6.1 GMR vs spin polarization

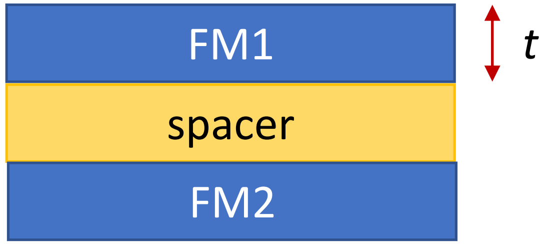
Consider a GMR device made of three layers with identical thickness *t*.

In the two current model the conductivity is $\sigma = \frac{1}{R} = \sigma_{\uparrow} + \sigma_{\downarrow} = \frac{1}{R_{\uparrow}} + \frac{1}{R_{\downarrow}}$.

Neglecting the resistance of the spacer and of defects at the interfaces, demonstrate that

1) $GMR = \frac{R_{AP}-R_P}{R_P} = \frac{(1-\alpha)^2}{4\alpha}$ *with* $\alpha = \frac{\rho_{\downarrow}}{\rho_{\uparrow}}$

This is also the maximum value expected for the GMR. Including spacer and interface resistances reduces the GMR value



2) Calculate the GMR when the spacer is considered (hint: assume the spacer as consisting of two identical portion of thickness *d=t/2*)

3) Using the α value given in the lecture, estimate the maximum GMR for Fe/Cu/Fe and Co/Cu/Co

6.1 GMR vs spin polarization

1) The resistance (per unit of area) of electrons travelling through a magnetic material is $R_{\uparrow,\downarrow} = \rho_{\uparrow,\downarrow} t$

In a GMR device in parallel configuration, we will have $R_{P\uparrow,\downarrow} = 2\rho_{\uparrow,\downarrow} t$ and thus $\frac{1}{R_P} = \frac{1}{R_{P\uparrow}} + \frac{1}{R_{P\downarrow}} = \frac{1}{2t}(\frac{1}{\rho_\uparrow} + \frac{1}{\rho_\downarrow}) \Rightarrow R_P = 2t\frac{\rho_\uparrow * \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow}$

In a GMR device in anti-parallel configuration, we will have $R_{AP\uparrow,\downarrow} = (\rho_\uparrow + \rho_\downarrow)t$ and thus $\frac{1}{R_{AP}} = \frac{1}{R_{AP\uparrow}} + \frac{1}{R_{AP\downarrow}} = \frac{1}{t}\frac{2}{\rho_\uparrow + \rho_\downarrow} \Rightarrow R_{AP} = t\frac{\rho_\uparrow + \rho_\downarrow}{2}$

We then find that:

$$R_{AP} - R_P = t\frac{\rho_\uparrow + \rho_\downarrow}{2} - 2t\frac{\rho_\uparrow * \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow} = t\left(\frac{(\rho_\uparrow + \rho_\downarrow)^2 - 4\rho_\uparrow * \rho_\downarrow}{2(\rho_\uparrow + \rho_\downarrow)}\right) = \frac{t}{2}\frac{(\rho_\uparrow - \rho_\downarrow)^2}{\rho_\uparrow + \rho_\downarrow},$$

$$R_{AP} + R_P = t\frac{\rho_\uparrow + \rho_\downarrow}{2} + 2t\frac{\rho_\uparrow * \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow} = t\left(\frac{(\rho_\uparrow + \rho_\downarrow)^2 + 4\rho_\uparrow * \rho_\downarrow}{2(\rho_\uparrow + \rho_\downarrow)}\right) = \frac{t}{2}\frac{(\rho_\uparrow + \rho_\downarrow)^2}{\rho_\uparrow + \rho_\downarrow} = \frac{t}{2}(\rho_\uparrow + \rho_\downarrow).$$

$$GMR = \frac{R_{AP} - R_P}{R_P} = \frac{t}{2}\frac{(\rho_\uparrow - \rho_\downarrow)^2}{\rho_\uparrow + \rho_\downarrow}\frac{1}{2t\frac{\rho_\uparrow * \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow}} = \frac{1}{4}\frac{(\rho_\uparrow - \rho_\downarrow)^2}{\rho_\uparrow * \rho_\downarrow} = \frac{1}{4}{\rho_\uparrow}^2\frac{(1 - \rho_\downarrow/\rho_\uparrow)^2}{\rho_\uparrow * \rho_\downarrow} = \frac{(1-\alpha)^2}{4\alpha}.$$

