DETERMINATION OF THE SPIN DIFFUSION LENGTH IN SILICON AT LOW TEMPERATURES

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Workshop on correlations and coherence in quantum systems

University of Évora, Portugal, 8-12 October 2012

Outline

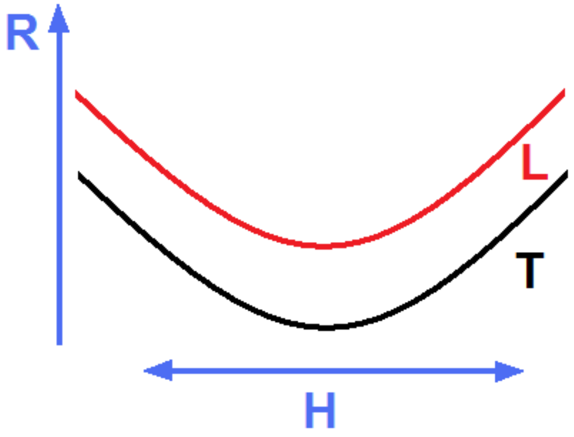
- **Spintronics**, **GMR** (giant magnetoresistance) and basic concepts related to **injection of spin polarized currents**
- Spin injection in permalloy clusters on silicon
- $\mathbf{L_{SD}}$ obtained from $Ni/Al_2O_3/Si$ ferromagnetic nanocontacts
- conclusion

Spintronics – **technology based on the injection of spin-polarized currents into metals and semiconductors**

Challenges – **injection and detection of spin polarized currents with high efficiencies**

Giant magnetoresistance (GMR)

Ordinary MR



semiconductors

In plane measurements

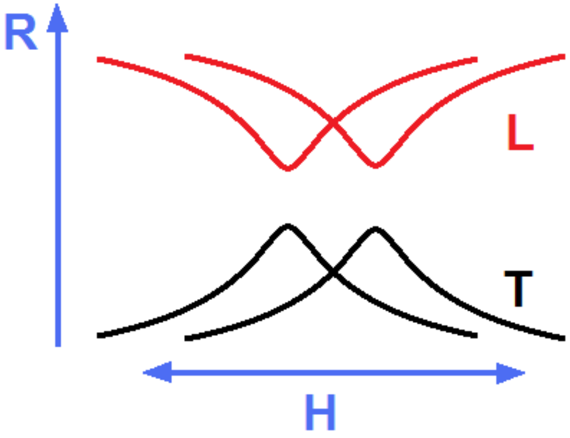
L = longitudinal

T = transversal

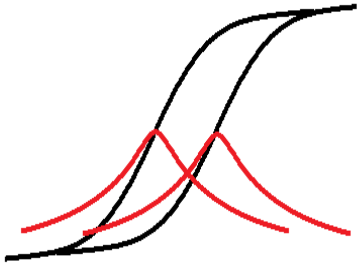
F = Ferromagnetic

N = non-magnetic

Anisotropic MR

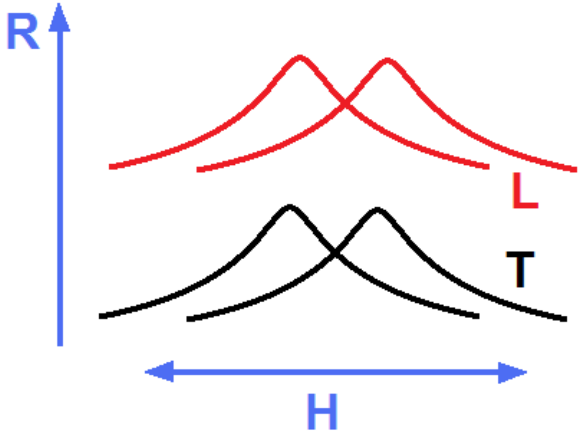


Ferromagnetic materials

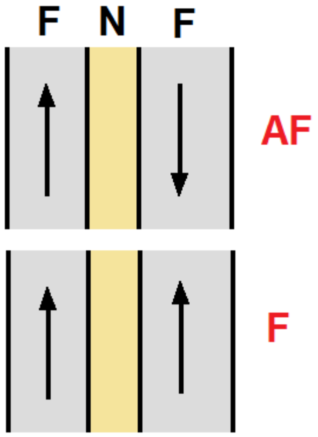


Hysteresis curve

Giant MR



F/N/F interfaces

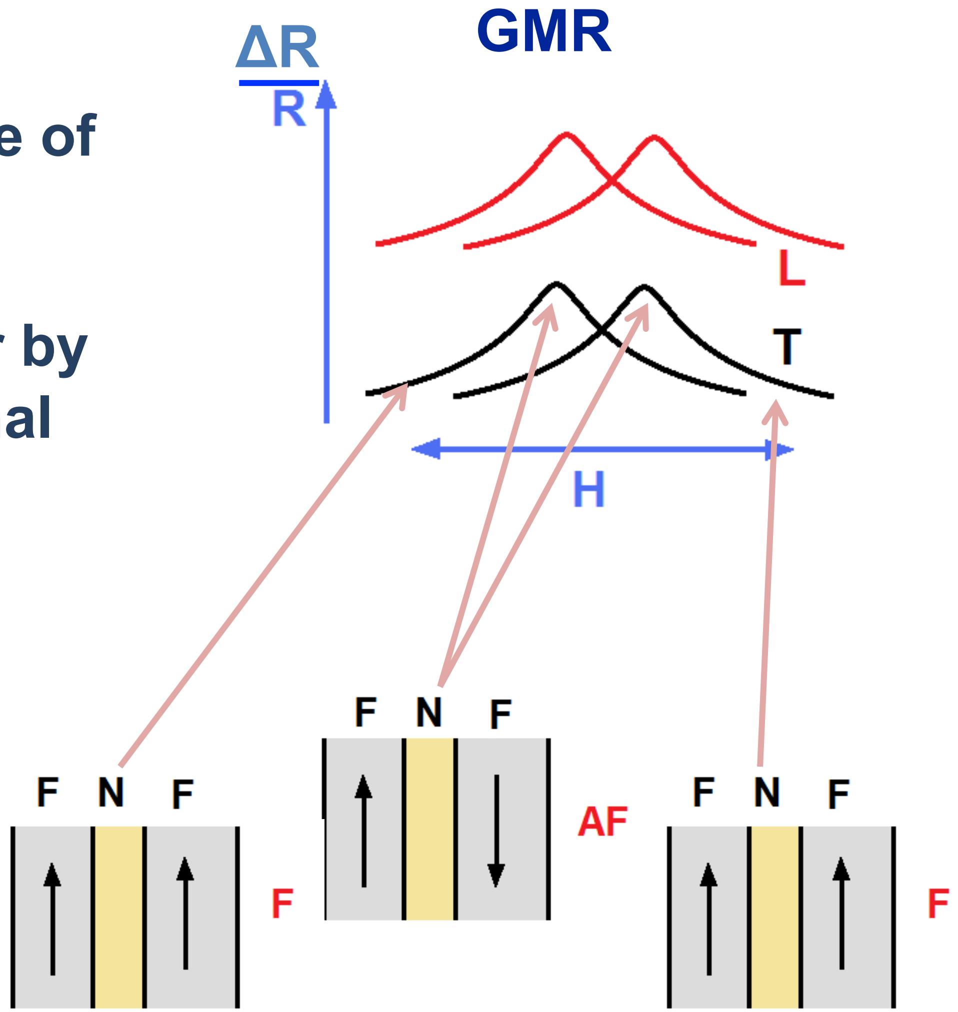


Giant magnetoresistance (GMR)

GMR

Is the change in electrical resistance of layered F/N/F systems when the magnetization of the ferromagnetic layers are reoriented to one another by the application of a magnetic external field.

$$MR = \frac{\Delta R}{R^F} = \frac{R^{AF} - R^F}{R^F}$$



Giant magnetoresistance (GMR)

GMR

Originates from the spin dependent electronic transport intrinsic to metal systems

Spin dependent electronic transport can be qualitatively understood using the Mott model that has 2 main points:

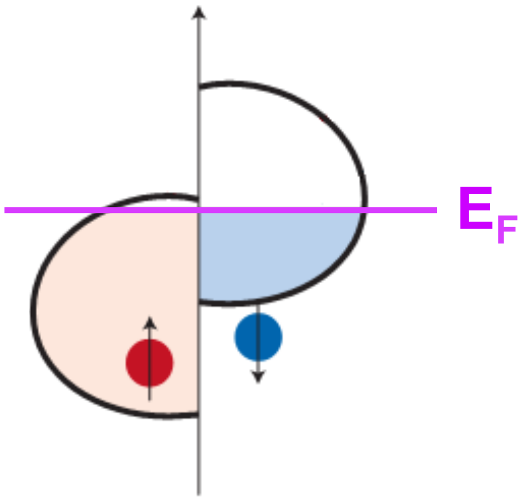
1. The electrical conductivity in metals can be described by 2 independent conducting channels, corresponding to up- and down-spin electrons

The probability of spin-flip scattering is normally small than the probability of scattering with conservation of spin, i. e. up- and down-spin do not mix over long distances.

Giant magnetoresistance (GMR)

GMR

2. In ferromagnetic metals the scattering rates of up- and down-spin electrons are quite different, whatever be the nature of the scattering centers.



