Temperature and Voltage MR dependencies for high performance Magnetic Junctions

H.G. Silva[1,2] and Y.G. Pogorelov[1]*

[1]IFIMUP-IN, University of Porto, Porto 4169-007, Portugal
[2]CEOT, University of Algarve, Campus de Gambelas, Faro, Portugal

** e-mail: hgsilva@fc.up.pt, huggsil@gmail.com*

OUTLINE

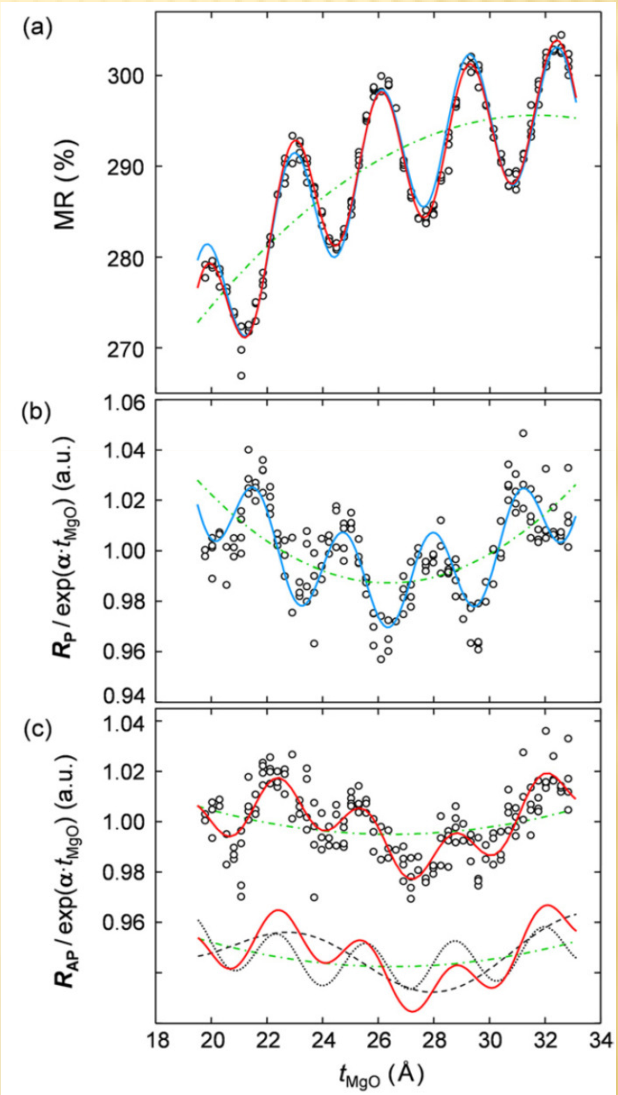
1. Introduction
2. Experimental Results
3. Transmission Coefficient
4. Magnetoresistance
5. Temperature and Voltage Effects
   - Generalized Landauer–Büttiker Formula
6. Shallow Band Regime
   - MR vs Temperature
   - MR vs Voltage
7. Conclusions

INTRODUCTION

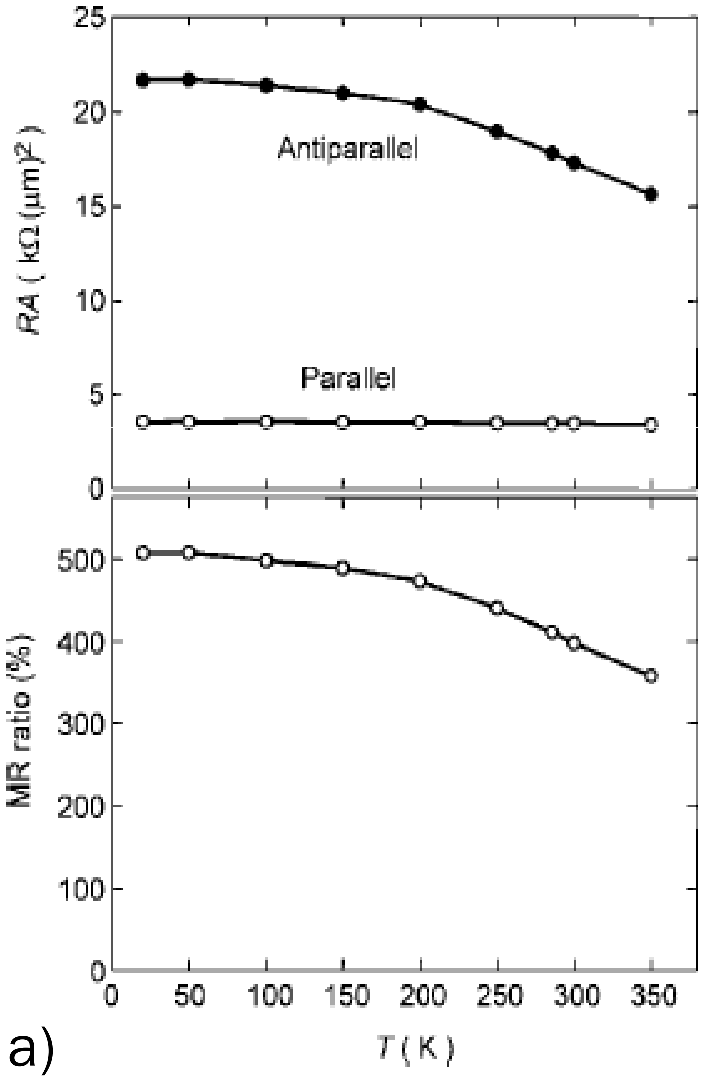
Recent advances in spintronics devices are greatly related to fabrication of perfect magnetic tunnel junctions with epitaxially deposited crystalline MgO nanobarriers.

