulent spin-current.
Angular variation of CPP GMR through nanoconstriction well represented by Slonczewski's expression

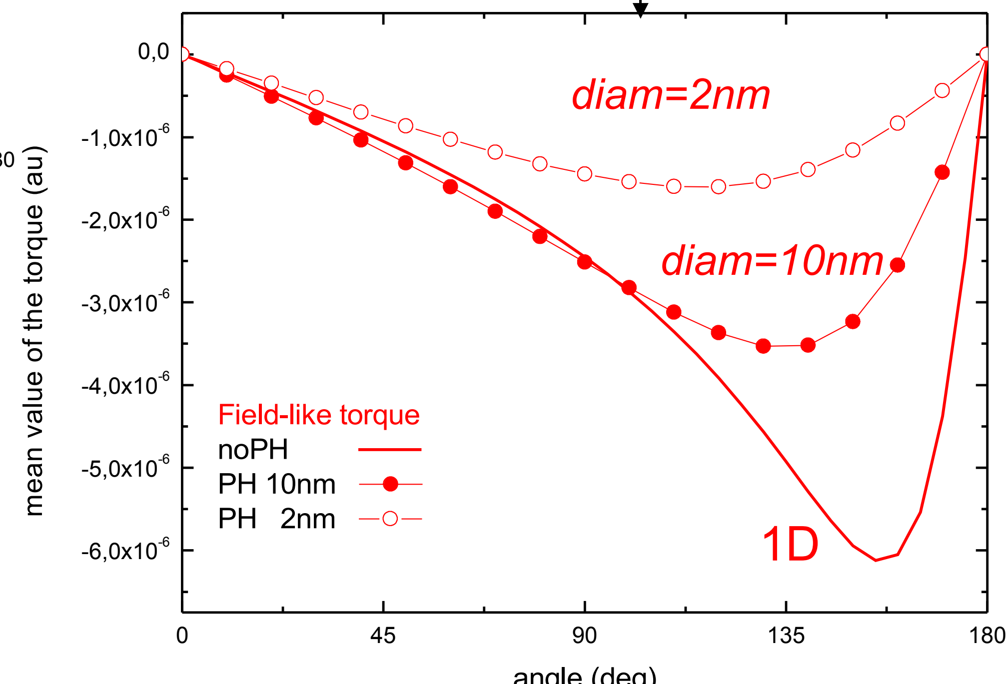
# Angular variation of spin-torque with nanoconstriction




**In-plane torque**

**Perpendicular torque**

2 orders of magnitude smaller than in-plane T




$$\tau(\theta)=\frac{\sin\theta}{\Lambda\cos^2\left(\frac{\theta}{2}\right)+\Lambda^{-1}\sin^2\left(\frac{\theta}{2}\right)}$$

| | $\Lambda$ |
|---|---|
| No PH | 4.75 |
| PH 10nm | 2.30 |
| PH 2nm | 1.60 |

*JC Slonczewski JMMM 247, 324 (2002)*

# Summary on spin-transfer torque

Due to exchange interactions between spin-polarized conduction electrons and those responsible to local magnetization.

Two terms: in-plane torque + perpendicular torque

In-plane torque acts as damping or antidamping.

If antidamping action of spin-torque larger than Gilbert damping, spin-torque pumps energy into the spin-polarized current and can induce magnetization switching or steady magnetic excitations.

Perpendicular torque acts as an effective field parallel to the spin polarization.

Perpendicular torque negligible in metallic magnetic multilayers but ~30% of in-plane torque in MTJ

# Models in spintronics (Part II)

OUTLINE :

**Spin-dependent transport in magnetic tunnel junctions**

-Introduction to tunnel effect

-magnetic tunnel junctions and tunnel MR

-Julliere model

-Slonczewski's model (free electron gas)