Ferromagnets

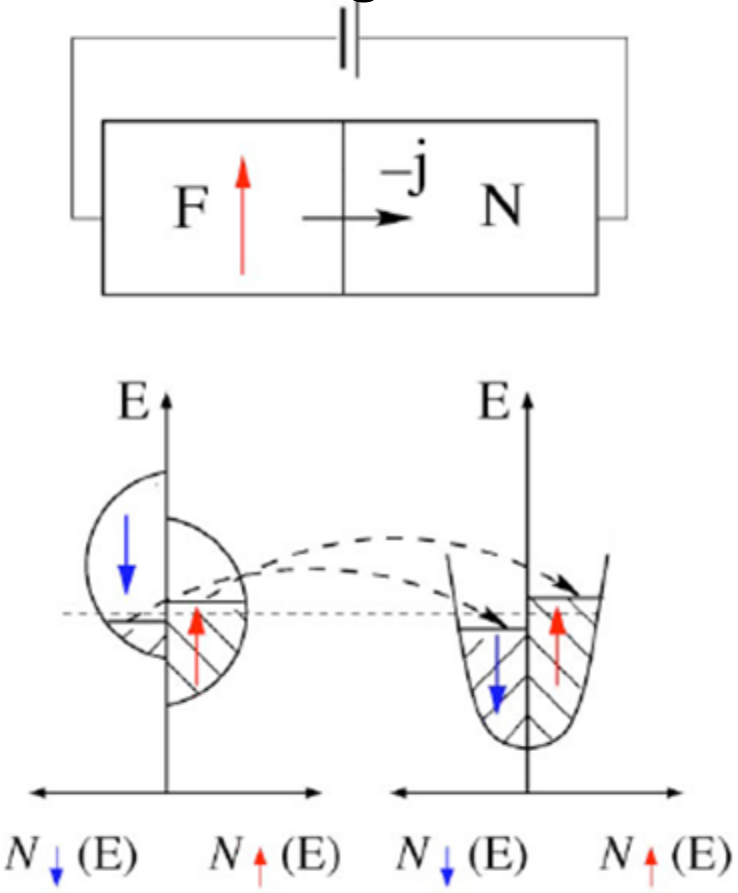
Different spin densities at Fermi level

The electric current is primarily carried by electrons from ***sp*** bands due to their low effective mass and high mobility. The ***d*** bands provide the final states for scattering of the ***sp*** electrons.

In ferromagnets the ***d*** band have exchange-split, and the density of states (DOS) is not the same for up- and down-spin electrons at the Fermi level. The probability of scattering into these states is proportional to their density, such that the scattering rates are spin dependent.

Spin polarized current

Ferromagnetic/non-ferromagnetic interface



γ = spin asymmetry interface coefficient

conductivity

$$\sigma_{\uparrow(\downarrow)} = e^2 N_{\uparrow(\downarrow)}(E_F) D_{\uparrow(\downarrow)}$$

N = density of levels

D = diffusion coefficient

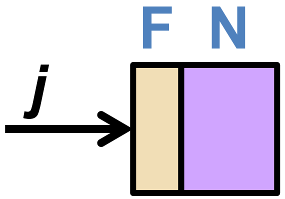
polarization

$$P_{corrente} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

Spin polarized current

Valet and Fert model

1. Current flowing perpendicular to the plane (CPP)

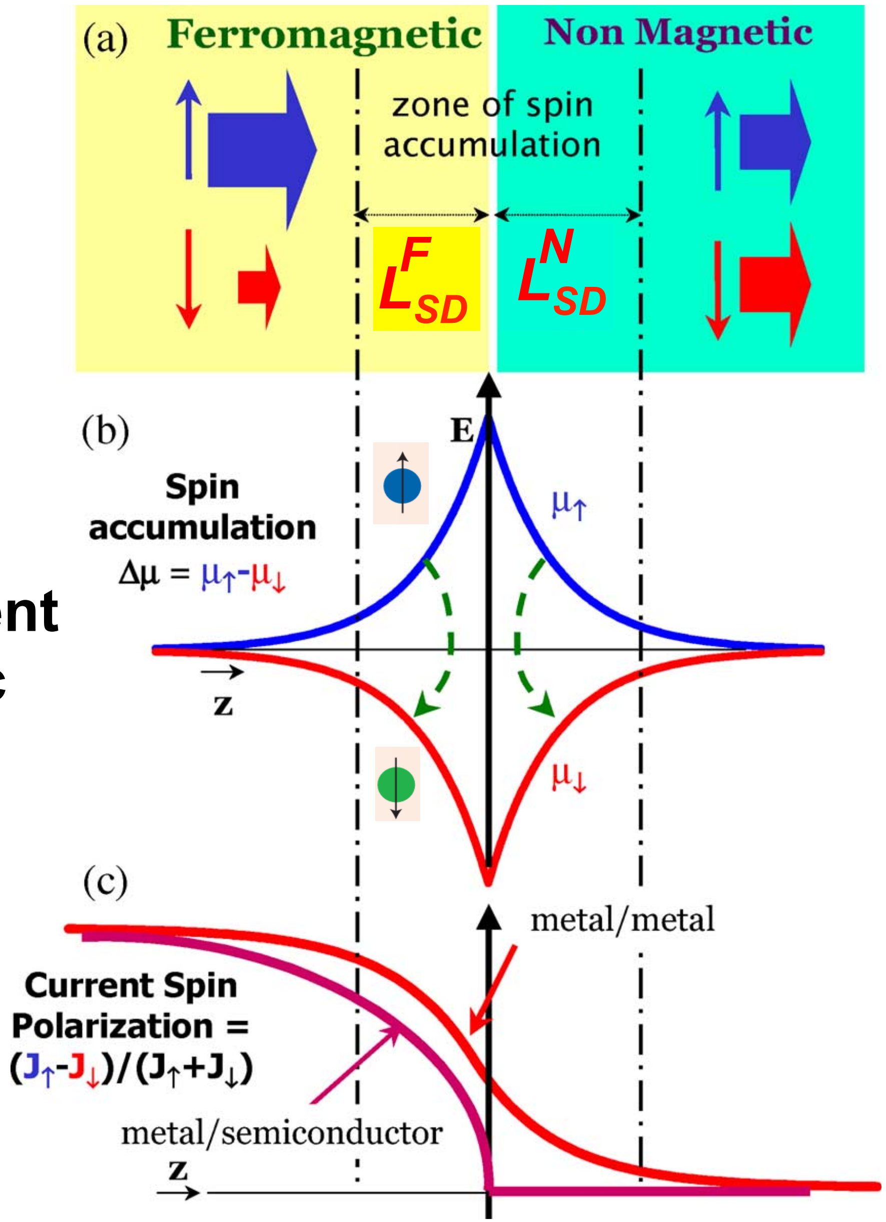


2. Take into account the diffusive spin transport through the interface (the current is spin polarized well beyond the ballistic range)

3a. Metal/metal case: $\mathrm{DOS_F \approx DOS_N}$

3b. Metal/semicond. case: $\mathrm{DOS_F >> DOS_S}$ (conductivity mismatch)

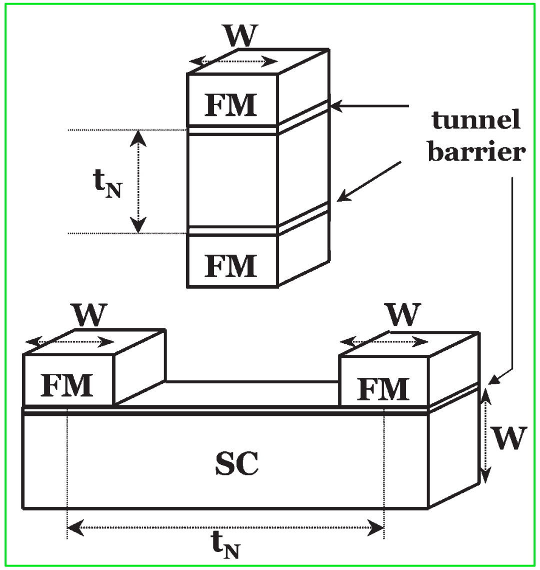
L_{SD} = spin diffusion length



G. Schmidt *et al.*, "Fundamental obstacle for electrical spin injection from a ferromagnetic metal into a diffusive semiconductor," *Phys. Rev. B, Condens. Matter*, vol. 62, no. 8, pp. R4790–R4793, Aug. 2000.

A. Fert, J.-M. George, H. Jaffrès, and R. Mattana IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 54, NO. 5, MAY 2007

Spin polarized current

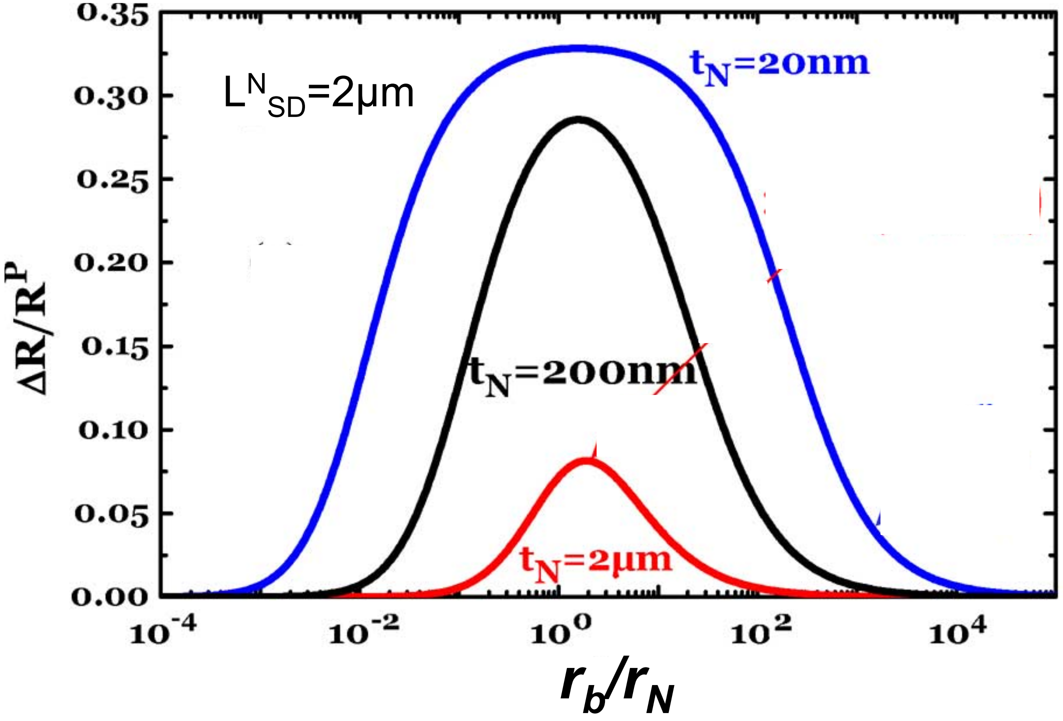


Using a tunnel barrier at the interface to balance the number of spin flips in F and N, restoring the spin polarization of the electric current.

