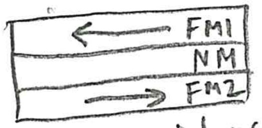
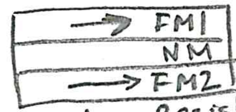


High resistance

Giant Magnetoresistance



low Resistance

- Observed in magnetic multilayers such as $(Fe/Cr)_n$, $(Co/Cu)_n$
- Resistance difference between parallel and anti-parallel configs.
- In practice, only a certain combinations show high value.

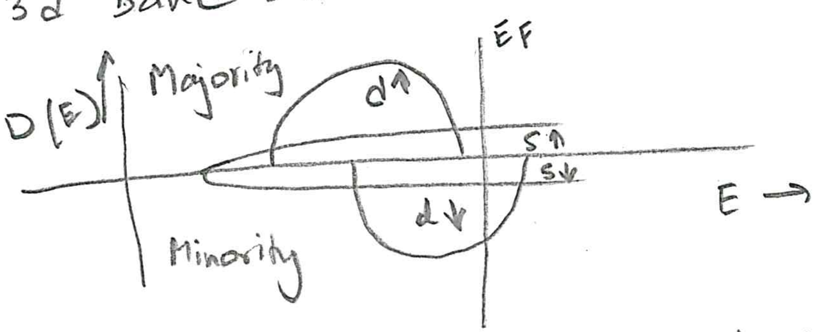
Best results obtained in $(Co/Cu)_n \rightarrow 120\%$ MR at low T and $(Fe/Cr)_n \rightarrow 220\%$ at low T.

Two Resistor Model of GMR

The GMR effect can be qualitatively explained using a two-resistor model that is based on two current model of Mott.

- Key concept is to realize that there is spin-dependent conductance/resistance in a magnetic material.

Why? Because the band structure is different for spin-up and spin down electrons. For eg. a typical 3d band structure is as follows:-



- d bands are more localized ie the spread in energy is low and are spin-split due to exchange interactions. (Review the Stoner model)
- s band is more free-electron like

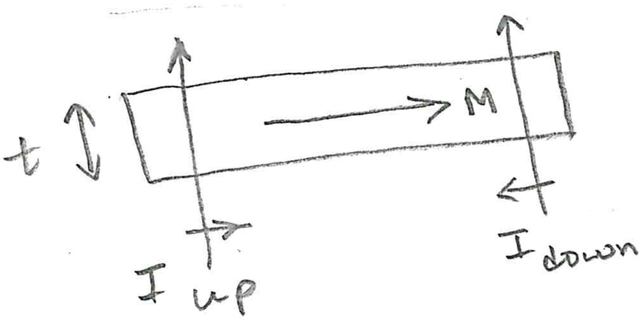
$$\rho = \frac{m}{ne^2}\frac{1}{\tau} \propto \frac{2\pi}{\hbar}|\langle f|V|i\rangle|^2 D(\varepsilon_F) \rightarrow \text{Fermi's golden rule}$$

Resistivity for an up electron is different than a down electron since the scattering probabilities are different for majority and minority due to different density of states $\rho_\uparrow \propto D_\uparrow(E_F)$ and $\rho_\downarrow \propto D_\downarrow(E_F)$ among other factors.

Therefore $\sigma_{total} = \sigma_\uparrow + \sigma_\downarrow \rightarrow$ Two-current model

or $1/\rho_{total} = 1/\rho_\uparrow + 1/\rho_\downarrow \Rightarrow \frac{1}{R_{total}} = \frac{1}{R_\uparrow} + \frac{1}{R_\downarrow}$

Lets calculate the resistance of an up & dn electron as it travels within a magnetic material thin film



up-electrons, by definition, are electrons whose moments are parallel to the magnetization M

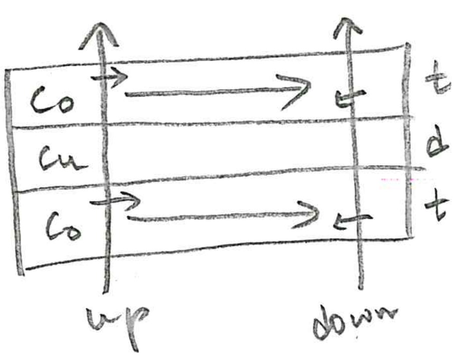
down-electrons have moments anti-parallel to magnetization.

$$R = \frac{\rho t}{A} \Rightarrow R_\uparrow = \frac{\rho_\uparrow t}{A} \text{ and } R_\downarrow = \frac{\rho_\downarrow t}{A}$$

$t \rightarrow$ thickness

$A \rightarrow$ Area.