Besides a huge enhancement of the MR, these devices reveal new peculiar effects (oscillatory MR) that indicates the regime of quantum conductance as the main source of giant TMR performance.

Theoretical approaches use first-principles numerical methods (W. Butler *et al*, PRB **63**, 054416, 2001) and Green functions (J. Mathon *et al*, PRB **63**, 220403R, 2001).



EXPERIMENTAL RESULTS

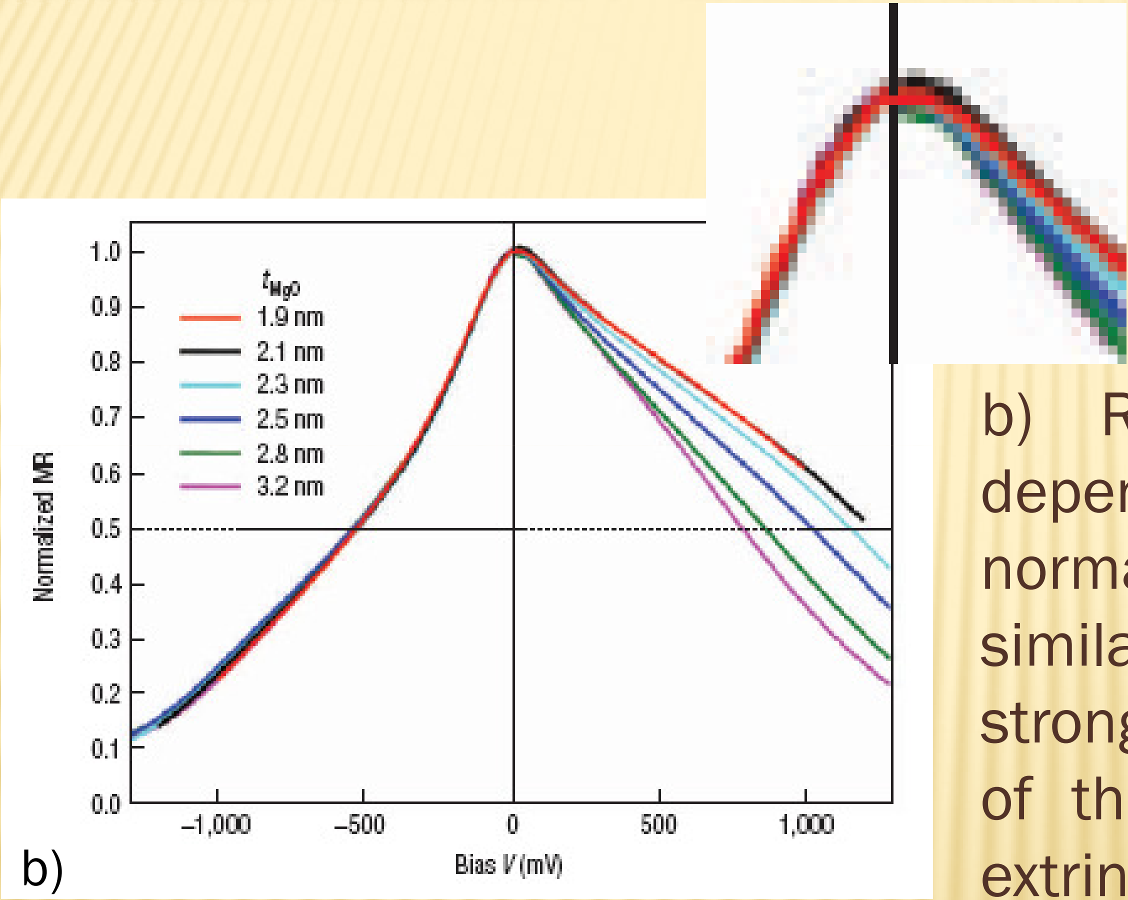


a)