The conditions for an efficient spin injection are:

$$r_1 = \rho_N t_N << r_b << \rho_N \frac{(L_{SD}^N)^2}{t_N} = r_2$$

r_b = barrier specific area resistance
r_1 and r_2 are lower and upper limits for r_b
ρ_N resistivity of semiconductor
t_N distance between contacts
$r_N = \rho_N.L^N_{SD}$ and $r_F = \rho_F.L^F_{SD}$



Rashba, PRB 62, R16267 (2000)
Fert and Jaffrès, PRB 64, 184420 (2001)

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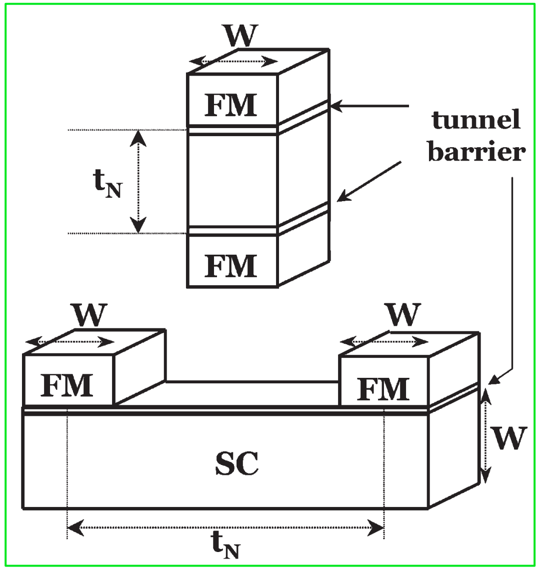
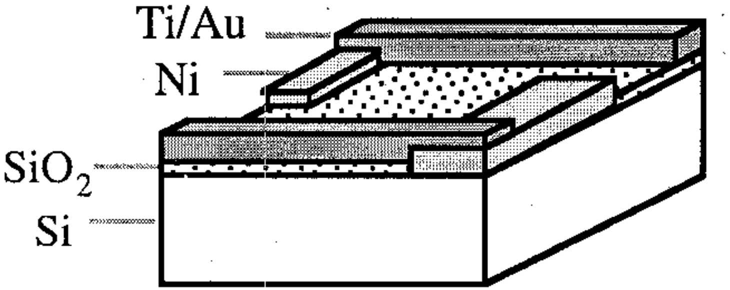


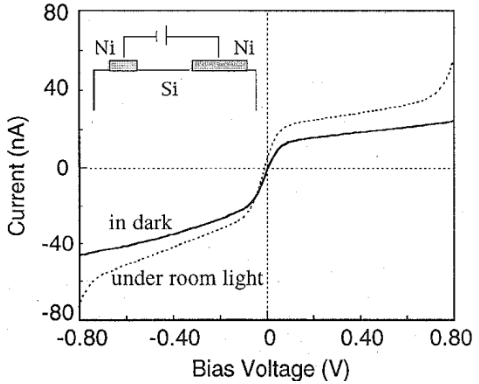
$$MR = \frac{\Delta R}{R} = \frac{\gamma^2/(1-\gamma^2)}{1 + r_b/r_2}$$

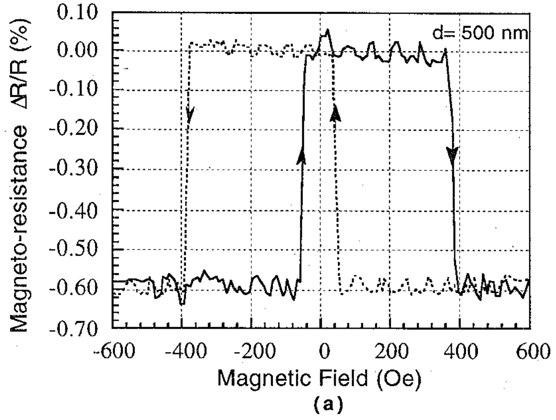
γ = spin asymmetry interface coefficient

Results from de literature



Ni electrode spacing of 500 nm.

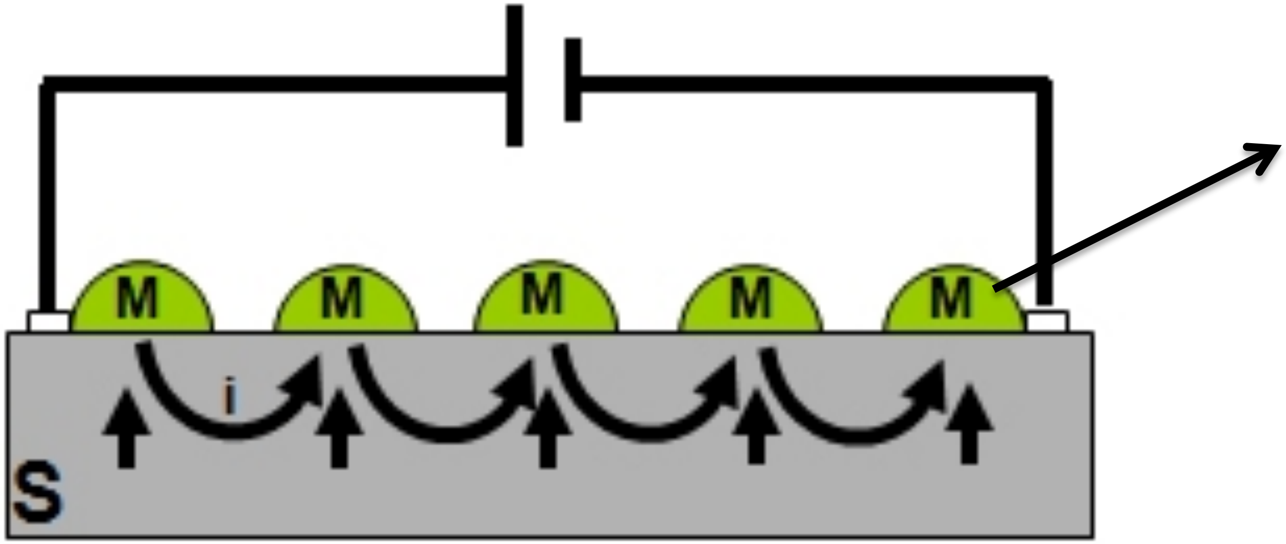




Y. Q. Jia, Rick C. Shi, and Stephen Y. Chou, IEEE TRANS. on MAGNETICS. 32 (1996)

Fabrication of the samples – first approach

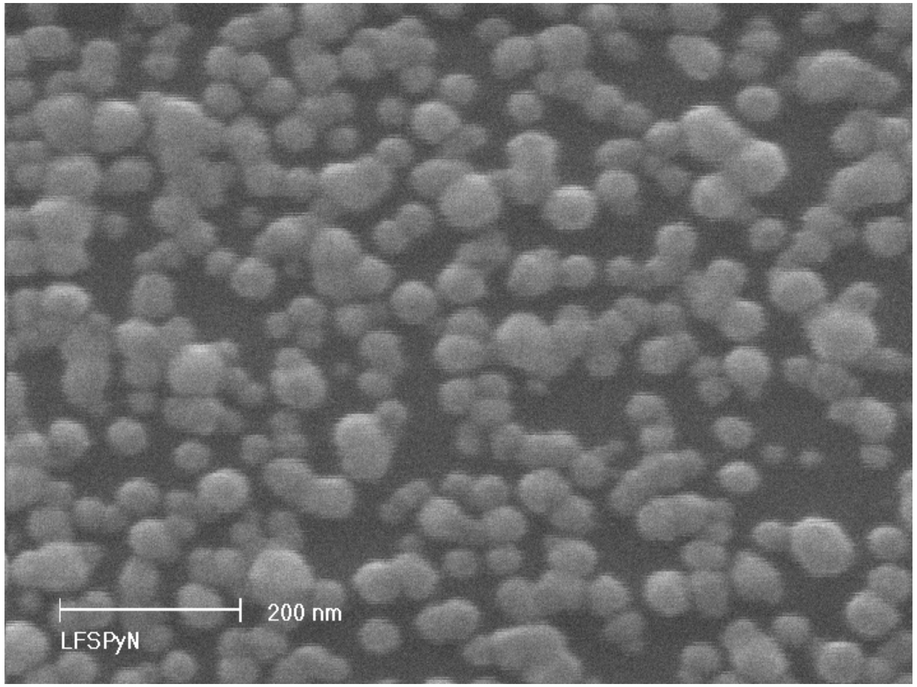
Electrodeposition



Permalloy (Py) clusters electrodeposited on Silicon (Si)

