

Giant Magnetoresistance effect: Hard-Disk head.Basic introduction to conduction in a ferromagnet:

- \* Amongst the d-transition metals, the 3d metals iron, cobalt and nickel are known to be ferromagnets.
- \* In these ~~materials~~ <sup>materials</sup>, the 3d and 4s atomic energy levels of the 3d-transition metal elements contribute to electrical conduction.
- \* The mobility of 3d-electrons is smaller than for 4s electrons.
- \* Moreover, the density of states (DOS),  $n(E)$ , which represents the number of electrons in the system having energy within the interval,  $E$  and  $E+dE$ , is split into majority and minority bands due to the exchange interaction.

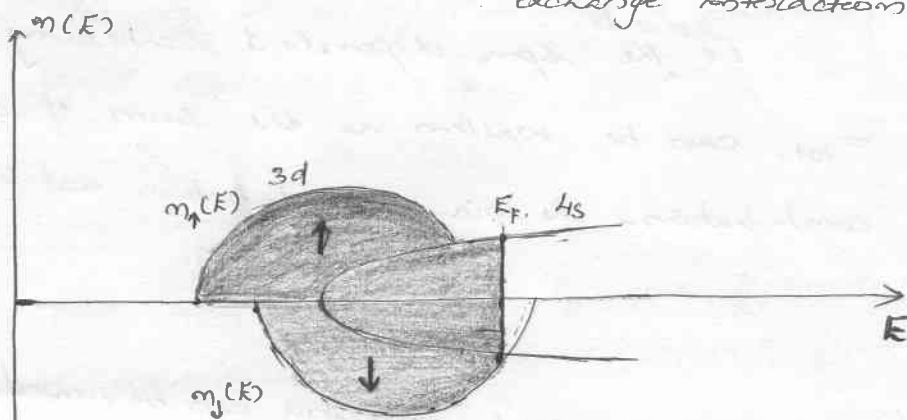


Figure 1:

- \* From the above figure, it is clear that the electrons with spin-down electrons have more empty (free) states to scatter to, i.e. the resistivity will be higher for these electrons; i.e.  $\rho_d > \rho_u$ .
- \* i.e. The conduction current in ferromagnets can be decomposed into two types - i.e. the contribution from majority carriers and that from minority carriers - Mott's two-current model

Mott's two-current model:

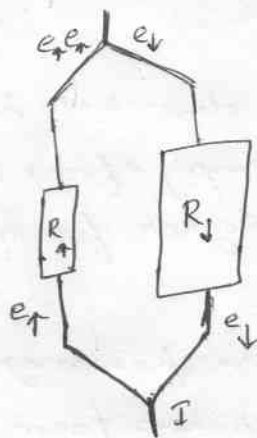
Any electric current through a metallic system will always experience a resistance  $R$  due to scattering of electrons against impurities, defects or due to electron-phonon interaction (Exception: Superconductors).

In the case of ferromagnets, though 4s and 3d electrons are available for conduction, the transport is dominated by 4s electrons. Since for 3d-electrons due to their larger effective mass, the mobility is much smaller than that of 4s electrons. Moreover, in the case of ferromagnets due to exchange interaction, the 3d sub bands are spin-split as shown in fig. 1. Hence, in a scattering process the spin-down s-electrons can scatter into the many d-states (spin-down) available at the Fermi-level. Therefore, they experience a strong scattering giving rise to a considerable resistance or in other words the mobility of these spin-down electrons are much smaller than that of spin-up electrons.

i.e. <sup>due to</sup> the spin-dependent scattering, the total conductivity  $\sigma_{tot}$  can be written as the sum of ~~contributions from~~ two contributions - the spin-up contribution and the spin-down contribution

$$\sigma_{tot} = \sigma^{\uparrow} + \sigma^{\downarrow}$$

and the total resistance can be viewed as the resistance of the equivalent circuit



Equivalent circuit

i.e. the current through the ferromagnet is spin-polarized.

## Magnetoresistance in ferromagnets:

\* In 1857, Lord Kelvin, discovered that when a current is passed through a magnetic conductor, the resistance changes based on the relative angle between the current and the conductor's magnetization.