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

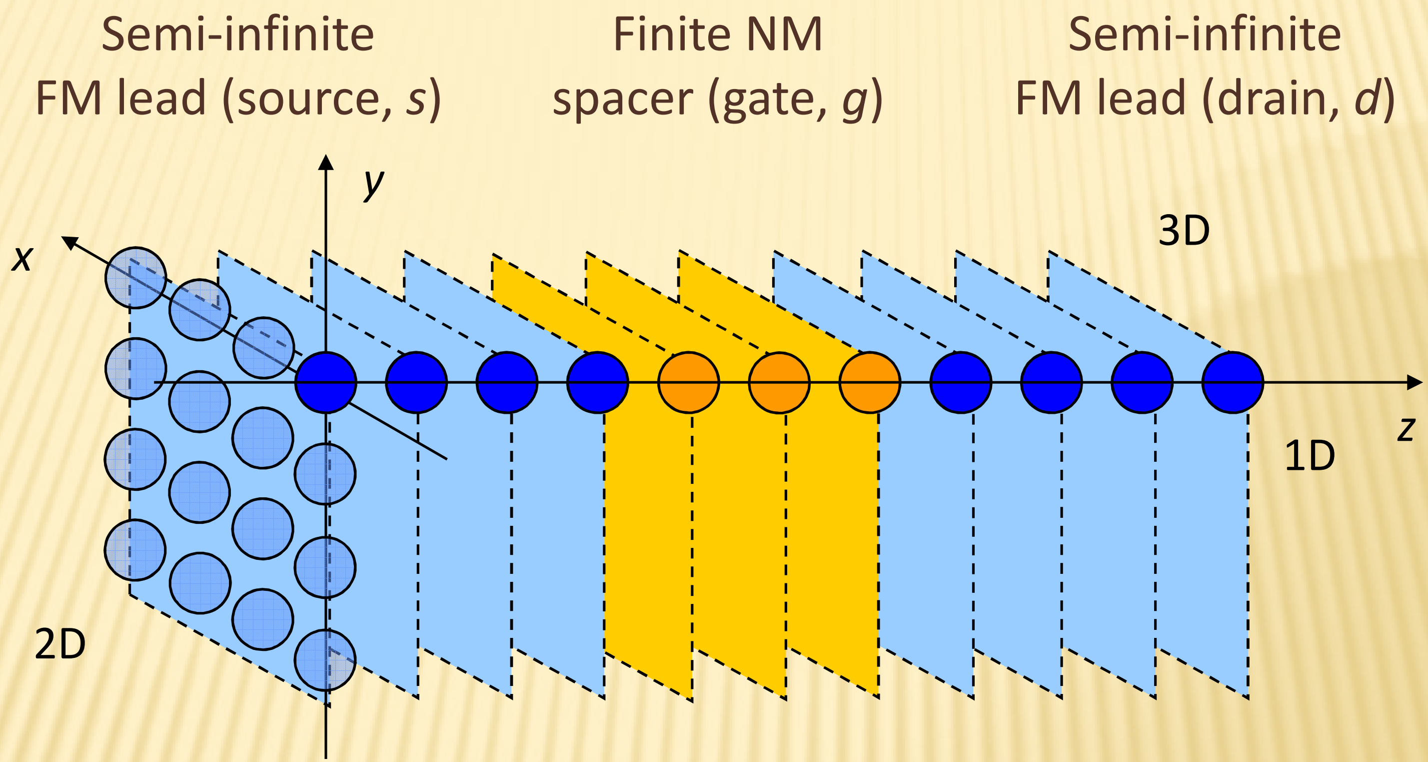
a) Typical temperature dependence of MR (V=10mV) for a fully epitaxial Co/MgO/Co MTJ. The thermal decrease of MR is due to a stronger temperature dependence of the AP channel compared with the P one.

EXPERIMENTAL RESULTS



b) Representative voltage dependence of the normalized MR at RT for similar perfect MTJ's. A strong voltage dependence of the MR is attributed to extrinsic and intrinsic scatterings.

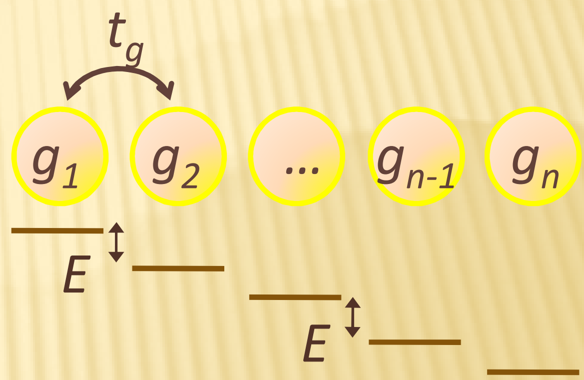
S. Yuasa *et al.*, NMat **3**, 868, 2004



The tight-binding approximation for simple cubic lattice is used to calculate an analytic transmission formula, through the exact *evaluation of the discrete wave function for the whole structure*, consider to be of the type $FM_1/NM/FM_2$ with FM parameters similar to Fe.