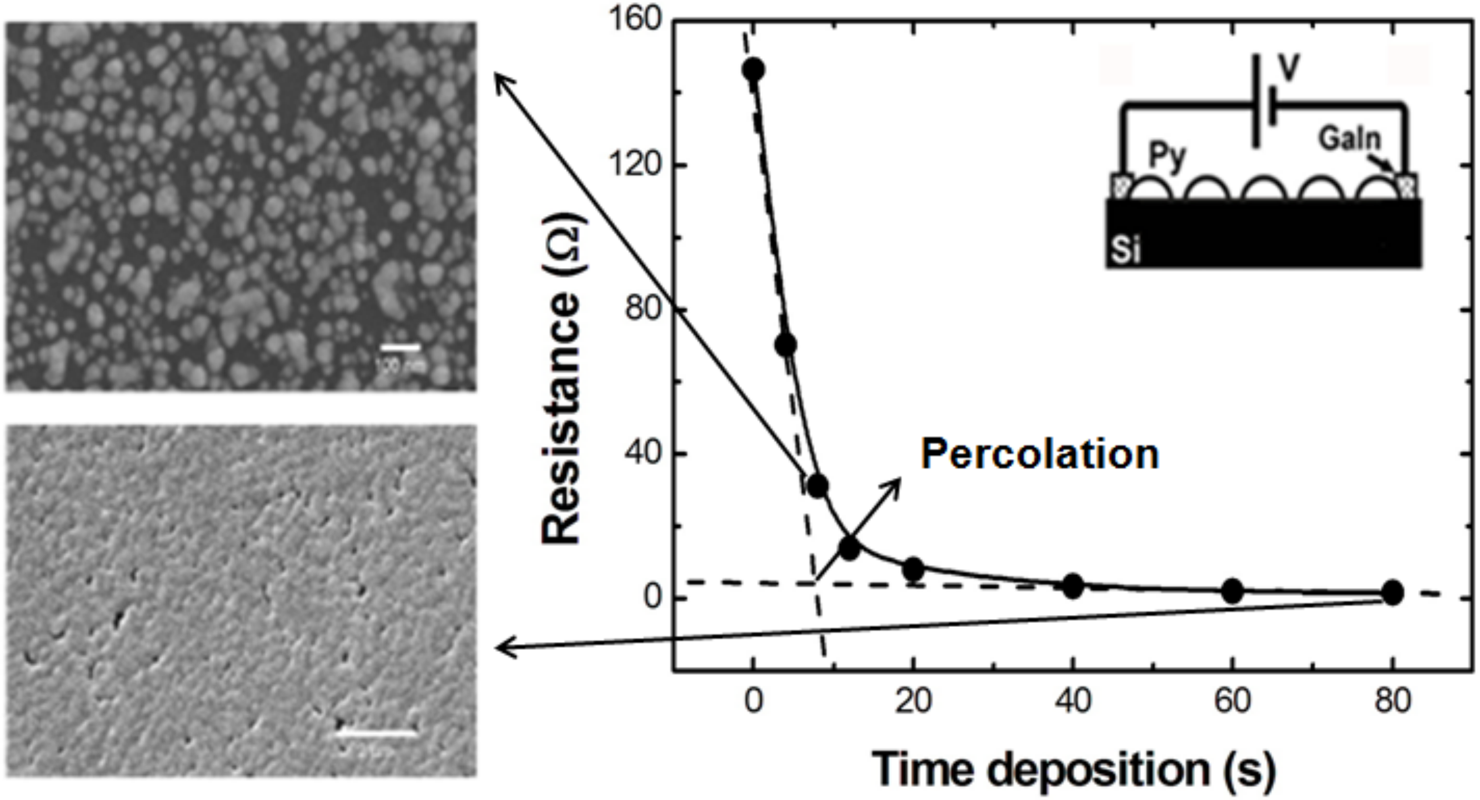
Permalloy: ferromagnetic alloy with 80% Ni and 20% Fe

Electrodeposition of FeNi (Py) clusters on silicon

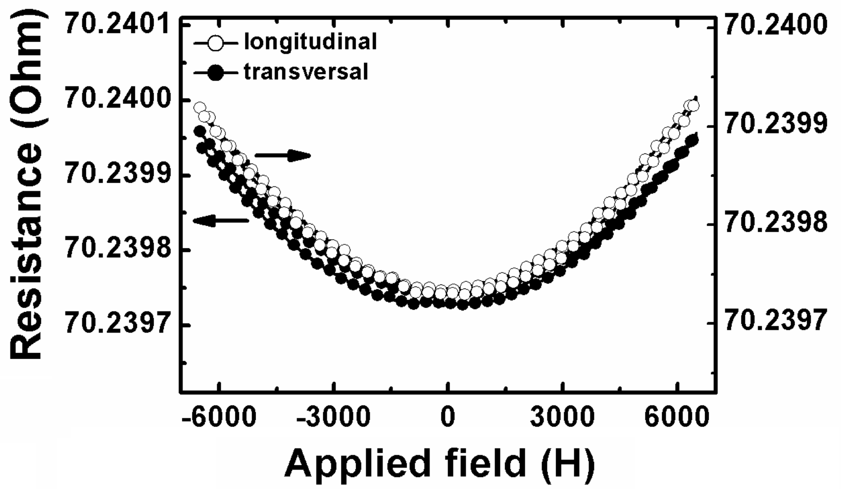


Deposition time t = 8 s

Py/Si system - Electrical measurements

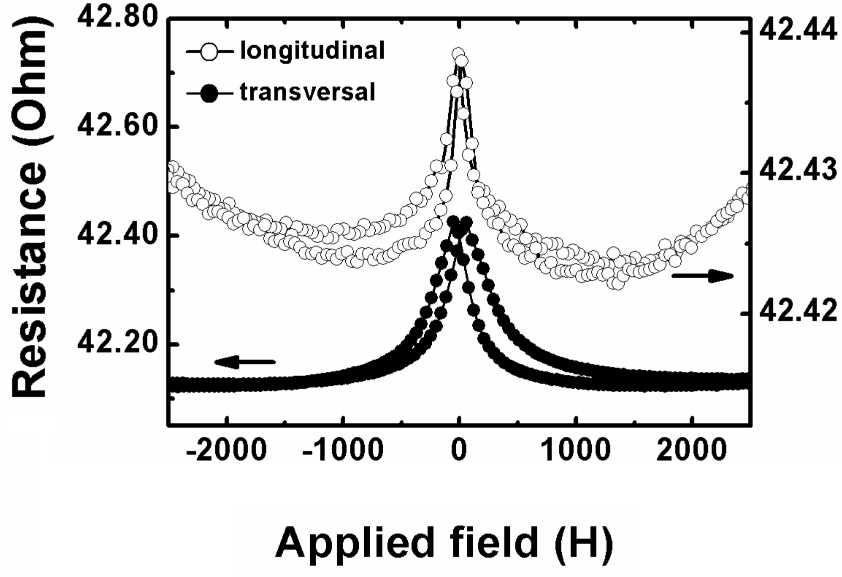


Py/Si system - MR measurements (room temperature)

