Spintronics II

1. Tunneling magnetoresistance
2. TMR sensors

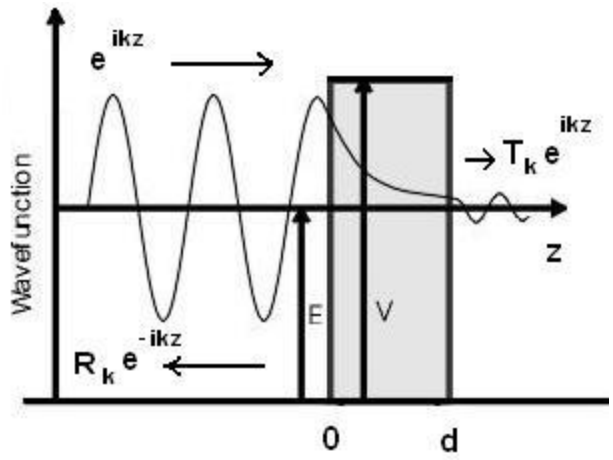
Italian School of Magnetism
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Outlook

- 1. Tunneling magnetoresistance
- 2. TMR sensors

Tunneling and WKB



$$-\frac{\hbar^2}{2m}\frac{\partial^2\Psi(z)}{\partial z^2}+V\Psi(z)=E_z\Psi(z)$$

$$\begin{cases} \Psi = e^{ik_z z} + R_k e^{-ik_z z} & \text{per} \quad z < 0 \\ \Psi = Ae^{-k'(E_z)z} + Be^{k'(E_z)z} & \text{per} \quad 0 < z < d \\ \Psi = T_k e^{ik_z z} & \text{per} \quad z > d \end{cases}$$

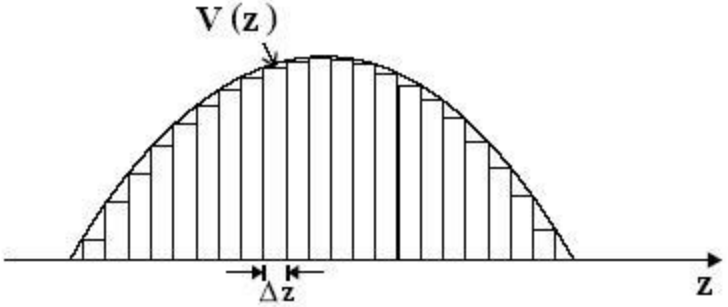
$$k_z = \sqrt{\frac{2mE_z}{\hbar^2}} \qquad k'(E_z) = \sqrt{\frac{2m(V-E_z)}{\hbar^2}}$$

$$|T_k|^2 = \frac{16k^2k'^2}{\left(k^2+k'^2\right)^2}e^{-2k'd}$$ for large values of k'd

Consider a non rectangular barrier:

$$\log|T|^2 \approx -2k'd + 2\log\frac{4(kd)(k'd)}{(kd)^2+(k'd)^2}$$ The first term dominates

Approximate the barrier with the series of rectangular barriers
Suppose that transmission coefficients are multiplicative.



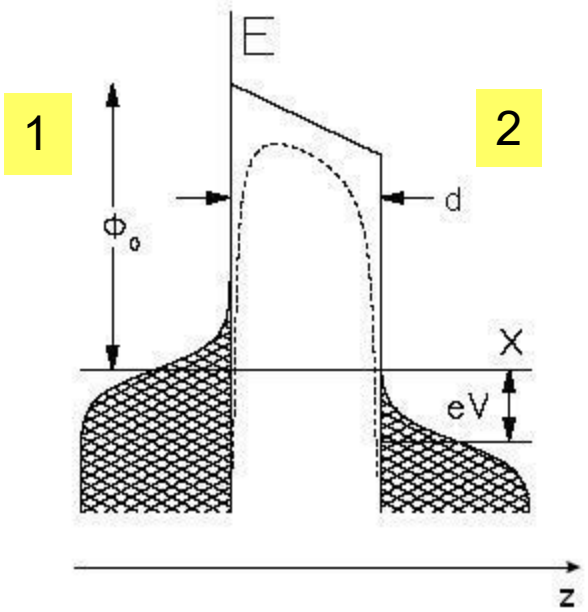
$$\log|T|^2 \approx \sum_{\substack{barriere\\ parziali}} \log\left|T_{\substack{barriere\\ parziali}}\right|^2 \approx -2\sum \Delta z\langle k'\rangle$$