For a GMR multilayer in parallel configuration (neglecting the resistance of the spacer layer:)



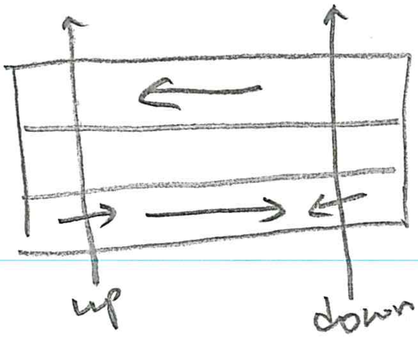
$$R_\uparrow = \frac{2\rho_\uparrow t}{A} \text{ and } R_\downarrow = \frac{2\rho_\downarrow t}{A}$$

$$\Rightarrow \frac{1}{R_P} = \frac{A}{2t}\left(\frac{1}{\rho_\uparrow} + \frac{1}{\rho_\downarrow}\right) \Rightarrow R_P = \frac{2t}{A}\left(\frac{\rho_\uparrow \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow}\right)$$

$P \rightarrow$ Parallel

we neglected the resistance of spacer layer since $\rho_{Cu} < \rho_{Co}$, but it can be included. Typically GMR effect will reduce because of the resistance of space layer.

For an anti parallel configuration



$$R_\uparrow = R_\downarrow = \frac{(\rho_\uparrow + \rho_\downarrow)t}{A}$$

$$\Rightarrow \frac{1}{R_{AP}} = \frac{2A}{(\rho_\uparrow + \rho_\downarrow)t} \Rightarrow R_{AP} = \frac{(\rho_\uparrow + \rho_\downarrow)t}{2A}$$

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

$$= \frac{t(\rho_\uparrow - \rho_\downarrow)^2}{2A(\rho_\uparrow + \rho_\downarrow)}$$

Define GMR ratio $= \dfrac{R_{AP} - R_P}{R_P} = \dfrac{t}{A}\dfrac{(\rho_\uparrow - \rho_\downarrow)^2}{2(\rho_\uparrow + \rho_\downarrow)} \times \dfrac{A}{2t}\left(\dfrac{\rho_\uparrow + \rho_\downarrow}{\rho_\uparrow\rho_\downarrow}\right)$

$$= \frac{(\rho_\uparrow - \rho_\downarrow)^2}{4\rho_\uparrow\rho_\downarrow}$$

Define $\alpha = \dfrac{\rho_\downarrow}{\rho_\uparrow}$, GMR $= \dfrac{\rho_\uparrow^2(1-\alpha)^2}{4\rho_\uparrow\rho_\downarrow} = \dfrac{(\alpha-1)^2}{4\alpha}$

$$\boxed{\underset{\text{ratio}}{\text{GMR}} = \frac{(\alpha-1)^2}{4\alpha}}$$

$\alpha \simeq 7$ for Co $\Rightarrow$ GMR $\simeq \dfrac{36}{28} \simeq 1.3 \simeq 130\%$..

This is indeed the maximum value observed for Co/Cu

with thickness of the non-magnetic space layer,

$$\boxed{\underset{\text{ratio}}{\text{GMR}} = \frac{(\alpha-1)^2}{4(\alpha + pd/t)(1 + pd/t)}}$$

$d \rightarrow$ thickness of spacer layer

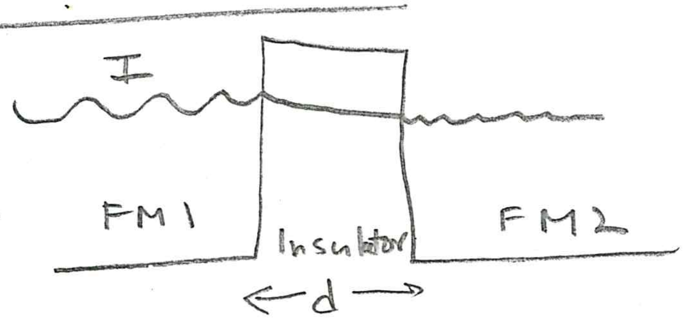
$p = \dfrac{\rho_{NM}}{\rho_\uparrow}$ NM $\rightarrow$ Nonmagnet

Tunnel magnetoresistance

- The tunnel magnetoresistance effect is similar to GMR
- Non magnetic spacer layer in GMR is replaced by an insulator.
- The physics change dramatically, however.
- Electrons can no longer scatter through an insulator They tunnel through.
- Therefore, resistance is caused due to the tunnel effect and not scattering → This is the most fundamental difference between GMR & TMR.

Julliere Model of TMR

Current in an insultor is due to quantum mechanical tunneling effect.