TRANSMISSION COEFFICIENT

Hamiltonian for an isolated *n*-element chain



$$\hat{H} = \sum_{l=1}^{n} \left[\left(\varepsilon_g - lE\right) \hat{g}_l^{\dagger} \hat{g}_l + t_g \left(\hat{g}_l^{\dagger} \hat{g}_{l+1} + \hat{g}_{l+1}^{\dagger} \hat{g}_l \right) \right]$$

Wave function

$$\psi = \sum_{l=1}^{n} g_l \left| l \right\rangle$$

Equation of motion

$$2(x_g - lz) g_l = g_{l+1} + g_{l-1},$$

with $x_g = \dfrac{\varepsilon - \varepsilon_g}{2t_g}, \quad z = \dfrac{E}{2t_g}$

Wave function amplitude in the gate

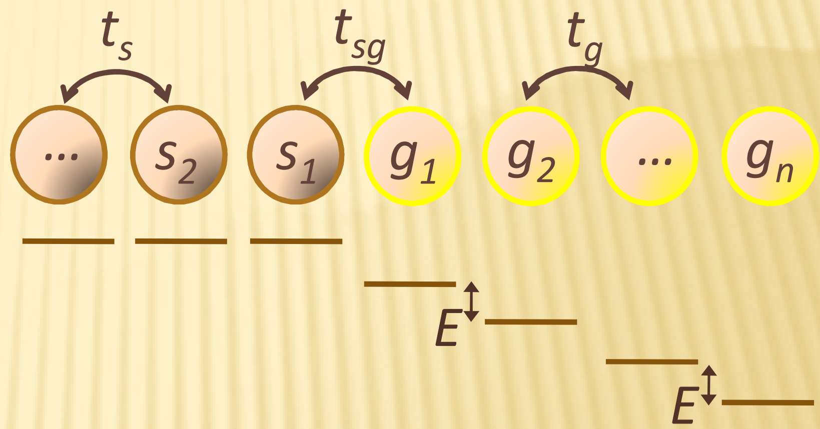
$$\boxed{g_l \equiv p_l(x) = (2z)^l \sum_{j=0}^{[l/2]} C_j^{l-j} \left(4z^2\right)^{-j} \left(\frac{x}{z} + j \right)_{l-2j},}$$

C_m^n, binomial coefficient; $[u]$ entire part; $(u)_n = u(u+1)\ldots(u+n-1)$, Pochhammer symbol.

TRANSMISSION COEFFICIENT

Wave function in the source

$$s_l = e^{iq_s l} + e^{-iq_s l} R$$



Hamiltonian for the *s/g* interface

$$\hat{H}_{sg} = t_{sg}\left(\hat{g}_1^{\dagger}\hat{s}_1 + \hat{s}_1^{\dagger}\hat{g}_1\right)$$

Boundary conditions

$$2x_s s_1 = s_2 + \frac{t_{sg}}{t_s} g_1,$$

with $x_s = \dfrac{\varepsilon - \varepsilon_s}{2t_s}, q_s = \arccos(x_s)$

$$2(x_g + z) g_1 = g_2 + \frac{t_{sg}}{t_g} s_1,$$

$$\boxed{g_l = g_l^{(sg)}\left(R, q_s, q_g\right)}$$

WF amplitude in the gate

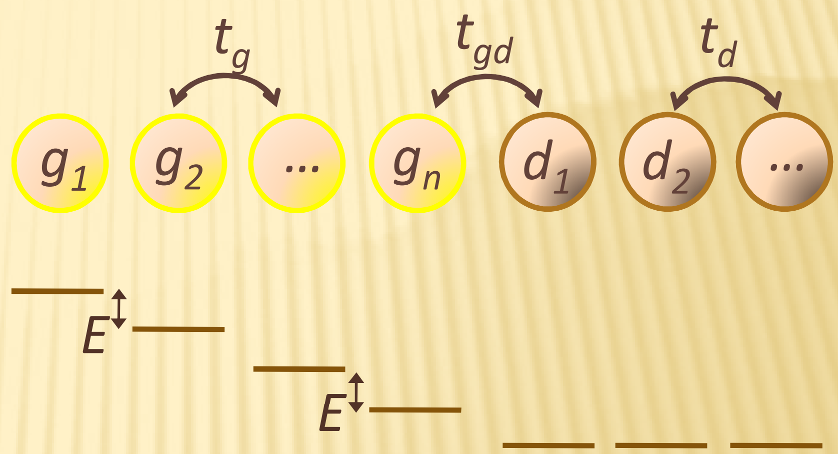
TRANSMISSION COEFFICIENT

Wave function in the drain

$$d_l = e^{iq_d l} T$$

Hamiltonian for the *g/d* interface

$$\hat{H}_{gd} = t_{gd} \left(\hat{d}_1^{\dagger} \hat{g}_n + \hat{g}_n^{\dagger} \hat{d}_1 \right)$$