For $\Delta z \to 0$:

$$\log|T|^2 \approx -2 \int_{barriera} dz\sqrt{\left(2m/\hbar^2\right)\left[V(z)-E\right]}$$

$$|T|^2 \approx e^{-2\int_{barriera} dz\sqrt{\left(2m/\hbar^2\right)\left[V(z)-E\right]}}$$

I-V characteristic of a tunneling junction



$$j = j_{1\to 2} - j_{2\to 1}$$

$$I^{\pm}_{1\to 2}(V,E) = D_1^{\pm}(E) f(E) |M|^2 D_2^{\pm}(E+eV)(1-f(E+eV))$$

$$I^{\pm}_{2\to 1}(V,E) = D_1^{\pm}(E)(1-f(E)) |M|^2 D_2^{\pm}(E+eV) f(E+eV)$$

$$j = \sum_k \int_{-\infty}^{+\infty} dE D_1(E) D_2(E+eV) |M(E)|^2 \left(f(E) - f(E+eV)\right)$$

Sum over transversal *k*, *D(E)* is the density of states at the energy E (with respect to the Fermi level) and *f(E)* is the Fermi distribution . The matrix element is proportional to $|T(E)|^2$ calculated with the WKB approximation.

J. G. Simmons, J. Appl. Phys. 34, 1793 (1963)

$$j(V) = \frac{J_0}{d^2}\left(\overline{\Phi} - \frac{eV}{2}\right)\exp\left[-Ad\sqrt{\overline{\Phi} - \frac{eV}{2}}\right] - \frac{J_0}{d^2}\left(\overline{\Phi} + \frac{eV}{2}\right)\exp\left[-Ad\sqrt{\overline{\Phi} + \frac{eV}{2}}\right]$$

$$A = \frac{4\pi}{h}\sqrt{2m_c^*} \qquad J_0 = \frac{e}{2\pi h}$$

d in Angstroms, Φ in V A=1.025 $eV^{-1/2}$ $Å^{-1}$ J_0=6.2 x 10^{10} eV^{-1} $Å^2$

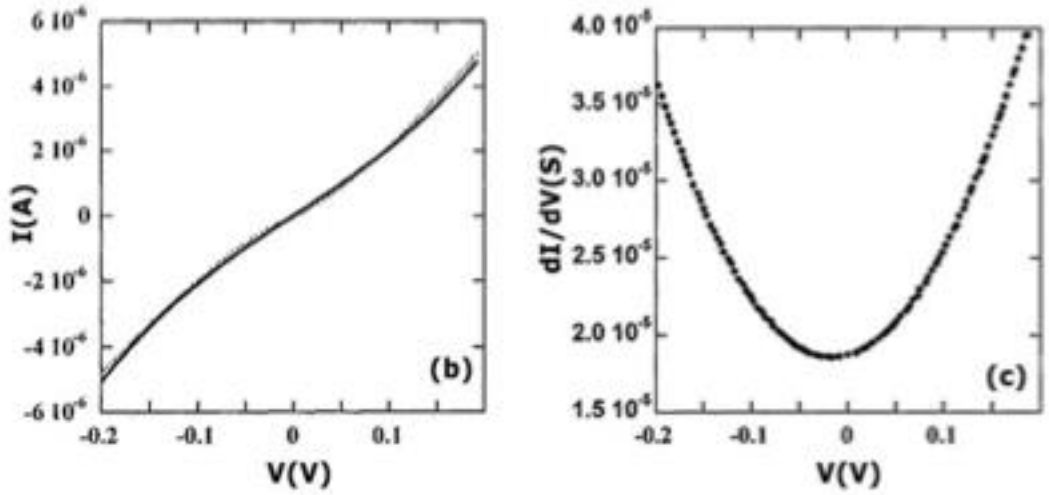
In this wayJ is expressed in A/cm^2

$$j(V)=\frac{J_0}{d^2}\left(\overline{\Phi}-\frac{eV}{2}\right)\exp\left[-Ad\sqrt{\overline{\Phi}-\frac{eV}{2}}\right]-\frac{J_0}{d^2}\left(\overline{\Phi}+\frac{eV}{2}\right)\exp\left[-Ad\sqrt{\overline{\Phi}+\frac{eV}{2}}\right]$$

For small values of the applied voltage:

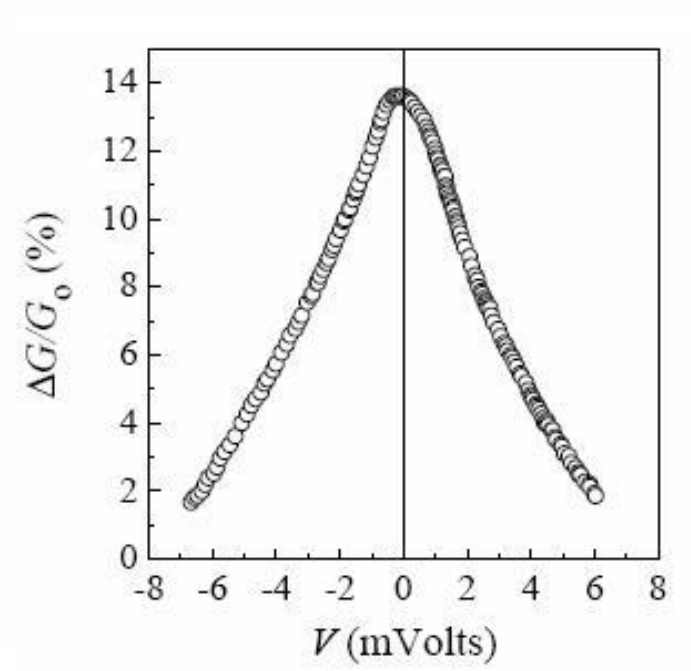
$J \approx \alpha V + \beta V^3$ The conductance G = dI/dV has a parabolic shape

The current depends exponentially on:
- the barrier thickness
- the square root of the barrier height



Adapted from: A Barry et al. A CrO2-based magnetic tunnel junction. *J. Phys. Condens. Matter* **12,** L173 (2000).

Jullière model for TMR (1975)



Fe/GeO_x/Co

Assumptions:
- Spin conservation during tunneling
- Constant transmission coefficients, independent on magnetization and energy
- Small applied voltage

$$G_P = G_{\uparrow\uparrow} + G_{\downarrow\downarrow} \propto D_{1\uparrow}D_{2\uparrow} + D_{1\downarrow}D_{2\downarrow}$$

$$G_{AP} = G_{\uparrow\downarrow} + G_{\downarrow\uparrow} \propto D_{1\uparrow}D_{2\downarrow} + D_{1\downarrow}D_{2\uparrow}$$

$$P = \frac{D_{1\uparrow} - D_{1\downarrow}}{D_{1\uparrow} + D_{1\downarrow}}$$

$$TMR = \frac{R_{AP} - R_P}{R_P} = \frac{G_P - G_{AP}}{G_{AP}} = \frac{2P_1P_2}{1 - P_1P_2}$$

It works, especially in case of Al_2O_3 barriers.

Fe/MgO/Fe: Coherent tunneling

TMR (RT) MTJ conventional (Al2O3) ~ 70%

TMR (RT) MTJ Fe/MgO/Fe ~ 800% (theoretical value = **1000%**)

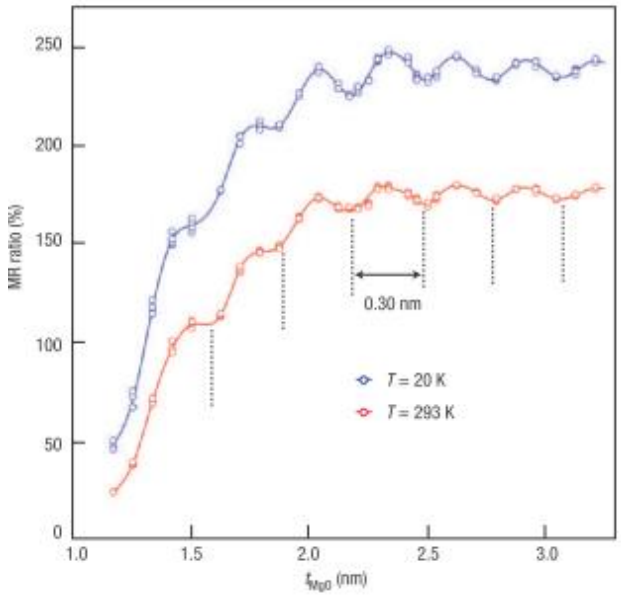
Giant room-temperature magnetoresistance in single-crystal Fe/MgO/Fe magnetic tunnel junctions