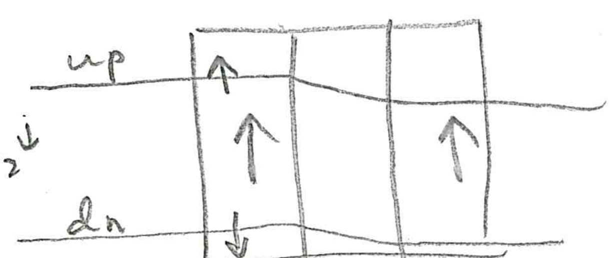
- Electrons from FM1 tunnel into empty states available in FM2.
- Tunneling current $\propto D_1 D_2$ $\quad D_{1(2)} \rightarrow$ Density of states in 1(2)
  - This relation also follows from Fermi Golden rule

$$I_{total} = I_{up} + I_{down} \quad \text{or} \quad \sigma = \sigma_\uparrow + \sigma_\downarrow$$

In the parallel configuration,

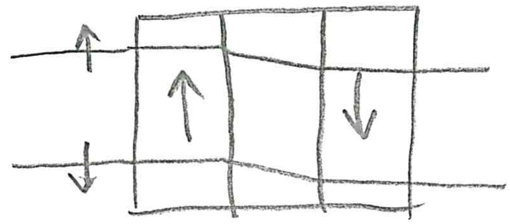
$$I_{up} \propto D_1^\uparrow D_2^\uparrow \quad \Rightarrow I_p \propto D_1^\uparrow D_2^\uparrow + D_1^\downarrow D_2^\downarrow$$

$$I_{dn} \propto D_1^\downarrow D_2^\downarrow$$



parallel

Similarly, $I_{AP} \propto \underbrace{D_1^\uparrow D_2^\downarrow}_{I_{up}} + \underbrace{D_1^\downarrow D_2^\uparrow}_{I_{dn}}$



$$\frac{I_P - I_{AP}}{I_{AP}} = \frac{\sigma_P - \sigma_{AP}}{\sigma_{AP}} = \text{TMR ratio}$$

Note, $\frac{\sigma_P - \sigma_{AP}}{\sigma_{AP}} = \frac{1/\rho_P - 1/\rho_{AP}}{1/\rho_{AP}} = \frac{\rho_{AP} - \rho_P}{\rho_P} \rightarrow$ Same as GMR ratio definition.

$$= \frac{\Delta R}{R_P}$$

$$\frac{\sigma_P - \sigma_{AP}}{\sigma_{AP}} = \frac{D_1^\uparrow(D_2^\uparrow - D_2^\downarrow) + D_1^\downarrow(D_2^\downarrow - D_1^\downarrow)}{D_1^\uparrow D_2^\downarrow + D_1^\downarrow D_2^\uparrow} = \frac{(D_1^\uparrow - D_1^\downarrow)(D_2^\uparrow - D_2^\downarrow)}{D_1^\uparrow D_2^\downarrow + D_1^\downarrow D_2^\uparrow}$$

Define spin-polarization, $P = \frac{D^\uparrow - D^\downarrow}{D^\uparrow + D^\downarrow} = \frac{D^\uparrow - D^\downarrow}{D_{tot}}$ $\quad D_{tot} = D^\uparrow + D^\downarrow$

Consider $1 - P_1 P_2 = 1 - \left(\frac{D_1^\uparrow - D_1^\downarrow}{D_1^\uparrow + D_1^\downarrow}\right)\left(\frac{D_2^\uparrow - D_2^\downarrow}{D_2^\uparrow + D_2^\downarrow}\right)$

$$= \frac{(D_1^\uparrow + D_1^\downarrow)(D_2^\uparrow + D_2^\downarrow) - (D_1^\uparrow - D_1^\downarrow)(D_2^\uparrow - D_2^\downarrow)}{(D_1^\uparrow + D_1^\downarrow)(D_2^\uparrow + D_2^\downarrow)}$$

$$= \frac{\cancel{D_1^\uparrow D_2^\uparrow} + D_1^\uparrow D_2^\downarrow + D_1^\downarrow D_2^\uparrow + \cancel{D_1^\downarrow D_2^\downarrow} - \cancel{D_1^\uparrow D_2^\uparrow} + D_1^\uparrow D_2^\downarrow + D_1^\downarrow D_2^\uparrow - \cancel{D_1^\downarrow D_2^\downarrow}}{D_{1tot} D_{2tot}}$$

$$= \frac{2(D_1^\uparrow D_2^\downarrow + D_1^\downarrow D_2^\uparrow)}{D_{1tot} D_{2tot}}$$

$$\Rightarrow D_1^\uparrow D_2^\downarrow + D_1^\downarrow D_2^\uparrow = \frac{(1 - P_1 P_2)}{2} \times D_{1tot} D_{2tot}$$

Substitituting in $\frac{\sigma_P - \sigma_{AP}}{\sigma_{AP}} = \frac{(D_1^\uparrow - D_1^\downarrow)(D_2^\uparrow - D_2^\downarrow)}{D_1^\uparrow D_2^\downarrow + D_1^\downarrow D_2^\uparrow} = 2 \overset{P_1}{\boxed{\frac{(D_1^\uparrow - D_2^\downarrow)}{D_{1tot}}}} \overset{P_2}{\boxed{\frac{(D_2^\uparrow - D_2^\downarrow)}{D_{2tot}}}} \frac{1}{(1 - P_1 P_2)}$

$$\Rightarrow \boxed{TMR = \frac{2 P_1 P_2}{1 - P_1 P_2}}$$

Julliere's model. when $P_1 = P_2 = 1$ TMR $\rightarrow \infty$ ideal switch