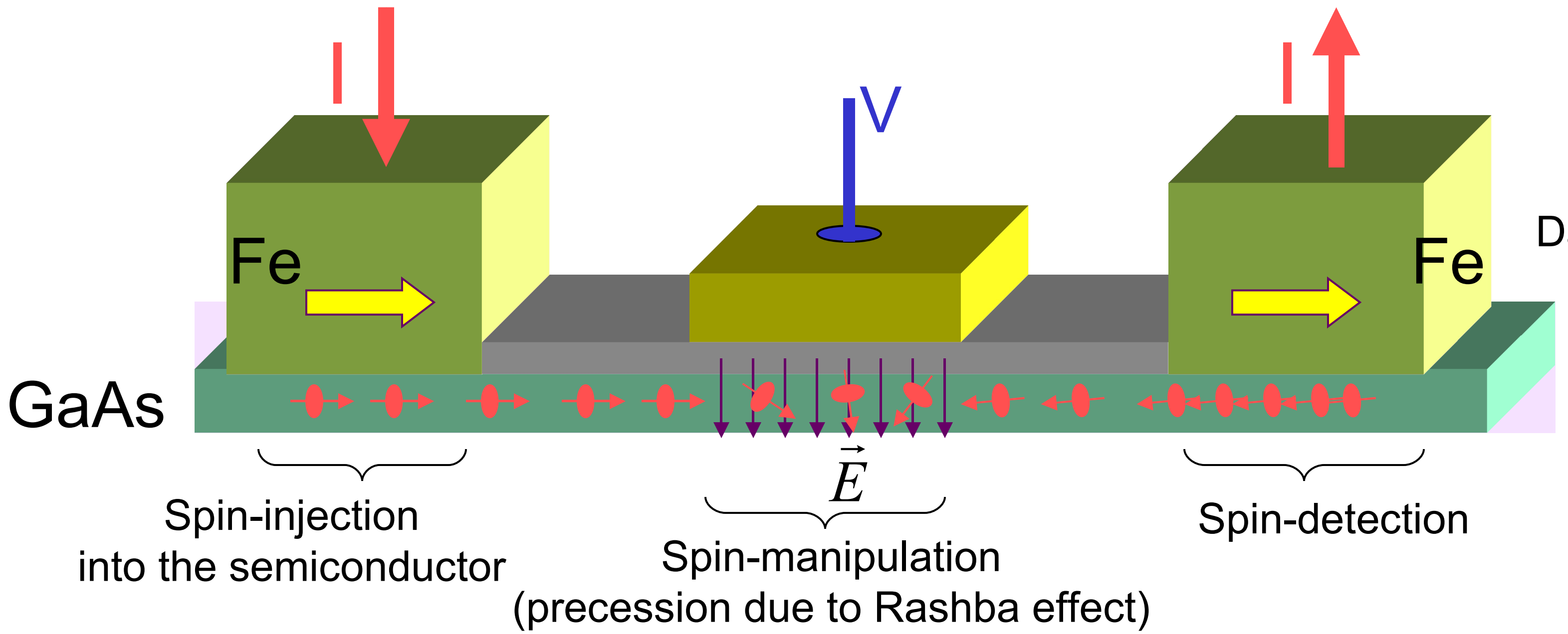
-Crystalline barrier: Spin-filtering according to symmetry of wave functions

**Spin-transfer in non collinear magnetic configuration**

-spin-torque term and effective field term

**Spin-injection in semiconductors**

# Three terminal device : Spin rotation transistor




Datta and Das, APL 1990

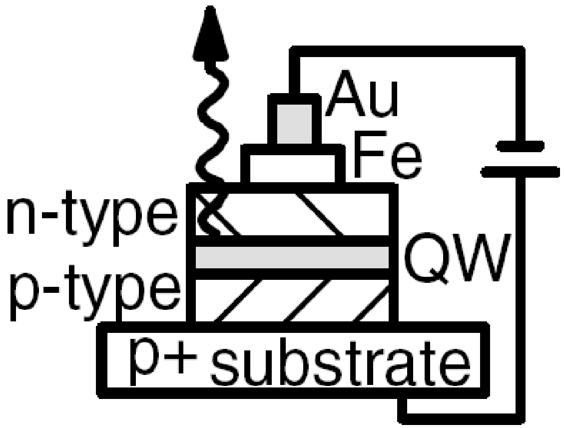
- Spin polarized electrons are injected into the semiconductor channel
- The spins are controlled by electric field (Rashba effect) or magnetic fields (id. MRAM) while they drift along the channel
- Spin-dependent collection at drain