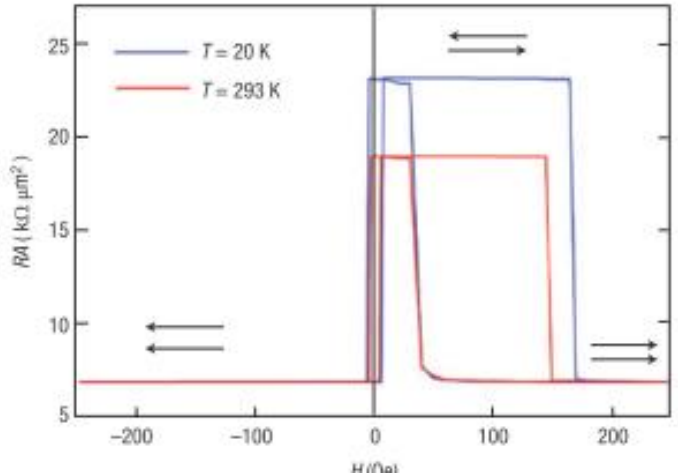
SHINJI YUASA[1,2]*, TARO NAGAHAMA[1], AKIO FUKUSHIMA[1], YOSHISHIGE SUZUKI[1] AND KOJI ANDO[1]

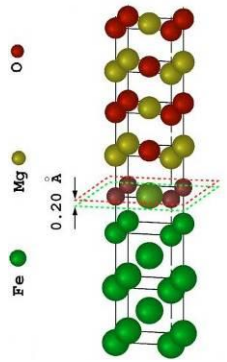
[1]NanoElectronics Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki 305-8568, Japan

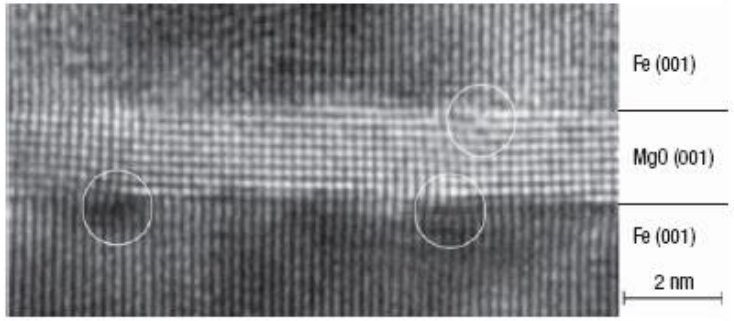
[2]PRESTO, Japan Science and Technology Agency, Kawaguchi, Saitama 332-0012, Japan