\* Resistance increased ~~when~~ and has a maximum value when the direction of current is parallel to the applied magnetic field and can be represented as

$$R(\varphi) = R_{\perp} + (R_{\parallel} - R_{\perp}) \cos^2 \varphi, \text{ where } \varphi \rightarrow \text{the angle between } I \text{ and } B.$$

(Anisotropic magnetoresistance).

\* This effect was used as the basis for hard drive reading.

\* Typically the size of the effect is only a fraction of a percent and the field scale  $\sim 5-10 \text{ Oe}$ .

## Giant Magnetoresistance:

\* Unlike the AMR, GMR is not shown by pure ferromagnets. They require nanostructured heterostructures of ferromagnet and non-magnetic materials.

\* Superlattice of very thin alternating layers of ferromagnet and metals.

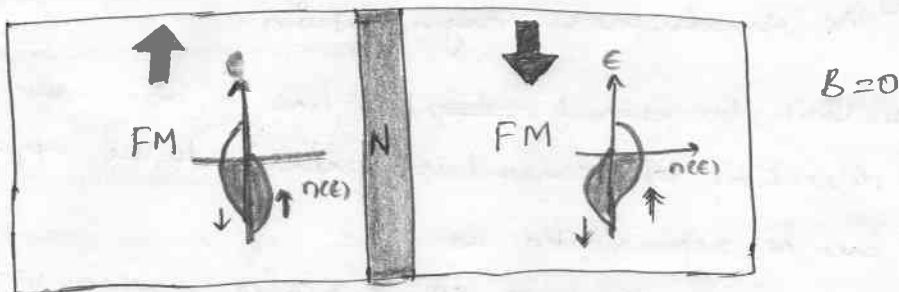
\* Discovered independently by Albert Fert and Peter Grünberg. Nobel Prize in Physics 2007.

## What is this effect:

The electric conductance of a layer consisting of a ferromagnetic and non-magnetic metals depends on the relative orientations of the magnetizations in neighbouring ferromagnetic layers. The ~~res~~ conductance was high when the

magnetization was parallel and vice-versa,

### Mathematical Model:



The relative magnetization of the two ferromagnets separated by a non-magnetic metal depends on the thickness of the non-magnetic metal. ~~and~~ The coupling between the two adjacent ferromagnetic layers oscillates with the thickness of the non-magnetic layer. Hence, for an initial anti-parallel coupling, it is important to control the thickness. ~~and~~

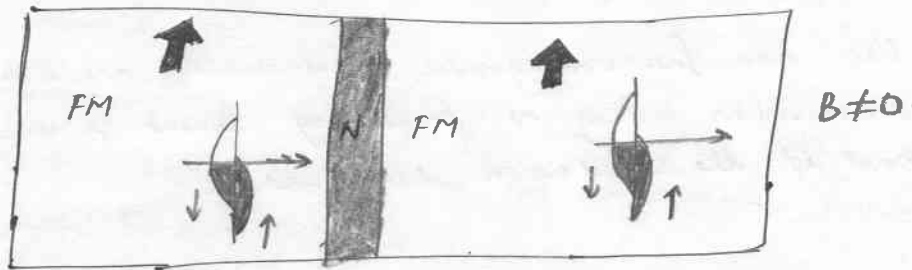
This coupling between the ferromagnetic layers mediated through the non-magnetic metal occurs via the RKKY interaction. Here, the inner d-electron spin of first ferromagnet interacts with the conduction electrons of the non-magnetic metal which then interacts with the d-electrons of the second ferromagnet. Here, ~~the~~ the thickness of the non-magnetic spacer determines whether the coupling will be ferromagnetic or anti-ferromagnetic (of anti-parallel magnetization) between the adjacent ferromagnets.

Now suppose that the thickness of the non-magnetic layer is so adjusted that the two adjacent ferromagnetic layers ~~are~~ have anti-parallel magnetizations. When a current is passed through this system, the following scenario happens.