Boundary conditions

$$2\left(x_g + n\,z\right) g_n = g_{n-1} + \frac{t_{gd}}{t_g} d_1$$

$$2\left[x_d + (n+1)\,z\right] d_1 = d_2 + \frac{t_{gd}}{t_d} g_n$$

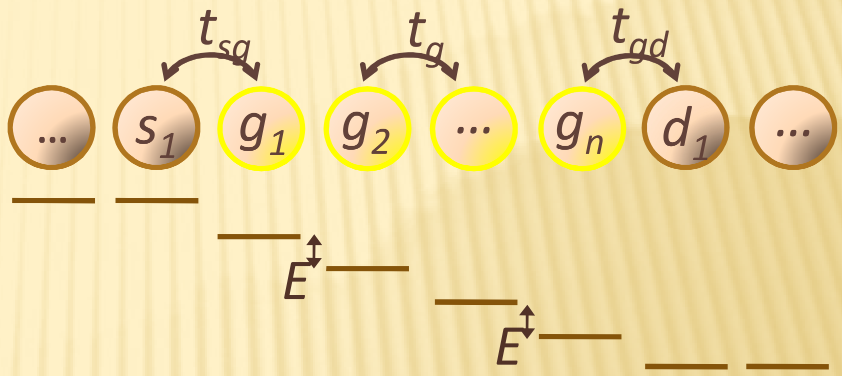
with $x_d = \dfrac{\varepsilon - \varepsilon_d}{2t_d}, q_d = \arccos\left(x_d\right)$

$$\boxed{g_l = g_l^{(gd)}\left(T, q_g, q_d\right)}$$

WF amplitude in the gate

TRANSMISSION COEFFICIENT

Linking the solutions from *s* to *d*, through two interfaces,



$$\boxed{g_l^{(sg)}\left(R, q_{s,\sigma}, q_g\right) = g_l^{(gd)}\left(T, q_g, q_{d,\sigma'}\right),}$$

an analytic solution for the field dependent transmission is found:

$$T = -2i\,\frac{t_{sg}\,t_{gd}}{t_g\,t_d}\sin q_s \cdot D^{-1}\left(z, q_s, q_g, q_d\right),$$

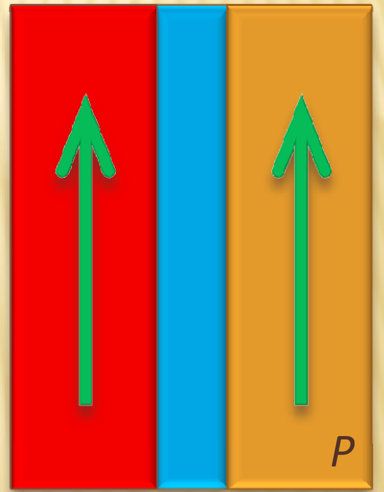
$$D = \varphi\left[p_n\left(x_g\right) - p_{n-1}\left(x_g + z\right)\gamma_s\right] - \gamma_d\left[p_{n-1}\left(x_g\right) + p_{n-2}\left(x_g + z\right)\gamma_s\right],$$

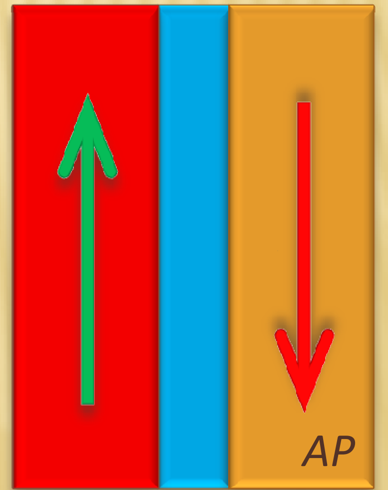
with $\varphi = 1 + (n+1) z e^{iq_b}$, $\gamma_s = \dfrac{t_{sg}^2}{t_s t_g} e^{iq_s}$ and $\gamma_d = \dfrac{t_{gd}^2}{t_g t_d} e^{iq_d}$.

MAGNETORESISTANCE

Considering, the magnetic states of the ferromagnetic leads, two main configurations exist:

1) Parallel (*P*)
2) Antiparallel (*AP*)





defining the magnetoresistance ratio as:

$$\boxed{MR = \frac{G_P - G_{AP}}{G_{AP} + G_0}}$$

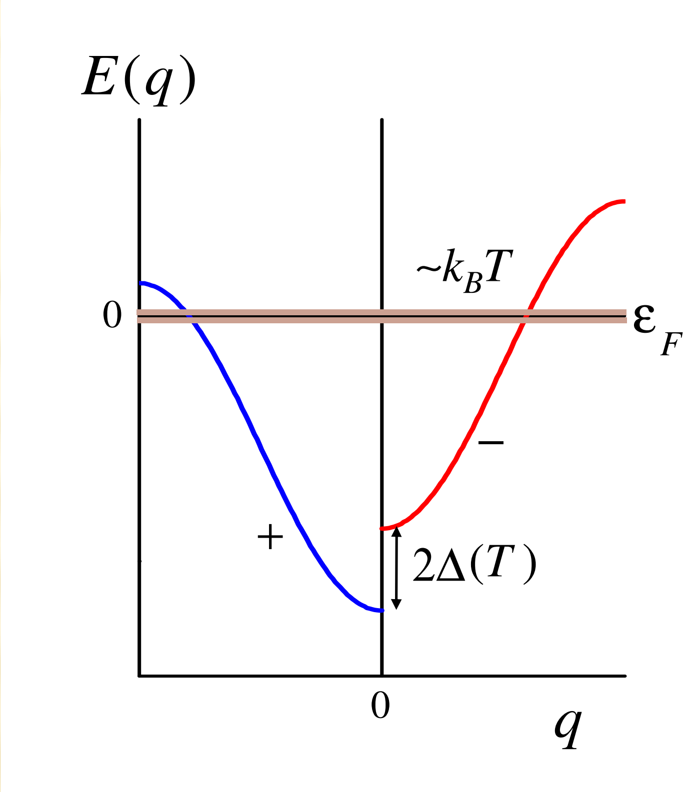
with

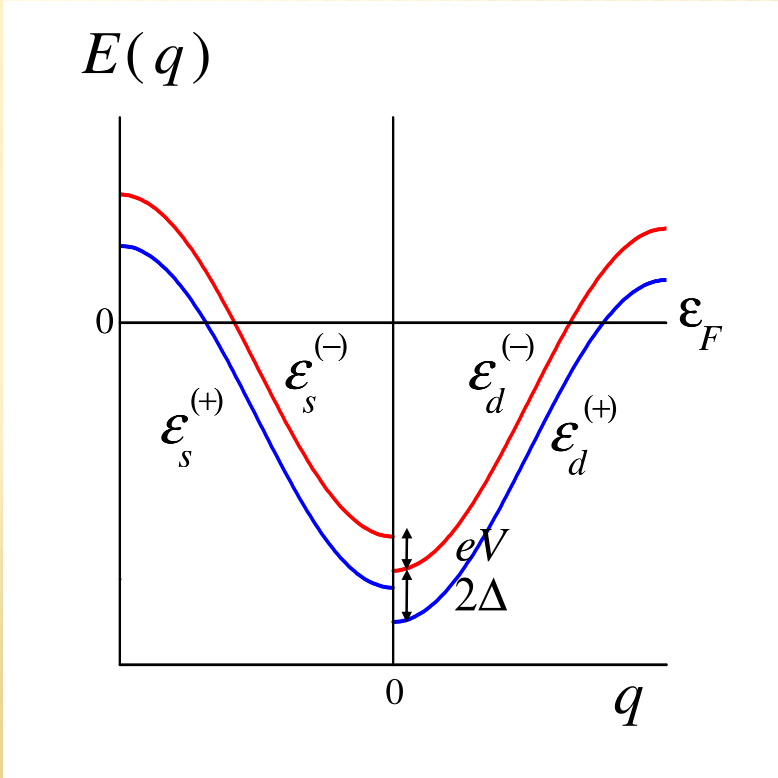
$$G_P = G_{++} + G_{--} \text{ and } G_{AP} = G_{+-} + G_{-+}$$

G_0, Spin-independent transmission due to s,p-bands.

TEMPERATURE AND VOLTAGE EFFECT

Single-band diagrams for temperature and voltage effects.





a) Important thermal broadening of the ε_F (pink) and temperature dependent Stoner splitting.

b) Rigid shift of bands in the drain (right) relative to the source (left), due to the applied bias, *V*.

GENERALIZED LANDAUER FORMULA

Landauer-Büttiker formula for real 3-D systems

$$I_C(V,T)=\frac{e^2}{h}\int d\varepsilon \sum_{k_\parallel \in K} \left|T_C(k_\parallel)\right|^2 \left[f_s(\varepsilon)-f_d(\varepsilon-V)\right]$$