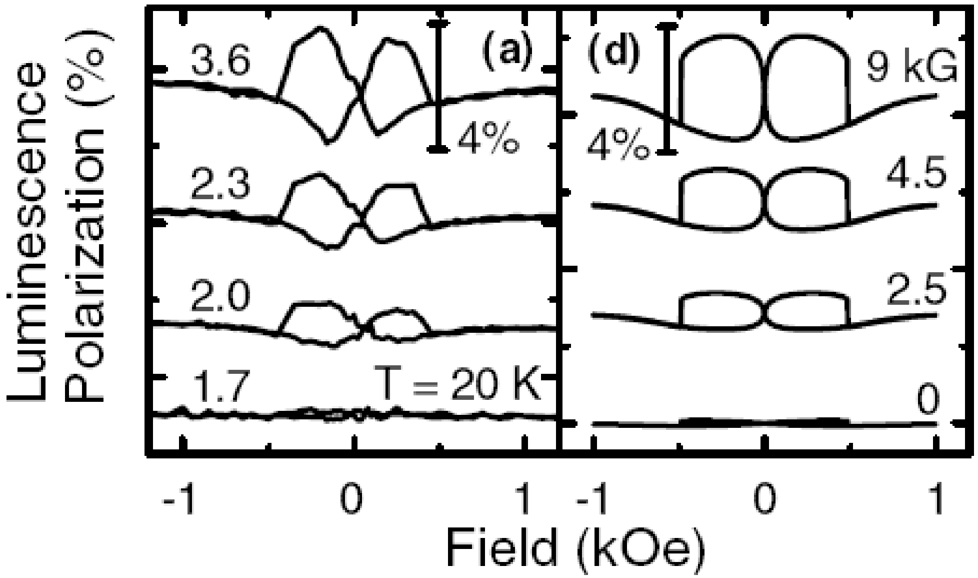
Transconductance expected to oscillate with gate voltage

# Weakly efficient spin injection directly from metal to semiconductor

J.Strand et al, Phys.Rev.Lett., 91, 036602 (2003)

Spin-LED: recombination of spin-polarized electrons and holes in a AlGaAs/GaAs/AlGaAs quantum well and emission of a circularly polarized photons. Measurement of the spin-polarization from the polarization of the emitted light.