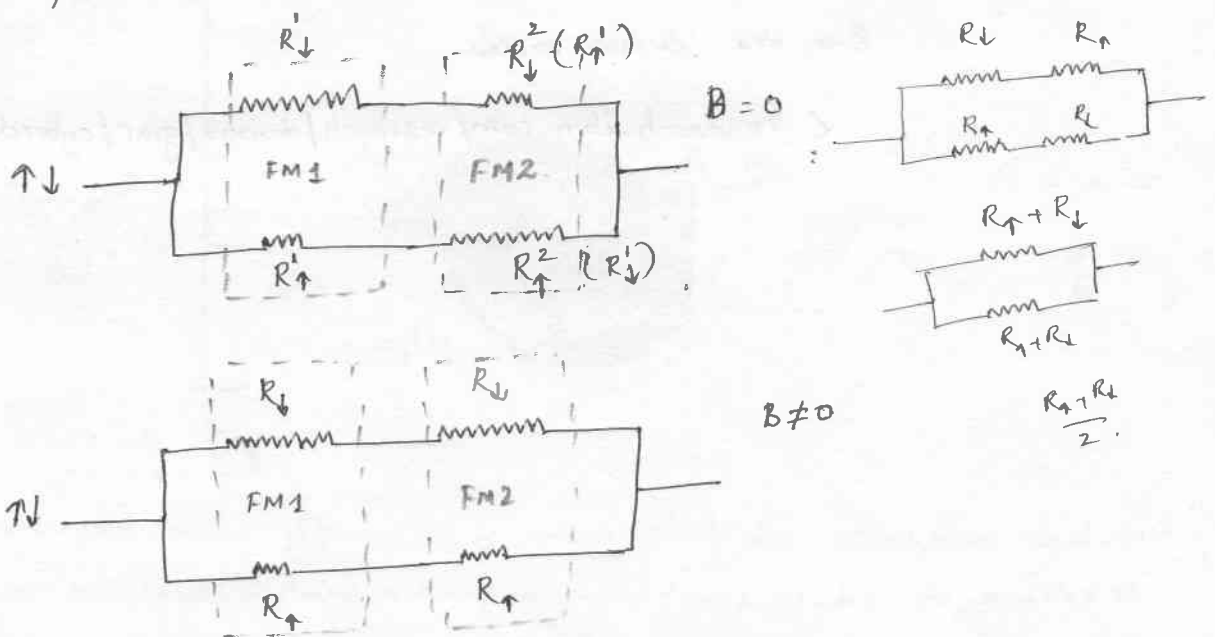
- (1) In the first ferromagnet, ~~due~~ due to the difference in 3d spin sub-bands, the up-spins see less resistance than the down-spins, which means the current through the first ferromagnet will give have higher up spin electrons than the down-spin ones.
- (2) In the non-magnetic metal layer, the ~~current~~ spin polarized current from first ferromagnet passes without any further changes to the spin-population
- (3) In the second-ferromagnet, ~~the~~ the magnetization is opposite

to that of the first, ~~the spin-down electrons~~ ferromagnet. Hence the spin-polarized current with majority of up-spins will <sup>more</sup> face higher resistance, since ~~sd-up spin sub-band~~ has <sup>more</sup> free states available. Hence the total resistance in the system is high.

Now when a magnetic field is applied, both the ferromagnets align parallel to each other. In this scenario, the spin-polarized current from the first ferromagnet easily passes through the second ferromagnet with a lower resistance. ~~the~~



The equivalent resistance circuit can be drawn as



When  $B=0$ , the total resistance will be

$$R_0 = \frac{R_\uparrow + R_\downarrow}{2}$$

When  $B \neq 0$ ,

$$R_B = 2 \left( \frac{R_\uparrow R_\downarrow}{R_\uparrow + R_\downarrow} \right)$$

Hence the difference in resistance is  $R_B - R_0 = \frac{(R_\uparrow - R_\downarrow)^2}{2(R_\uparrow + R_\downarrow)}$

\* This change in resistance can be as high as 100%.

\* This effect is used widely in magnetic read heads of hard drives.

What happens if there is no initial Anti-ferromagnetic coupling between the adjacent layers

The following solutions can be employed

(1). Pin one of the ferromagnetic layer magnetization by coupling to a adjacent anti-ferromagnetic layer (exchange anisotropy)

(2). Use two ferromagnetic materials exhibiting different coercivities either as building block in multilayer or as part of the sandwich structure.

Now how this principle is used in GMR based hard drives.

See the below video:

[research.ibm.com/research/demos/gmr/cyberdemo1.htm](http://research.ibm.com/research/demos/gmr/cyberdemo1.htm)