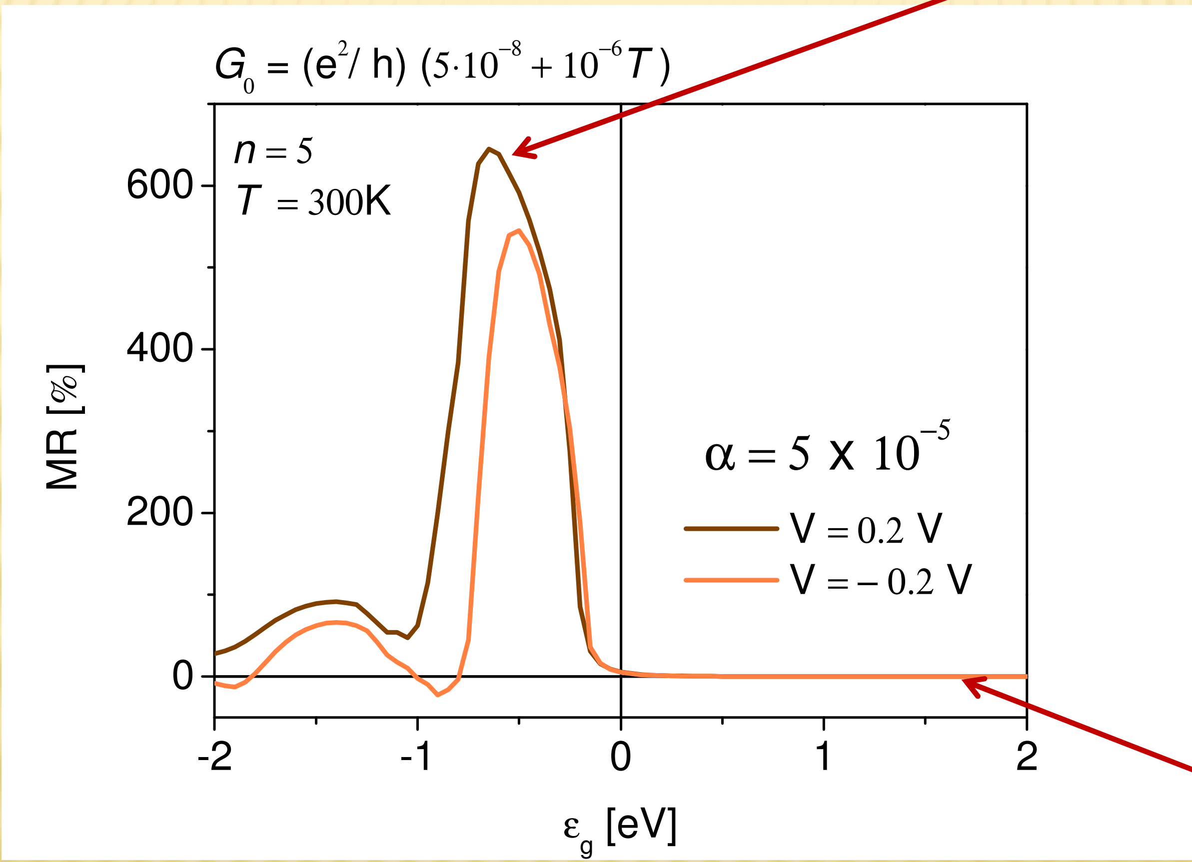
K is the restricted area of "permitted" $k_\parallel$ at an energy ε near the Fermi level $\varepsilon_{F,}$ for a given magnetic configuration "C = (P, AP)" and Voltage "*V*", for which the in- and out- momenta q_s and q_d in the leads are *real*.

The Stoner parameter follows thermal "Bloch $T^{3/2}$ Law":

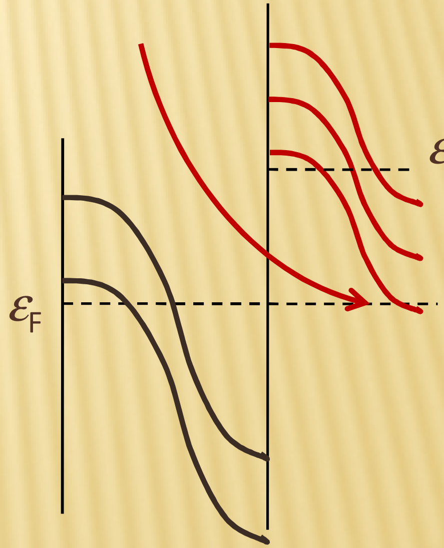
$$\Delta=\Delta_0\left(1-\alpha T^{3/2}\right)$$