*e-mail: yuasa-s@aist.go.jp



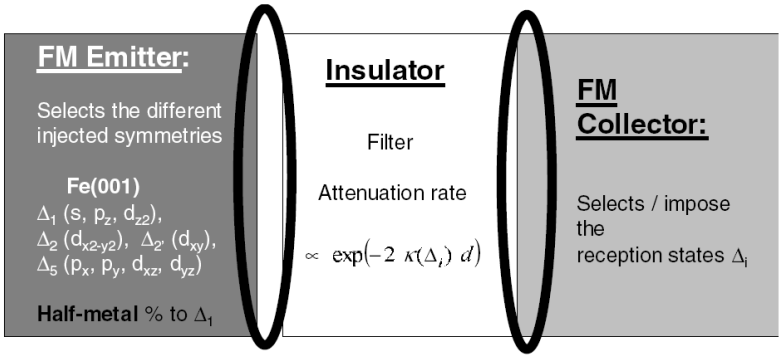






*S. Yuasa et al, Nature Materials, **3** 868 (2004)*

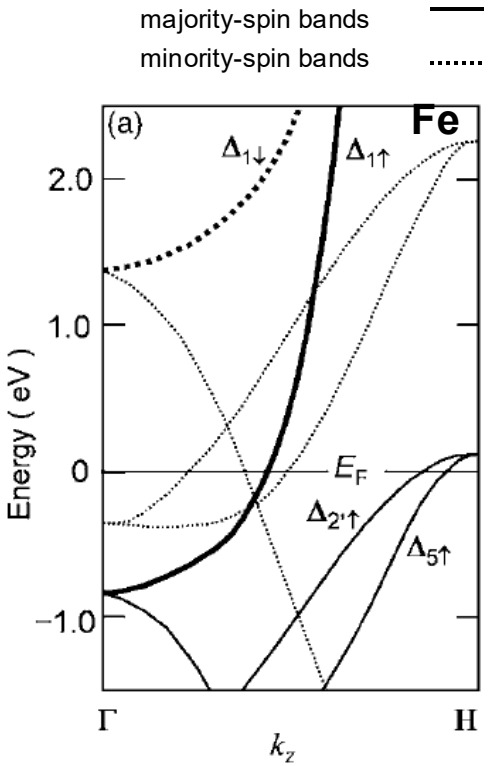
Coherent tunneling



*C. Tiusan et al, J.Phys.:Cond. Matter **19** 165201 2007*

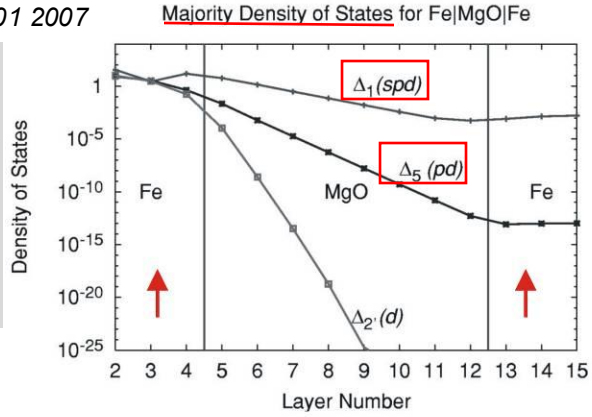
Symmetry based spin filtering

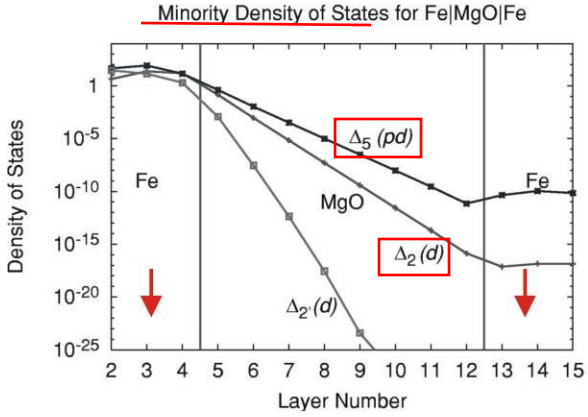
- coupling of electronic states in the collector and emitter through the MgO barrier (FM emitter, FM collector)
- different attenuation (*k*) in the barrier depending on the symmetry of states



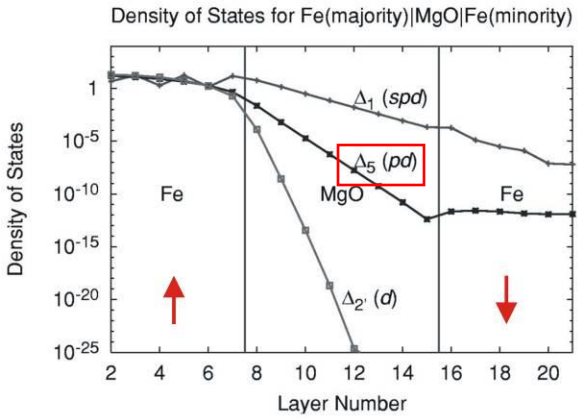
*S. Yuasa et al, APL **89** 042505 2006*

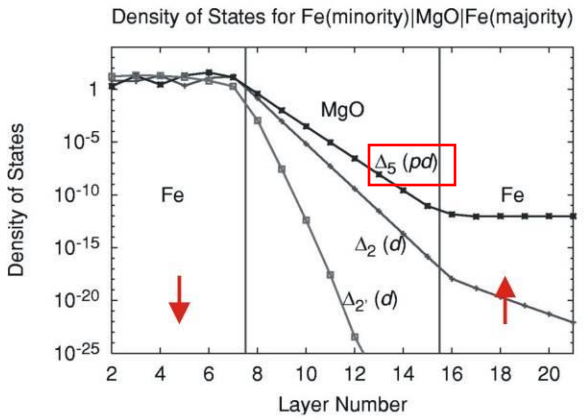
Parallel





Antiparallel





*W. H. Butler et al, PRB **63** 054416 (2001)*

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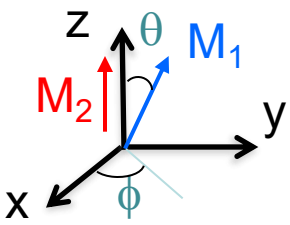
TMR SENSORS

TMR for non collinear magnetization in the two layers

If two adjacent layers M_1 and M_2 form an angle different from $n\pi$ an up electron in the layer 1 must be described as a mixture of states up and down in the layer 2, where the quantization axis is rotated by θ.

Consider M_2 ($\theta = 0$) ; M_1 (θ, ϕ) ; **e** : unit vector in the direction (θ, ϕ). Find out the equations connecting the pure states of spin in the two layers.