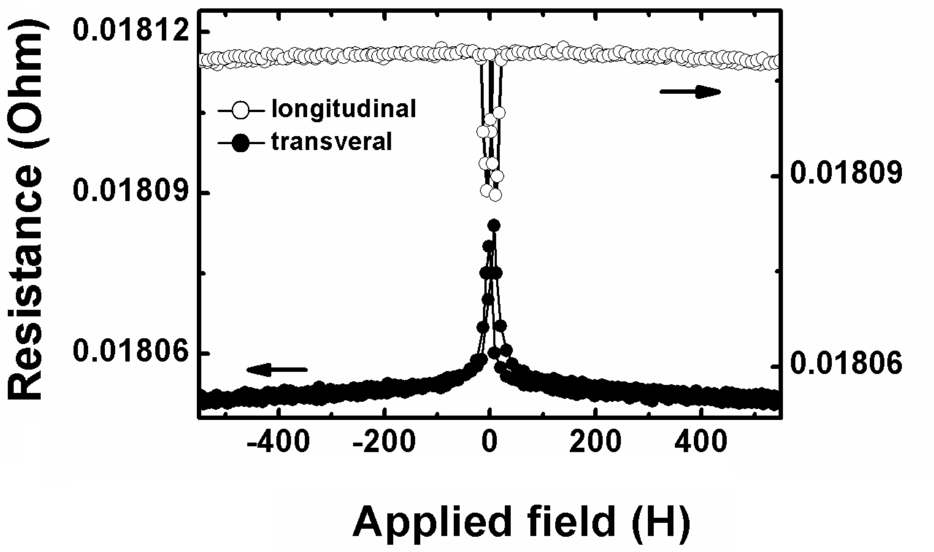


t = 0 s

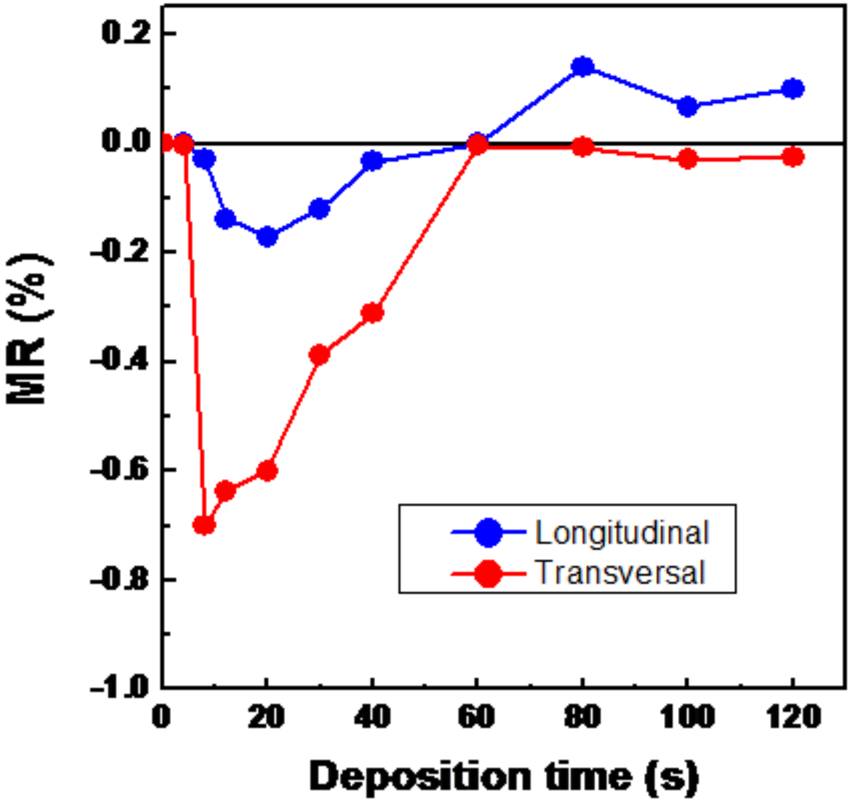
t = 8 s



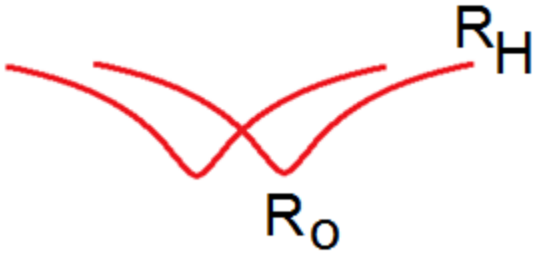
t = 80 s



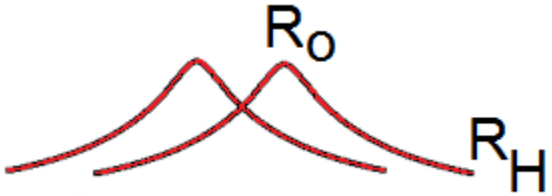
Py/Si system - MR measurements (room temperature)



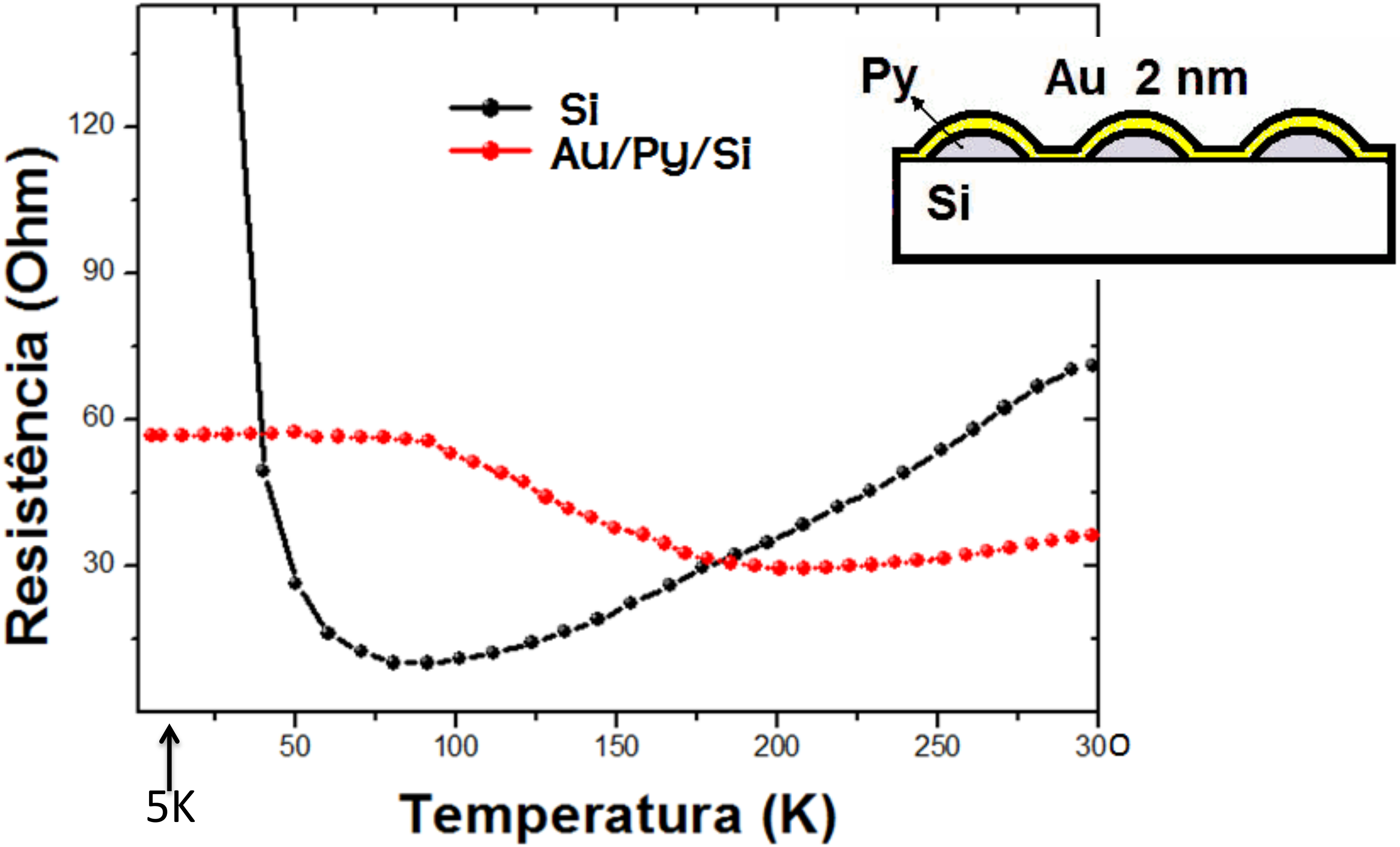
$$MR(positive) = \frac{(R_H - R_o)}{R_o}$$