2) The effect of the spacer can be easily understood considering each FM layer as composed by the FM itself + half spacer such that

$R_{\uparrow,\downarrow} = \rho_{\uparrow,\downarrow} t + d\,\rho_{NM} = \rho_{\uparrow,\downarrow} t + \frac{t}{2}\rho_{NM} = \rho_{\uparrow,\downarrow} t(1 + \frac{1}{2}\frac{\rho_{NM}}{\rho_{\uparrow,\downarrow}})$. Then, the GMR is easily found by replacing $\rho_{\uparrow,\downarrow}$ with $\rho_{\uparrow,\downarrow} t(1 + \frac{1}{2}\frac{\rho_{NM}}{\rho_{\uparrow,\downarrow}})$, giving

$GMR = \frac{R_{AP} - R_P}{R_P} = \frac{(1-\alpha)^2}{4\alpha(1 + \frac{1}{2}\frac{\rho_{NM}}{\rho_\uparrow})(1 + \frac{1}{2}\frac{\rho_{NM}}{\rho_\downarrow})}$. Since $\rho_{Cu} < 0.1\,\rho_{Co.Fe}$, the correction is small

3) $\alpha_{Fe} \approx 1.3 \Rightarrow$ GMR = 1.7%

$\alpha_{Co} \approx 4.7 \Rightarrow$ GMR = 73%

Consider the trilayer of a TMR spin valve. Assuming that electron tunneling does not depend on the wave function symmetry, demonstrate that the magnetoresistance is related to the spin polarizations of layer *i* (P_i) by the relation:

$$\mathrm{TMR} = \frac{I_P - I_{AP}}{I_{AP} + I_P} = P_L P_R.$$

(see M. Julliere, Phys. Lett. A **54**, 225 (1975))