The spinors describing the eigenstates in M_1 satisfy the equation:



$$(\boldsymbol{\sigma}\cdot\mathbf{e})\chi = \lambda\chi$$

$$\boldsymbol{\sigma} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\mathbf{u}_x + \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}\mathbf{u}_y + \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\mathbf{u}_z$$

Eigenstates in the first layer:

$$\chi_1 = \begin{bmatrix} \cos\vartheta/2 \\ \sin\vartheta/2\, e^{i\varphi} \end{bmatrix}$$

λ = 1 spin up

$$\chi_2 = \begin{bmatrix} \sin\vartheta/2 \\ -\cos\vartheta/2\, e^{i\varphi} \end{bmatrix}$$

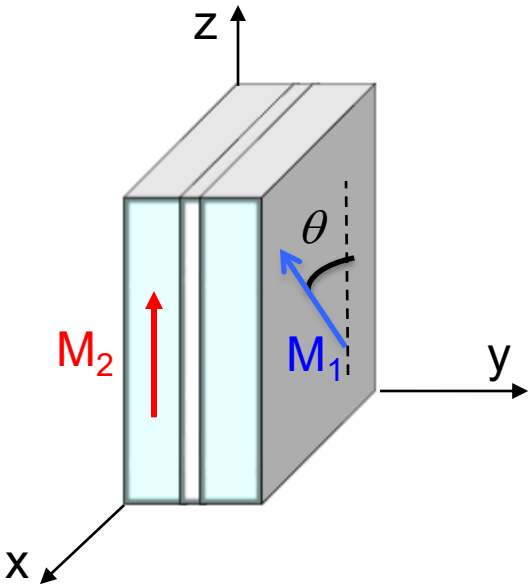
λ = -1 spin down

Eigenstates in the second layer:

$$\chi_1' = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \qquad \chi_2' = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

There is a mixing of the spin channels in the first layer when passing in the second layer:

$$\chi_1 = \cos\vartheta/2\, \chi_1' + \sin\vartheta/2\, e^{i\varphi} \chi_2'$$



For a MTJ

$$\chi_1 = \cos\vartheta/2\ \chi_1' + \sin\vartheta/2\ \chi_2'$$

$$\chi_2 = \sin\vartheta/2\ \chi_1' - \cos\vartheta/2\ \chi_2'$$

Jullière model (φ = 0)

$$G_P = G_{\uparrow\uparrow} + G_{\downarrow\downarrow} \propto D_{1\uparrow} D_{2\uparrow} + D_{1\downarrow} D_{2\downarrow}$$

Digitare l'equazione qui.

$$G_{AP} = G_{\uparrow\downarrow} + G_{\downarrow\uparrow} \propto D_{1\uparrow} D_{2\downarrow} + D_{1\downarrow} D_{2\uparrow}$$

Hp: constant transition probabilities

For θ not null, there is a mixing of G_{AP} and G_P:

$$G(\theta) \propto D_{1\uparrow} \cos^2\frac{\theta}{2}\ D_{2\uparrow} + D_{1\uparrow} \sin^2\frac{\theta}{2}\ D_{2\downarrow} + D_{1\downarrow} \sin^2\frac{\theta}{2}\ D_{2\uparrow} + D_{1\downarrow} \cos^2\frac{\theta}{2}\ D_{2\downarrow}$$

$$G(\theta) \propto \underbrace{(D_{1\uparrow}D_{2\uparrow} + D_{1\downarrow}D_{2\downarrow})}_{G_P} \cos^2\frac{\theta}{2} + \underbrace{(D_{1\uparrow}D_{2\downarrow} + D_{1\downarrow}D_{2\uparrow})}_{G_{AP}}{}^2 \sin^2\frac{\theta}{2}.$$

$= G_P + (G_{AP} - G_P)\sin^2(\theta/2) = G_P + (G_{AP} - G_P)((1-\cos\theta)/2)$

$R(\theta) = 1/G(\theta)$

For small values of TMR :

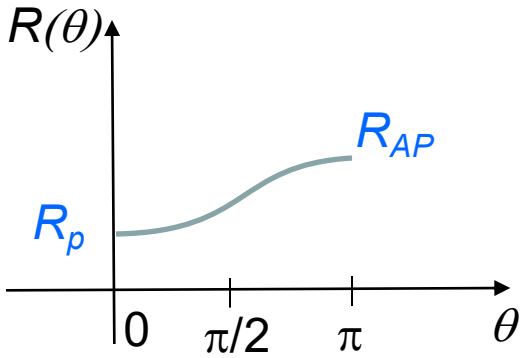
$$R(\theta) \simeq R_P\left(1 - \sin^2\frac{\theta}{2}\left(\frac{R_P - R_{AP}}{R_{AP}}\right)\right) \approx R_P + (R_{AP} - R_P)\sin^2\frac{\theta}{2}$$