$$MR(negative) = \frac{(R_o - R_H)}{R_H}$$



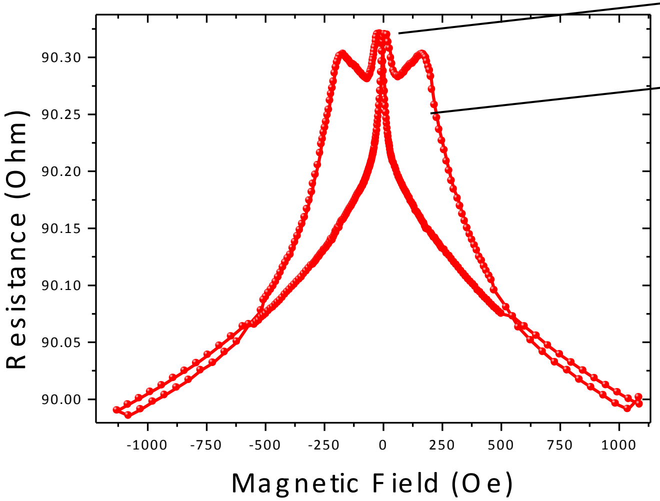
Py/Si system with an Au layer



MR vs Temperature

transversal measurements

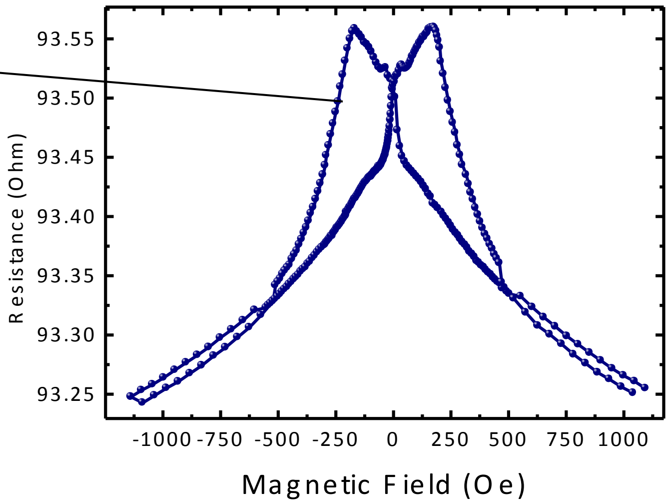
5 K



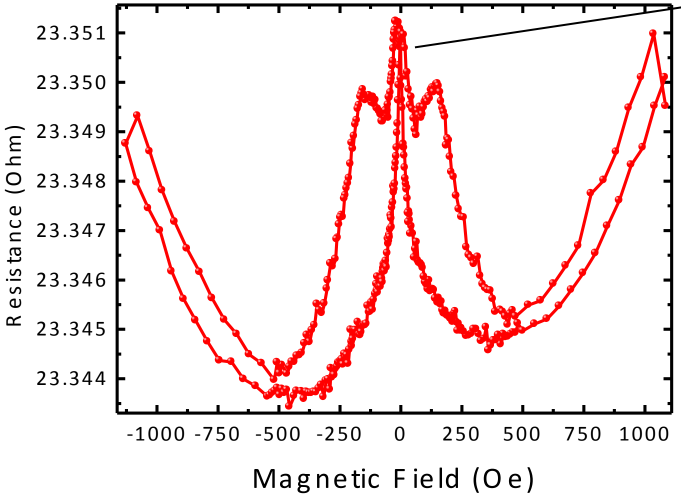
GMR

AMR

5 K - Au

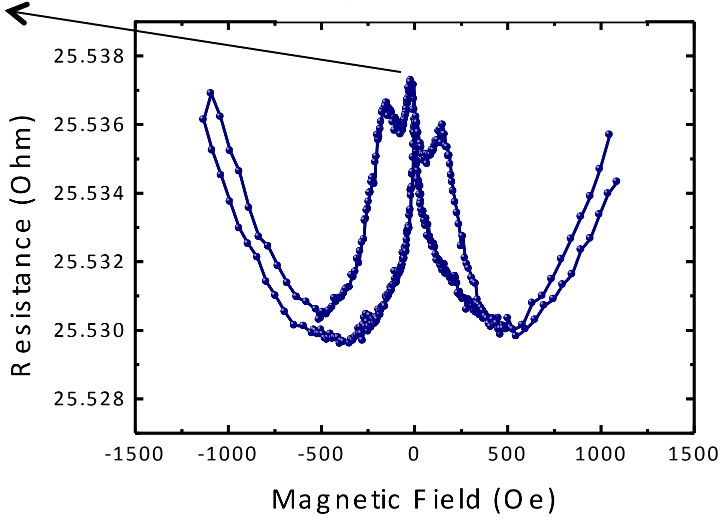


180 K



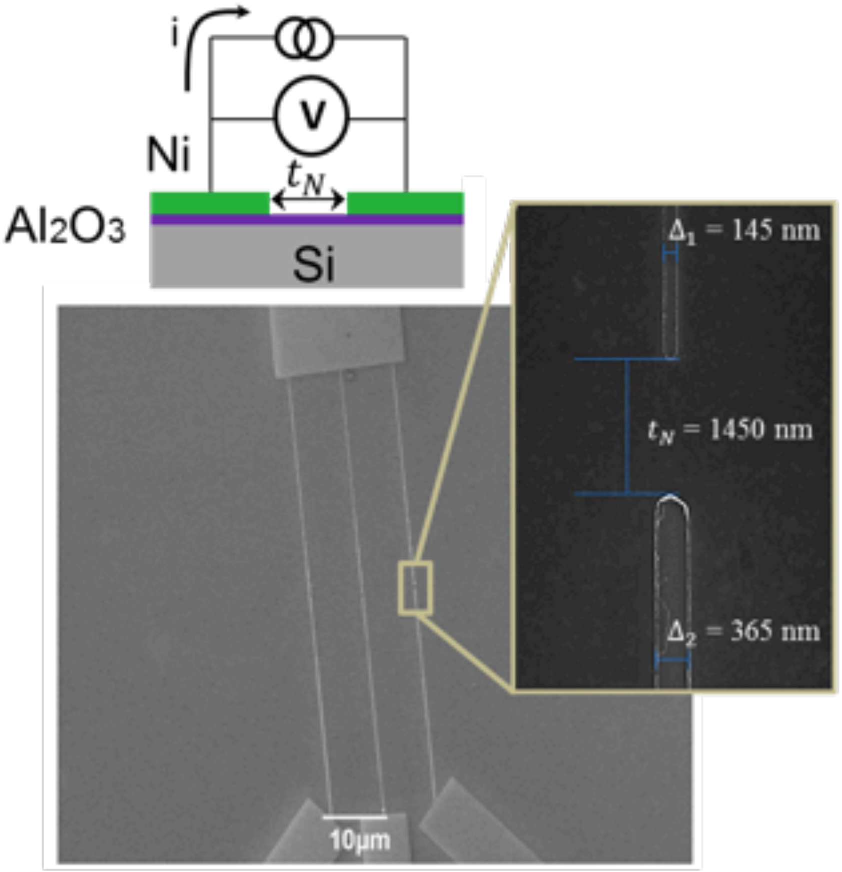
GMR

180 K - Au



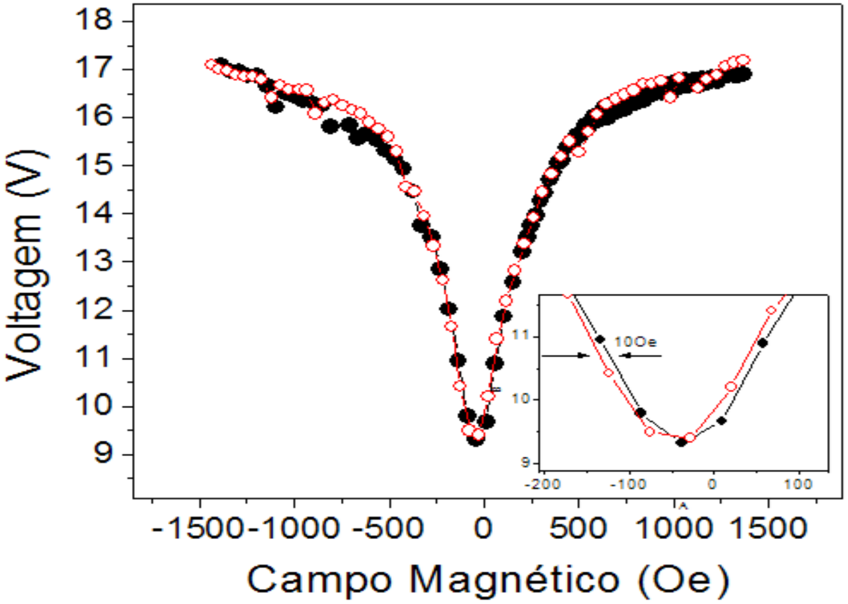
Fabrication of the samples – second approach

Nanofabrication

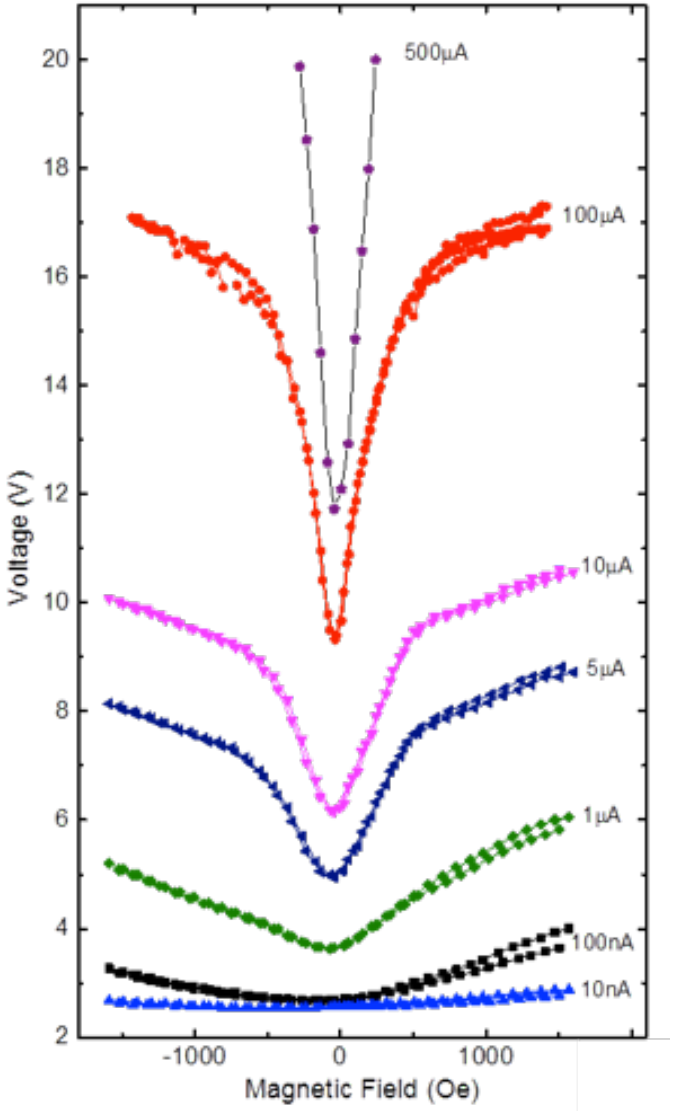


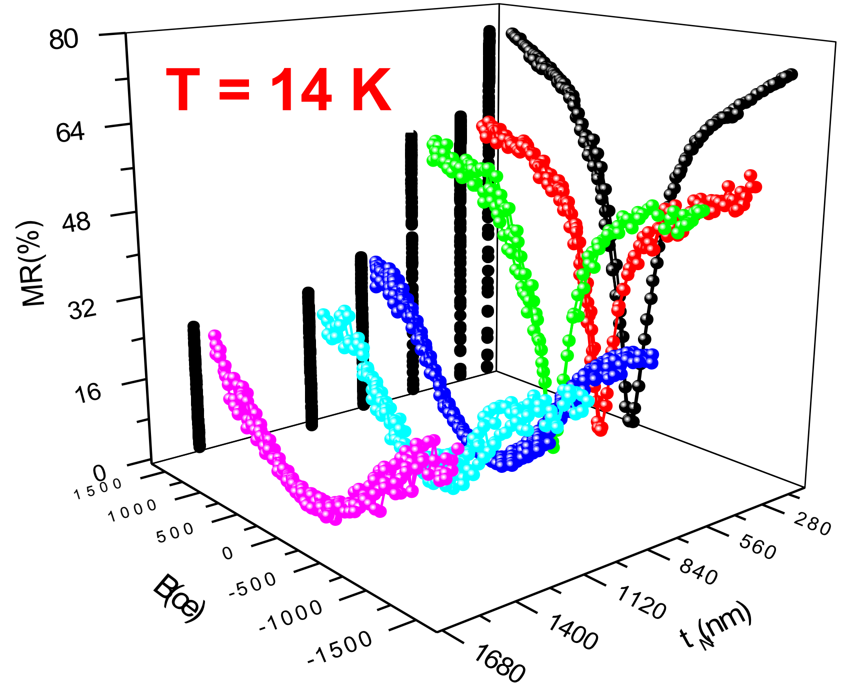
Electron beam lithography (CBPF/RIO de Janeiro)