SHALLOW BAND REGIME

Analyzing MR in function of the on-site energy ε_g in the G-layer



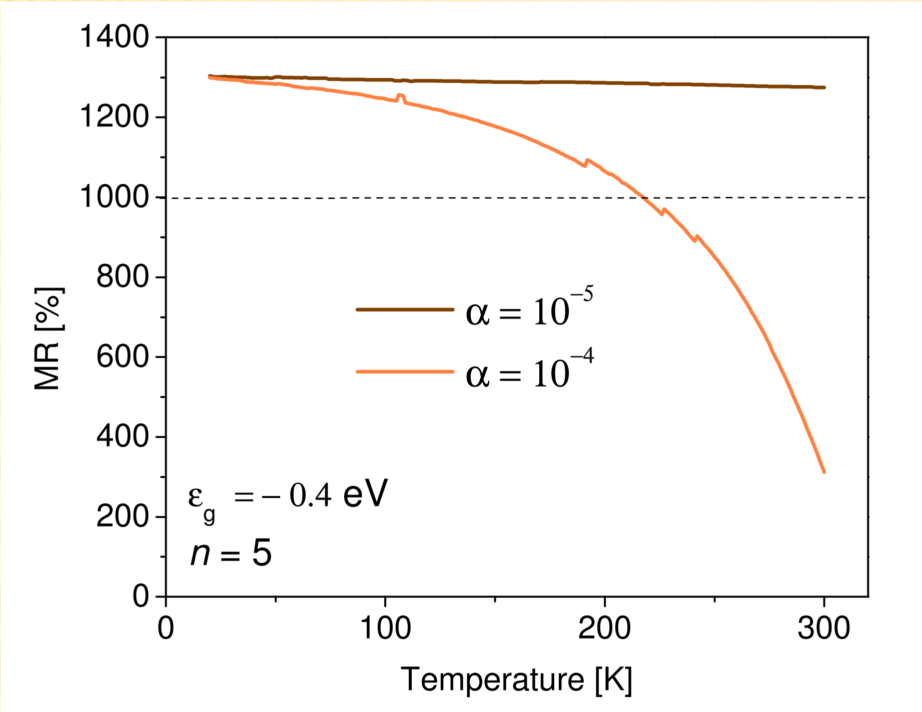
The strongest peak in MR vs ε_g relates to the "shallow band" regime (SBR)



Compared to the common tunneling regime (TR)

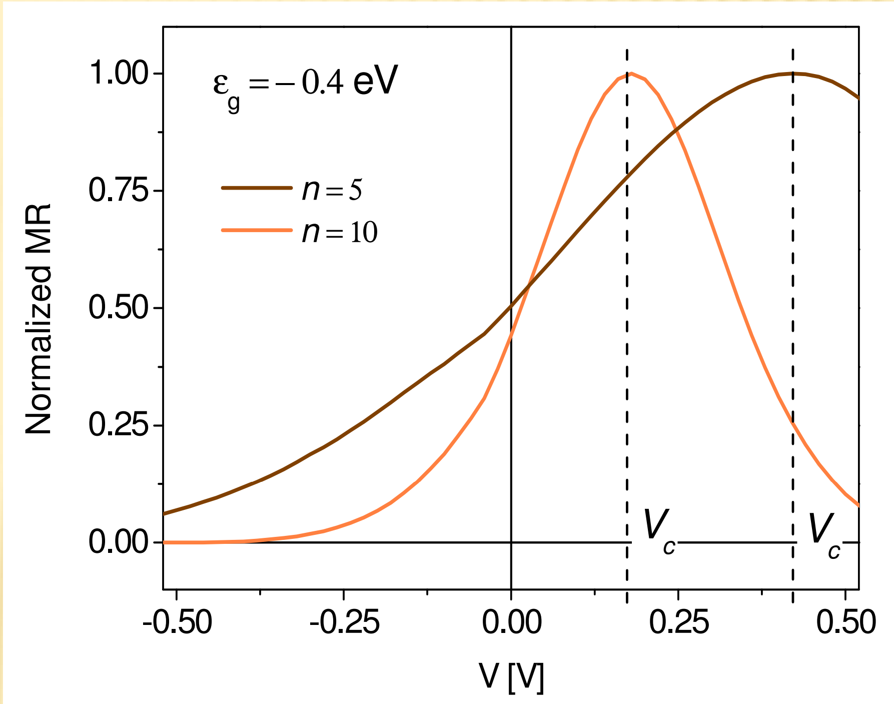
H. G. Silva, Y. G. Pogorelov, PRB to be published, for (T, V) = 0, a much higher effect is found

MR vs Temperature (V→0)



While greatly enhanced MR in SBR, it can sizeably decrease with temperature (very sensible to α). *It is important to build junctions with weakly temperature dependent magnetization.*

MR vs Voltage (T→0)



For SBR it is found that MR is strongly dependent on the bias, *V*. The MR peak is shifted, the stronger the smaller *n* is, and the peak width decreases with *n*. *This suggests the use of very thin junctions.*

CONCLUSIONS

• The calculations indicate that in the shallow band regime, SBR, a great enhancement of MR develops at low temperature, but gets reduced with temperature, due to thermal degradation of the ferromagnetic leads magnetization.

• In the SBR regime, it is found that MR is asymmetrically dependent on voltage and the MR peak shifted, the stronger the smaller *n* is. It suggests that, in order to decrease the voltage dependence, thinner junctions are preferable.

• Finally, we propose new junctions in which the insulating spacer is replaced by the one chosen from metals (Cu, Ru, Al,…), semiconductors (Si, Ge, …), or semimetals (Bi, Sb, …), to achieve SBR. However, this can require the issue of reasonable lattice matching for epitaxial growth (besides the non-wetting and so on) to be met.

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Thank you for your attention!

e-mail: hgsilva@fc.up.pt, huggsil@gmail.com