$$= R_P + (R_{AP} - R_P)\left(\frac{1-\cos\theta}{2}\right) = \frac{R_P + R_{AP}}{2} + \frac{R_P - R_{AP}}{2}\cos\theta$$

$$= R_\perp + \frac{\Delta R}{2}\cos\theta$$

$\theta = 0$ parallel

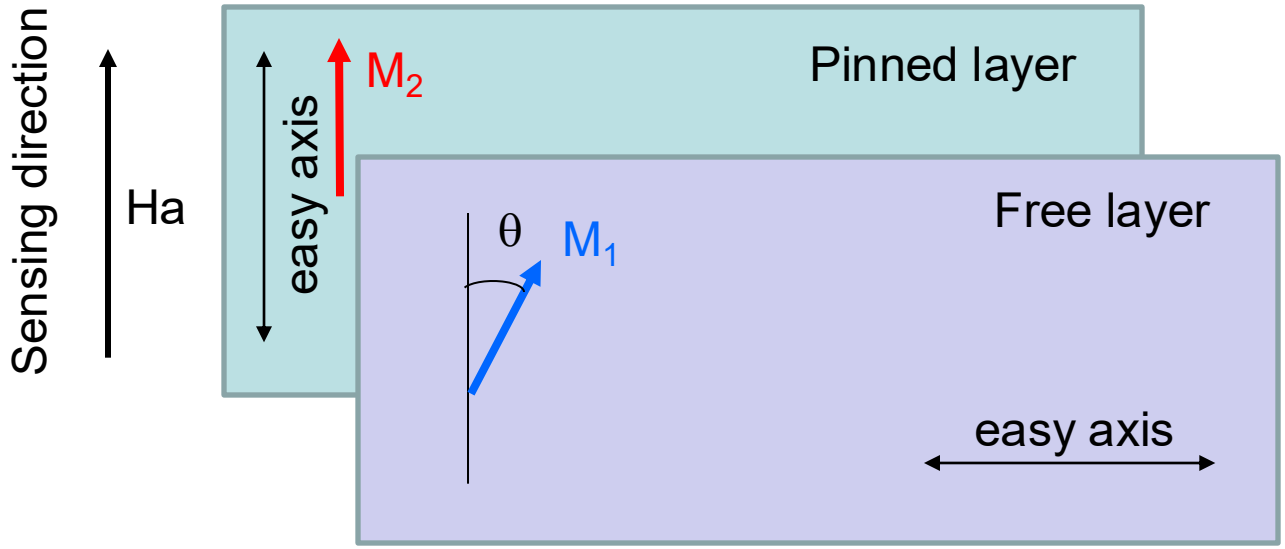
$\theta = \uparrow$ antiparallel

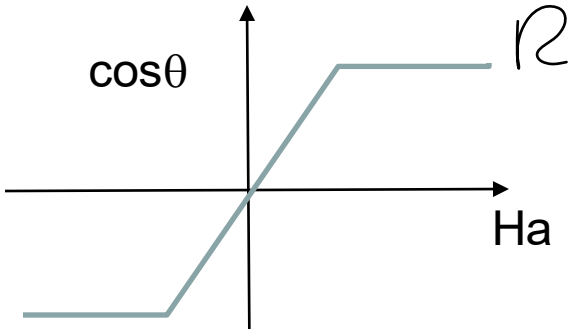


$\Delta R = R_P - R_{AP} < 0$

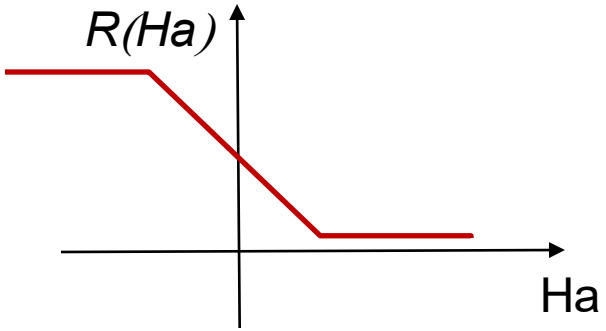
To build up a sensor we need a magnetic configuration where $\cos\theta$ varies linearly with the applied field.