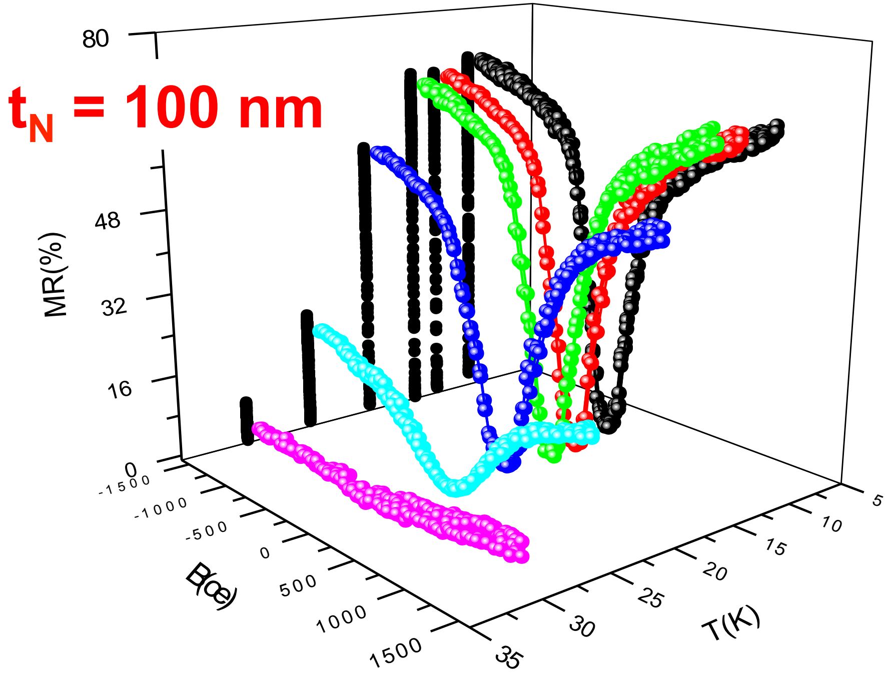
- **Ni and Al_2O_3 evaporated**
- **t_N from 100 nm up o 1450 nm**
- **$\rho_{n\text{-}Si} = 1 \times 10^{15}\ \Omega.cm^{-3}$**