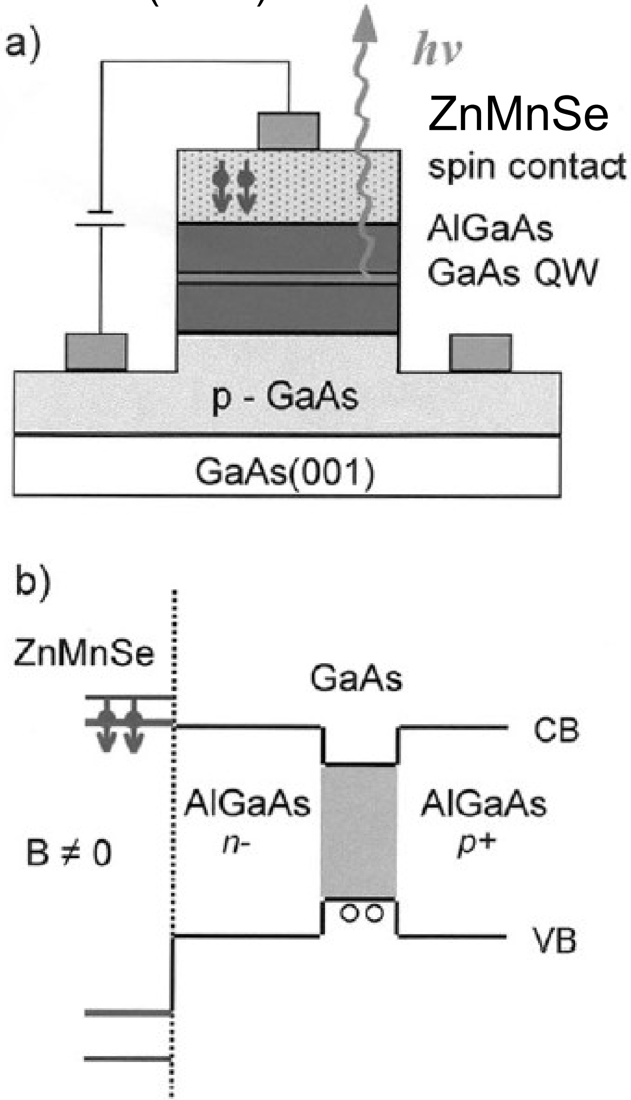



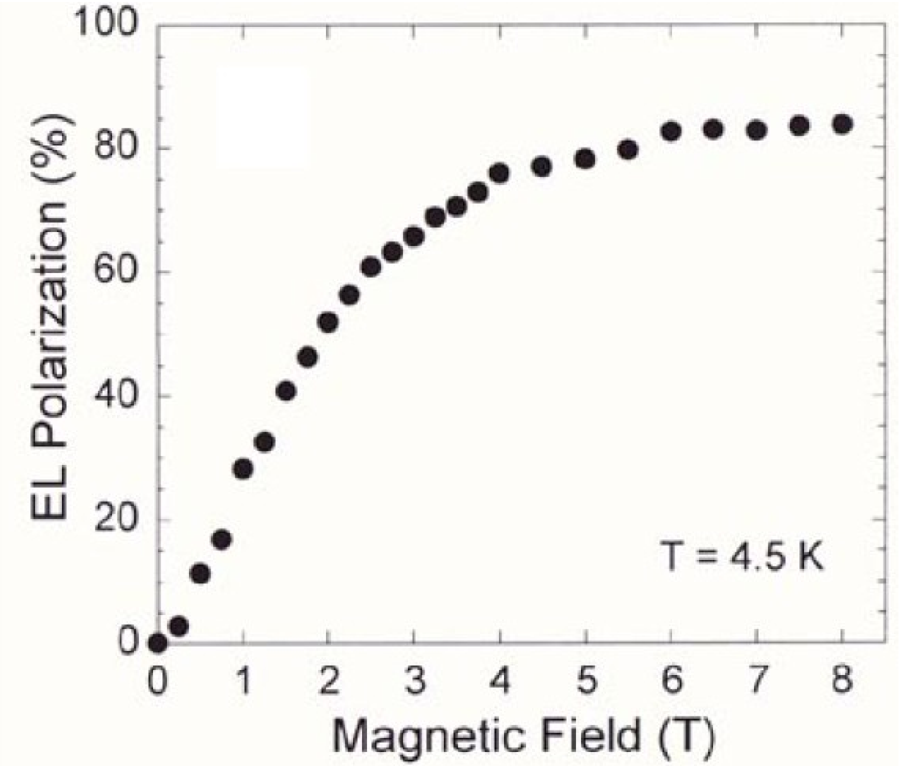

$$P_{\text{circ}} = \frac{[I(\sigma+) - I(\sigma-)]}{[I(\sigma+) + I(\sigma-)]} = \frac{0.5(n\downarrow - n\uparrow)}{(n\downarrow + n\uparrow)} = 0.5\, P_{\text{spin}}$$

Spin-polarization of only a few% observed when injecting from metal directly into a semiconductor

# Efficient spin injection from magnetic semiconductor to non-mag. semiconductor

B.Jonker et al (2004)



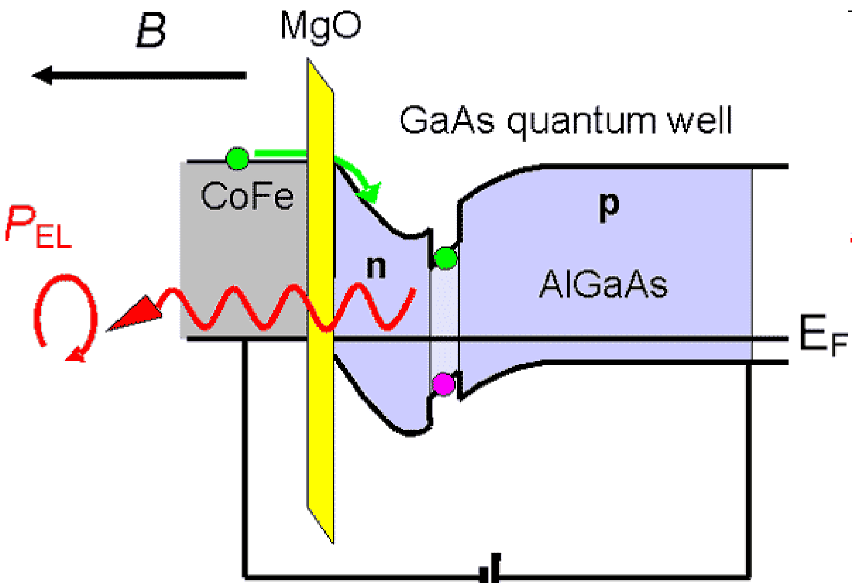

Spin-polarization of injected electrons in GaAs: 82% at 4.5K!