TMR: Tunnel magneto resistance

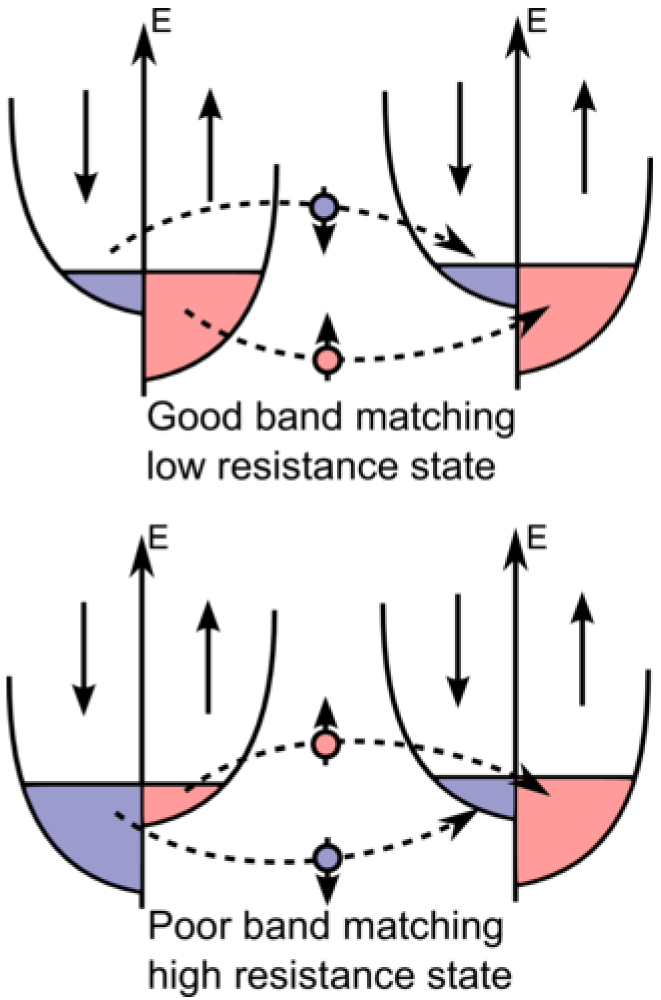


Image from https://www.iue.tuwien.ac.at/phd/makarov/dissertationch4.html

6.2 TMR vs spin polarization - Solution

The tunneling current is proportional to $N_L N_R$

Thus, we have: $I_{\uparrow\uparrow} = N_{L\uparrow}N_{R\uparrow}$; $I_{\downarrow\downarrow} = N_{L\downarrow}N_{R\downarrow}$; $I_{\uparrow\downarrow} = N_{L\uparrow}N_{R\downarrow}$; $I_{\downarrow\uparrow} = N_{L\downarrow}N_{R\uparrow}$

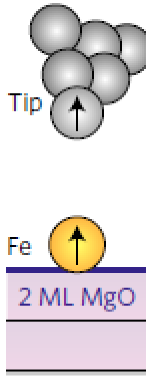
We also obtain that: $I_P = I_{\uparrow\uparrow} + I_{\downarrow\downarrow} = N_{L\uparrow}N_{R\uparrow} + N_{L\downarrow}N_{R\downarrow}$ and $I_{AP} = I_{\uparrow\downarrow} + I_{\downarrow\uparrow} = N_{L\uparrow}N_{R\downarrow} + N_{L\downarrow}N_{R\uparrow}$

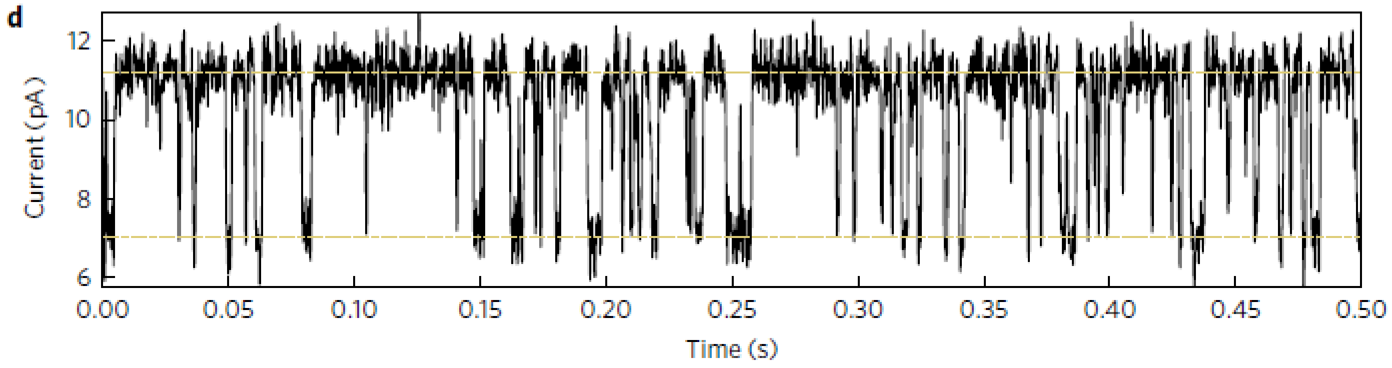
$$I_P - I_{AP} = N_{L\uparrow}N_{R\uparrow} + N_{L\downarrow}N_{R\downarrow} - N_{L\uparrow}N_{R\downarrow} - N_{L\downarrow}N_{R\uparrow} = N_{L\uparrow}(N_{R\uparrow} - N_{R\downarrow}) - N_{L\downarrow}(N_{R\uparrow} - N_{R\downarrow}) = (N_{L\uparrow} - N_{L\downarrow})(N_{R\uparrow} - N_{R\downarrow})$$
$$I_P + I_{AP} = N_{L\uparrow}N_{R\uparrow} + N_{L\downarrow}N_{R\downarrow} + N_{L\uparrow}N_{R\downarrow} + N_{L\downarrow}N_{R\uparrow} = N_{L\uparrow}(N_{R\uparrow} + N_{R\downarrow}) + N_{L\downarrow}(N_{R\uparrow} + N_{R\downarrow}) = (N_{L\uparrow} + N_{L\downarrow})(N_{R\uparrow} + N_{R\downarrow})$$