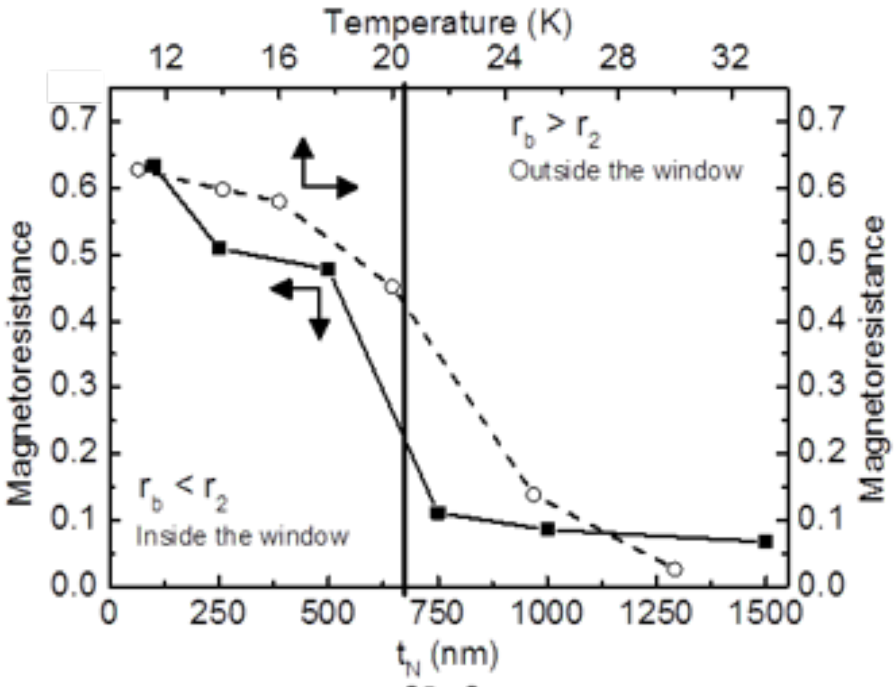


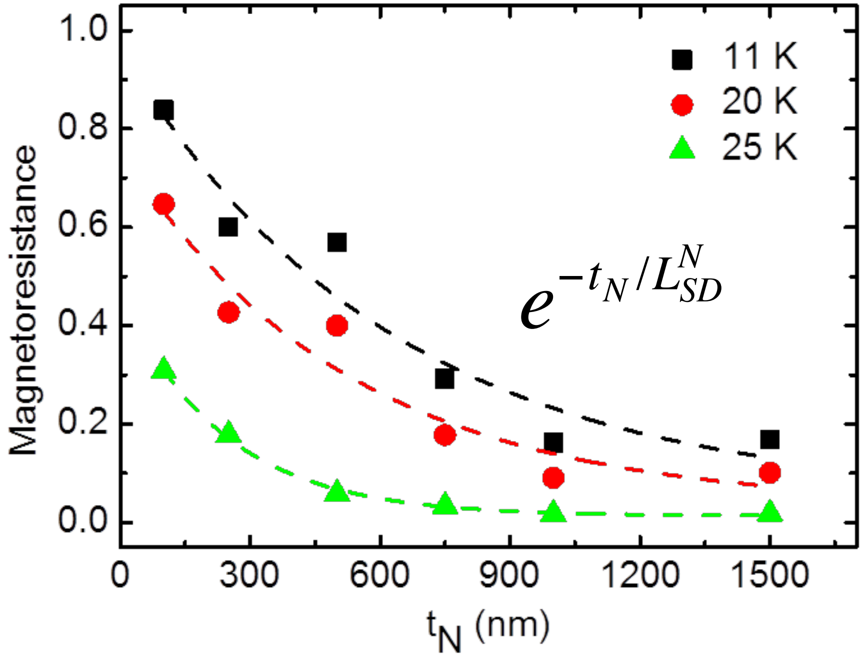
Results for nanocontacts



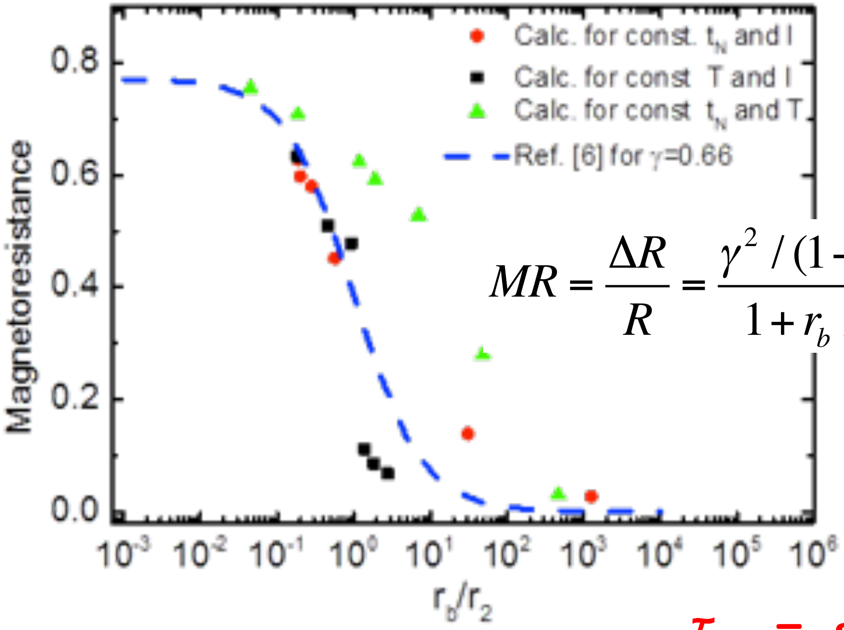




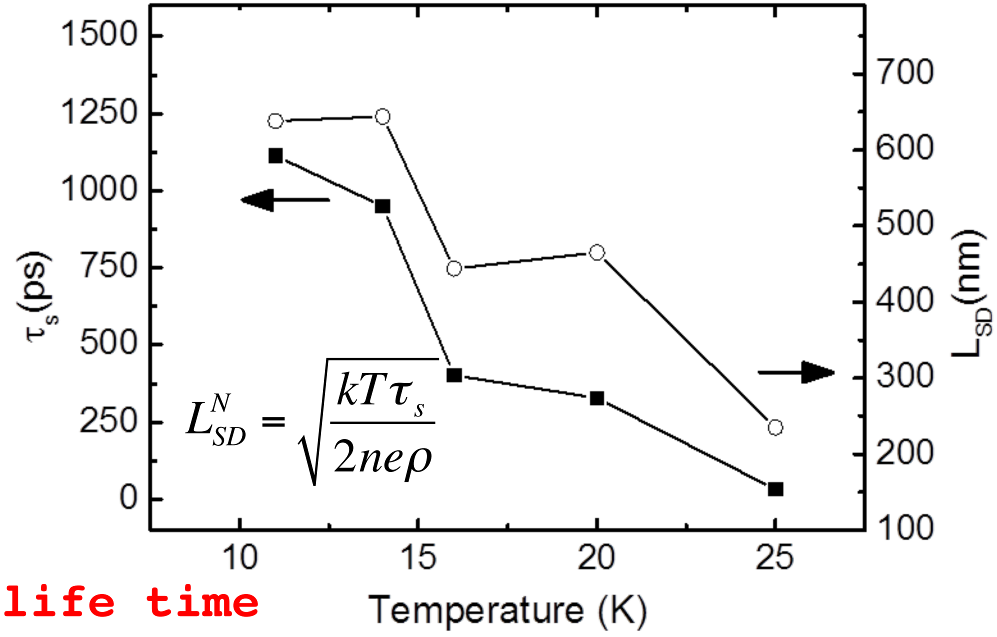




$$e^{-t_N/L_{SD}^N}$$

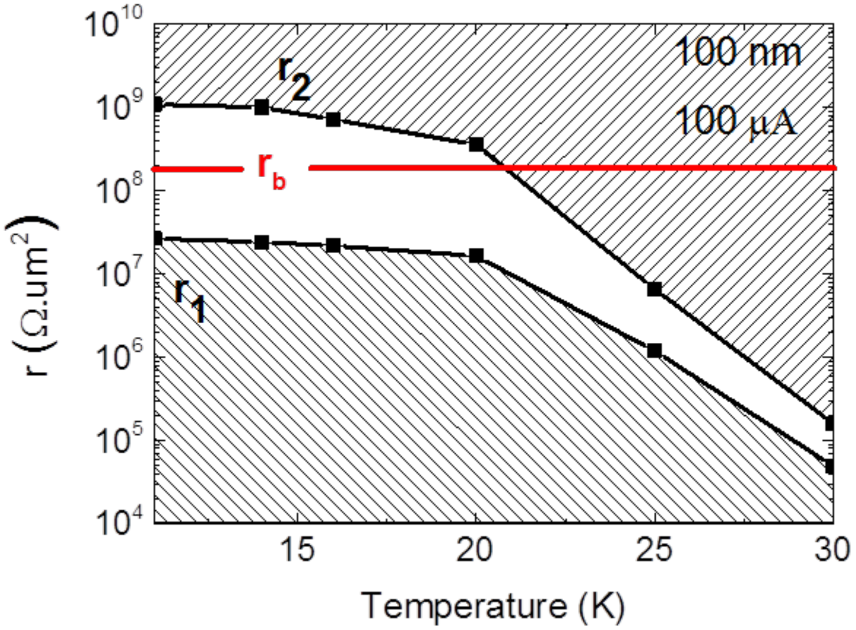


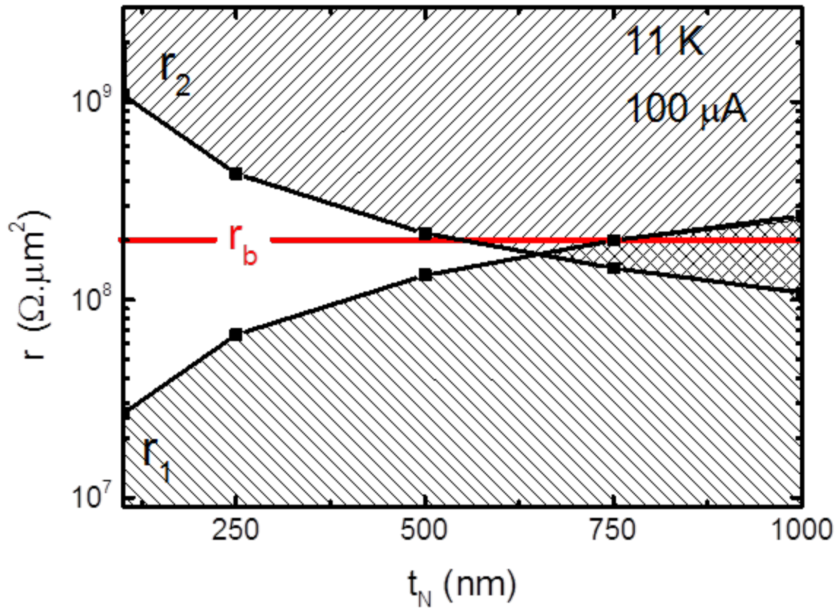
$$MR = \frac{\Delta R}{R} = \frac{\gamma^2/(1-\gamma^2)}{1 + r_b/r_2}$$

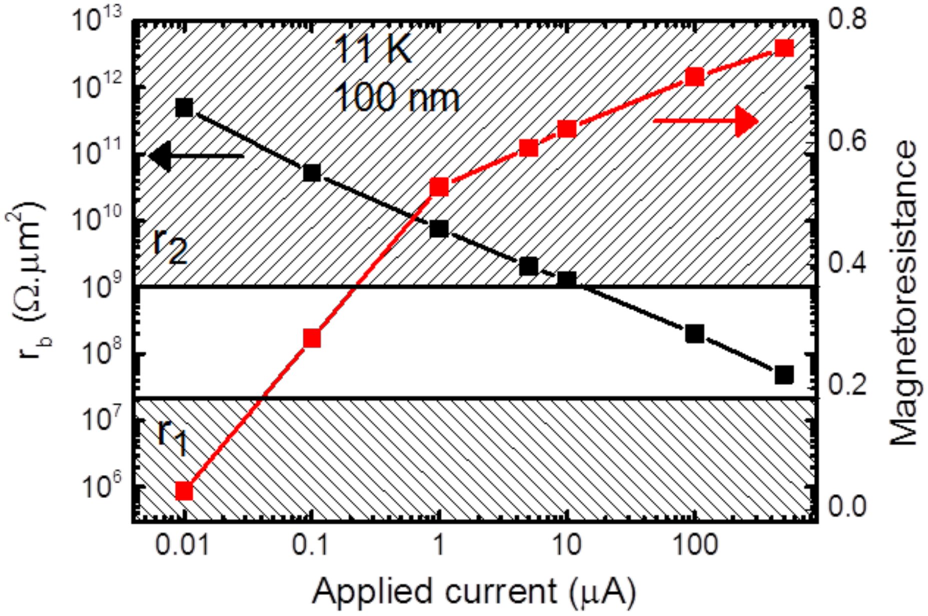


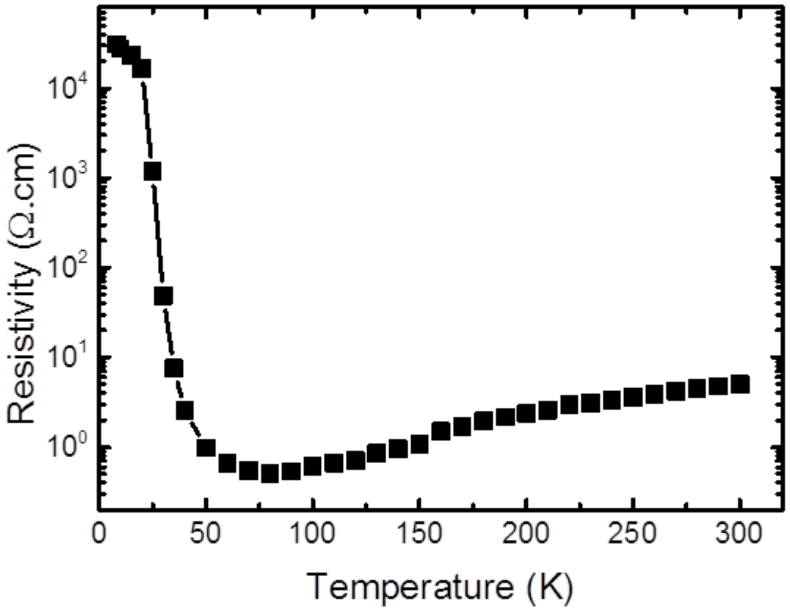
$$L_{SD}^N = \sqrt{\frac{kT\tau_s}{2ne\rho}}$$

τ_s = spin life time


100 nm
100 μA
r_2
r_b
r_1
$r\ (\Omega.\mathrm{um}^2)$
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
15
20
25
30
Temperature (K)


11 K
100 μA
r_2
r_b
r_1
$r\ (\Omega.\mu\mathrm{m}^2)$
10^9
10^8
10^7
250
500
750
1000
t_N (nm)


11 K
100 nm
r_2
r_1
$r_b\ (\Omega.\mu\mathrm{m}^2)$
10^{13}
10^{12}
10^{11}
10^{10}
10^9
10^8
10^7
10^6
Magnetoresistance
0.8
0.6
0.4
0.2
0.0
0.01
0.1
1
10
100
Applied current (μA)


Resistivity (Ω.cm)
10^4
10^3
10^2
10^1
10^0
0
50
100
150
200
250
300
Temperature (K)

Conclusions:

- ✓ High MR values (up to 75%) at temperatures below 35 K
- ✓ Results follow very well the model developed by Valet and Fert with a tunnel barrier at the interface introduced by Fert and Jaffrès that consider the spin injection as a diffusional process
- ✓ Determination of L^{N}_{sf} varying in the range from 200 nm to 700 nm for temperatures decreasing from 35 K to 10 K (n-Si with a resistivity of 10^{15} cm^{-3}.
- ✓ The dependency of the silicon resistance with the temperature is main factor contributing to the upper limit of the resistance window, where the GMR exists.

Thank you for the attention!