**Efficient spin-injection from magnetic SC**

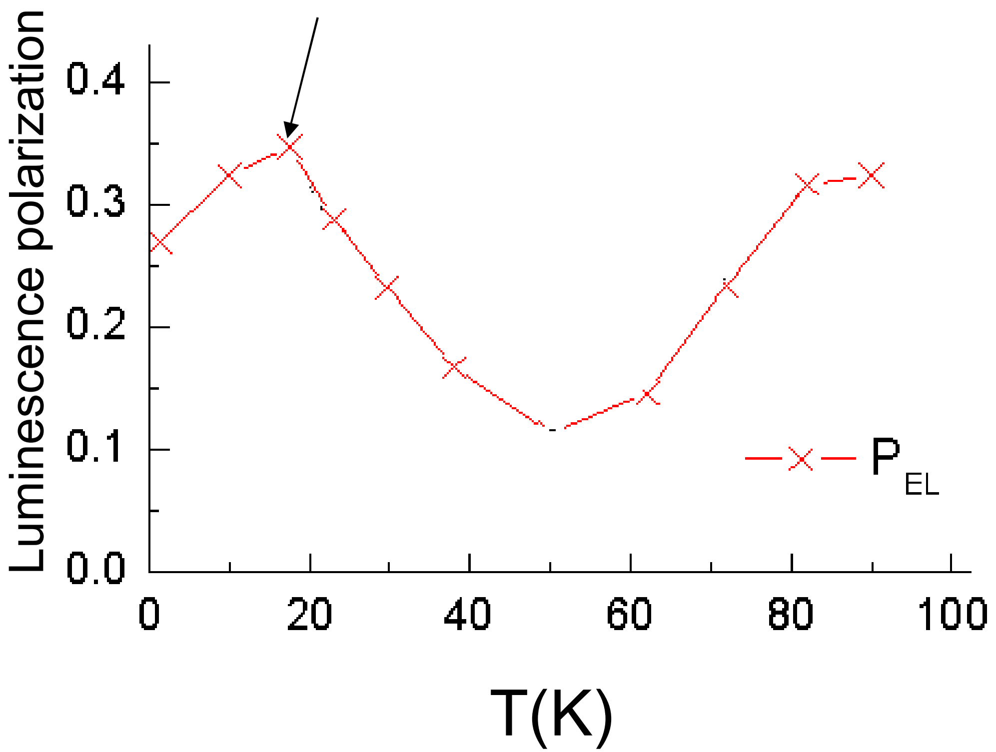
⇒Need to find magnetic SC with higher Tc

# Efficient spin injection from a ferromagnetic metal into a semiconductor through a tunnel barrier

*Safarov et al (Marseille, 2006), Alvaredo et al (IBM Zurich, 2006)*



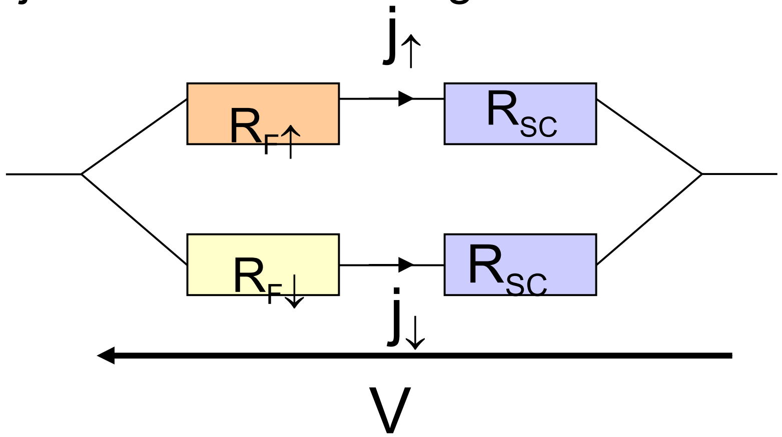

35% light polarization ➡ 70% spin polarization



# Weak spin-injection efficiency: Impedance mismatch issue

C.Schmidt et al, PRB 62, R4790 (2000); Rashba, PRB62, 16267 (2000)