Then we have that $\mathrm{TMR} = \frac{I_P - I_{AP}}{I_{AP} + I_P} = \frac{(N_{L\uparrow} - N_{L\downarrow})(N_{R\uparrow} - N_{R\downarrow})}{(N_{L\uparrow} + N_{L\downarrow})(N_{R\uparrow} + N_{R\downarrow})} = P_L P_R$

6.3 Spin polarization of a single Fe atom on MgO

In a spin polarized STM measurement we position the STM tip covered with a magnetic layer on top of an Fe atom on MgO and we observe the time dependence of the tunneling current as reported in the figure. By an independent measurement we know that the tip spin polarization is about 30%.
Calculate the spin polarization of the Fe atom and compare with the spin polarization of the Fe bulk of about 45%



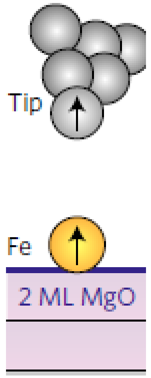


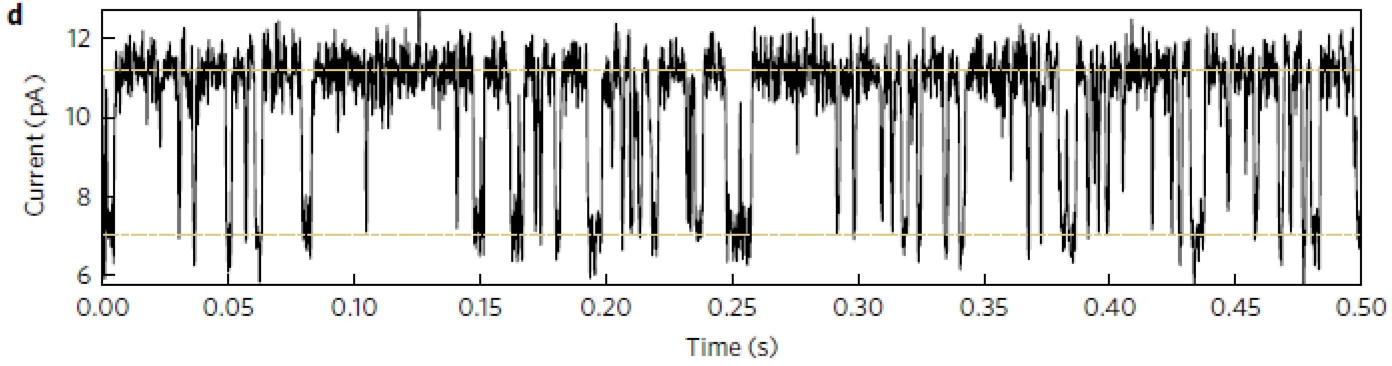
6.3 Spin polarization of a single Fe atom on MgO - Solution

The low current value corresponds to antiparallel states of tip and atom magnetization $I_{AP} = 7\ pA$ while the high value is observed for parallel alignment of the two magnetizations $I_{AP} = 11\ pA$. Then we observe a TMR = 4/18=22%

From exercise 6.1 we know that $TMR = P_1 * P_2$
from where we obtain that P_{atom} = 0.22/0.3= 0.73

As expected, the atom value (73%) is higher than the one for bulk due to band narrowing and splitting for reduced dimensionality





6.4 TMR using Fe, Co, and CoFe

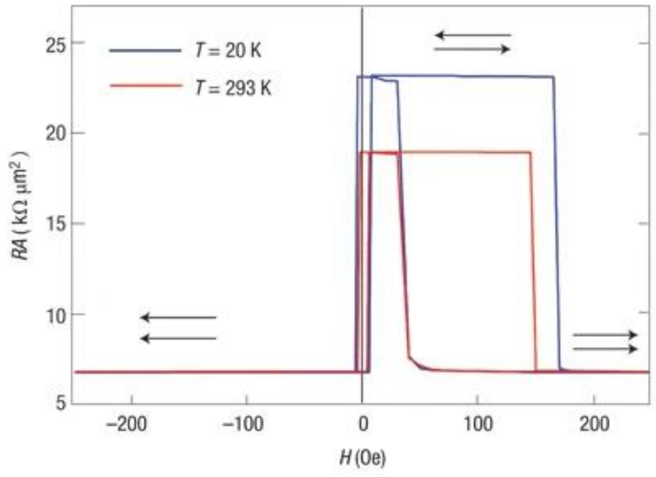
We compare the TMR values in M_1/MgO/M_2 spin valves as we vary the materials used to make the two ferromagnetic layers.