Micromagnetic configuration of a TMR sensor





$$R(\theta) \simeq R_1 + \frac{\Delta R}{2} \cos\theta$$

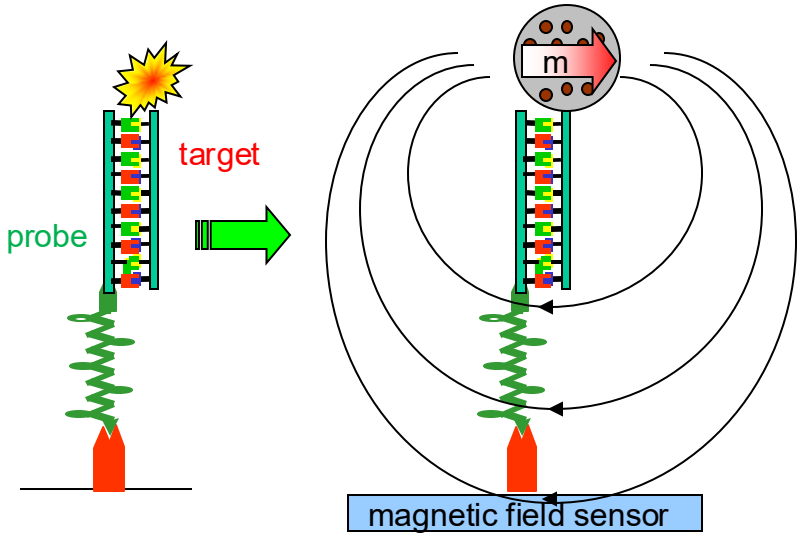


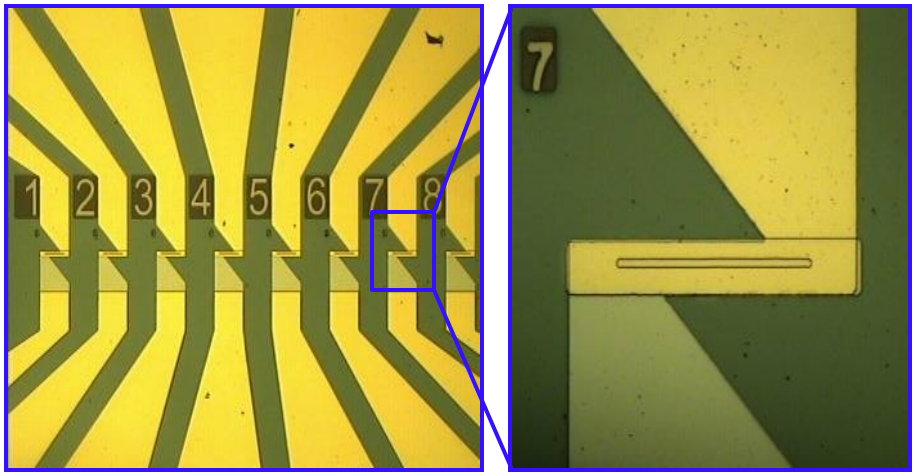
Spintronic biosensors

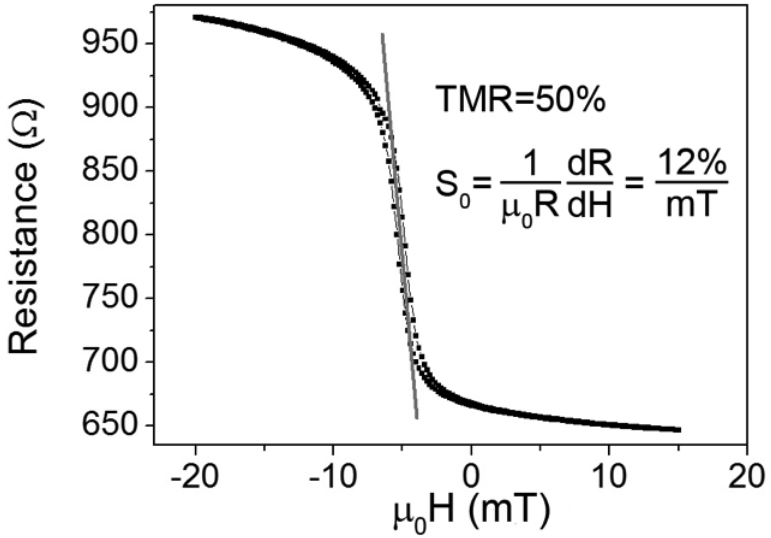
Magnetic sensors for the read-out of biomolecular recognition at their surface

- ✓ No quenching
- ✓ Direct electrical read-out: easily integrable
- ✓ No magnetic background
- ✓ High sensitivity (below 1 fM) without chemical amplification

[R. S. Gaster et al., Lab Chip 2011 and Nat. Nanotech.2011]







The sensor is relevant, but targets and probes make the difference!