Case of direct injection from ferromagnetic metal into semiconductor:



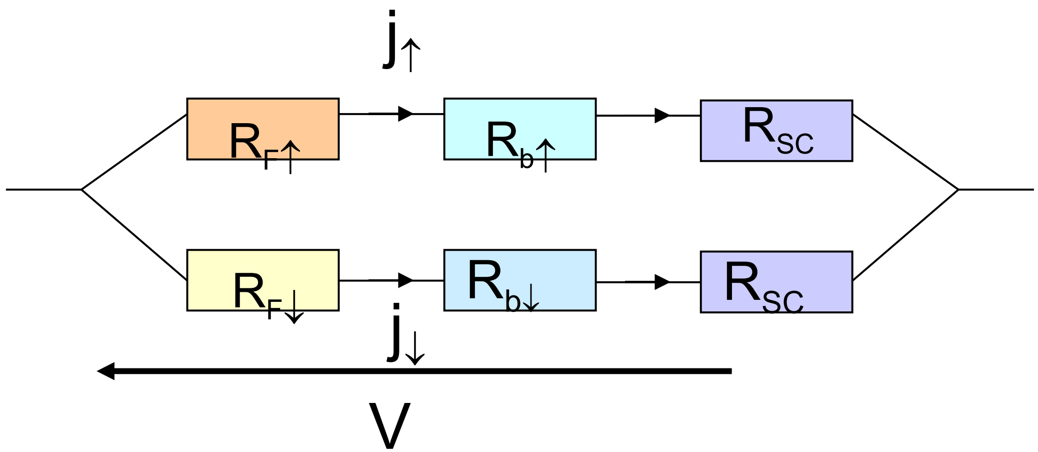

$$j_{\uparrow} = \frac{V}{R_{F\uparrow} + R_{SC}} \qquad j_{\downarrow} = \frac{V}{R_{F\downarrow} + R_{SC}}$$

$$\frac{\Delta j}{j_{\uparrow} + j_{\downarrow}} = \frac{R_{F\downarrow} - R_{F\uparrow}}{R_{F\uparrow} + R_{F\downarrow} + 2R_{SC}} \approx \frac{\Delta R}{2R_{SC}} << 1$$

Weak polarization because resistance of the stack fully dominated by spin-independent SC resistance. Even worse if spin-flip is taken into account.

# Weak spin-injection efficiency: Impedance mismatch issue (cont'd)

Case of injection from ferromagnetic metal into semiconductor through a <u>tunnel barrier</u> :




$$\frac{\Delta j}{j_\uparrow + j_\downarrow} = \frac{(R_{F\downarrow} - R_{F\uparrow}) + (R_{b\downarrow} - R_{b\uparrow})}{R_{F\uparrow} + R_{F\downarrow} + R_{b\downarrow} + R_{b\uparrow} + 2R_{SC}}$$

For $R_{b\downarrow} + R_{b\uparrow} >> 2R_{SC} >> R_{F\downarrow} + R_{F\uparrow}$

For free electrons

$$\frac{\Delta j}{j_\uparrow + j_\downarrow} = \frac{(R_{b\downarrow} - R_{b\uparrow})}{R_{b\downarrow} + R_{b\uparrow}} \approx \frac{k_F^\uparrow - k_F^\downarrow}{k_F^\uparrow + k_F^\downarrow} \approx \frac{D_F^\uparrow - D_F^\downarrow}{D_F^\uparrow + D_F^\downarrow}$$

can be large

**Efficient spin-injection**

# Summary on injection

- Poor spin-injection from ferromagnetic metal directly into SC
- Efficient spin-injection from magnetic SC into non–magnetic SC
- Efficient spin-injection from magnetic metal into non–magnetic SC through a tunnel barrier

# Thank you !