1) Using the bulk values for the spin polarization of different materials given in the lecture, calculate the expected TMR value for the three configuration shown below

2) Calculate the spin polarization of the materials based on the measurements shown below (use the LT value).

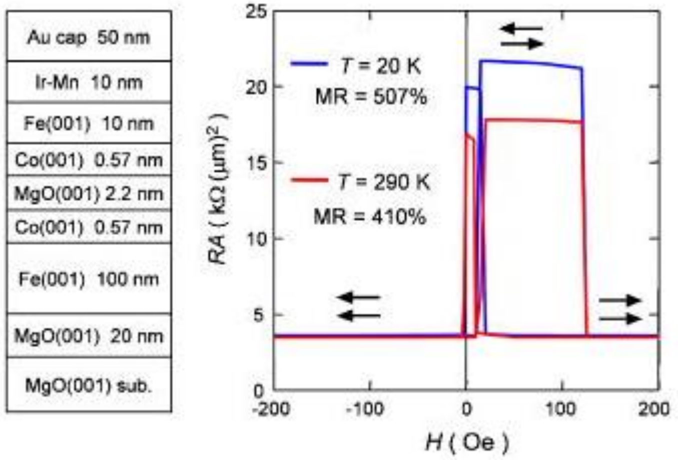
3) Fe, Co, and FeCo have roughly the same bulk spin polarization; then, why we observe different TMR values?

Fe/MgO/Fe



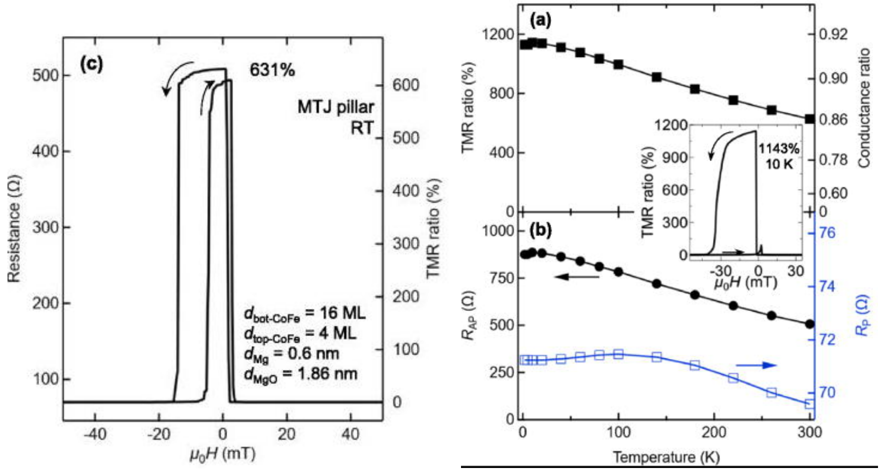
https://doi.org/10.1038/nmat1257

Co/MgO/Co



https://doi.org/10.1063/1.2236268

CoFe/MgO/CoFe



https://doi.org/10.1063/5.0145873

6.4 TMR using Fe, Co, and CoFe - Solution

1) Fe, Co, FeCo have roughly the same spin polarization of 42%, then in the three cases we expect roughly the same TMR = 18%

2)

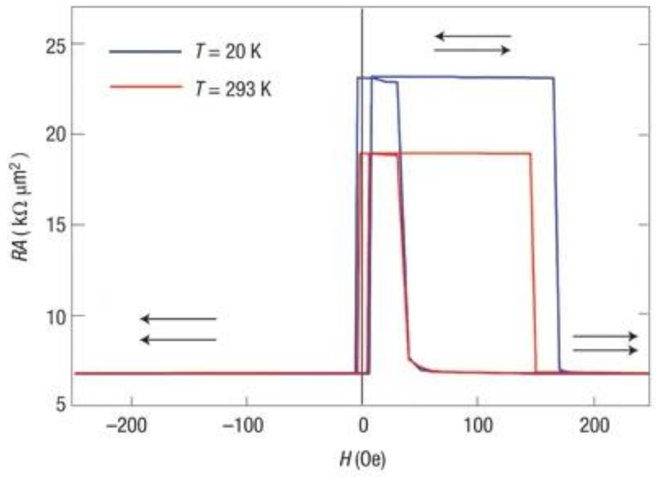
Fe/MgO/Fe: $TMR \approx \frac{23-7}{23+7} = 53\% \quad \Rightarrow P_{Fe} = \sqrt{0.53} = 73\%$

Co/MgO/Co: $TMR \approx \frac{22-4}{22+4} = 69\% \quad \Rightarrow P_{Co} = \sqrt{0.69} = 83\%$

FeCo/MgO/FeCo: $TMR \approx \frac{900-75}{900+75} = 85\% \quad \Rightarrow P_{FeCo} = \sqrt{0.85} = 92\%$

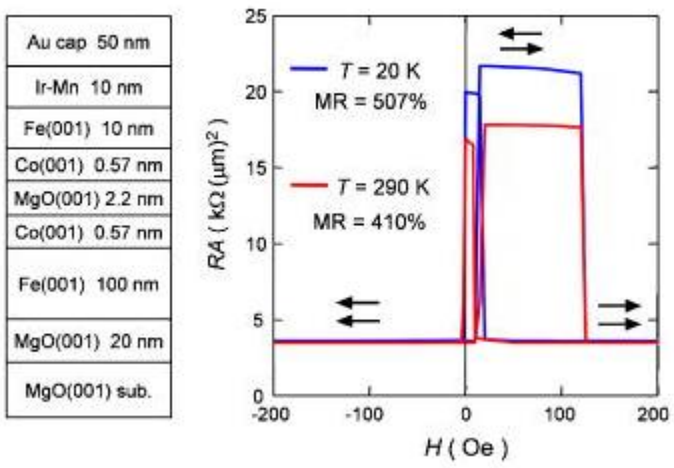
3) The Julliere model giving *TMR = P_1 * P_2* is a simplified model which does not take into account the selective spin tunneling, depending on the electron wave function symmetries. When the wave function symmetries are taken into account, Δ1 states are the states giving the largest contribution to the tunneling current. The tunneling probability of these states is material dependent (see lecture)

Fe/MgO/Fe



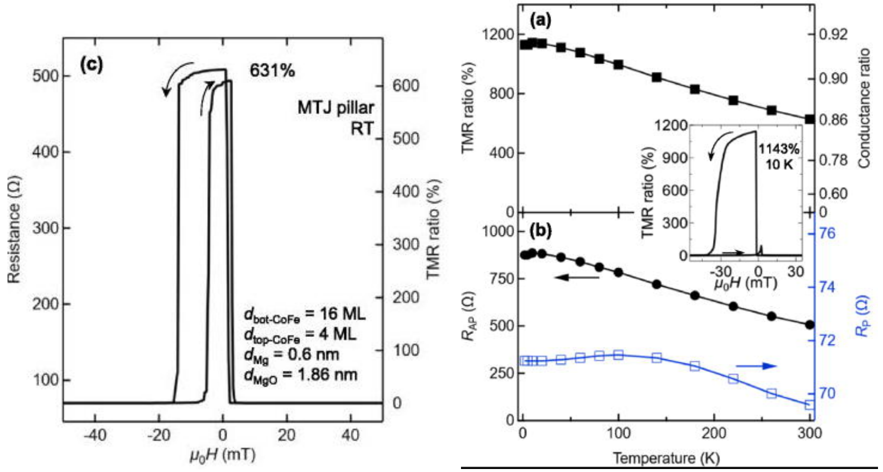
https://doi.org/10.1038/nmat1257

Co/MgO/Co



https://doi.org/10.1063/1.2236268

CoFe/MgO/CoFe



https://doi.org/10.1063/5.0145873