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ANALYSIS OF MAGNETORESSISTANCE

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ABSTRACT

This work has as objective learning about the magnetoresistance measurement in two samples, one for analysing the Anisotropic Magnetoresistance (AMR) and other for the Giant Magnetoresistance (GMR). In the spin valve it was observed GMR, with a maximum variation of 11%, found for 90 degrees between the current and the magnetic field. In the NiFe sample, it was observed Anisotropic Magnetoresistance, however, these results were faulty mainly because of the Joule effect. The maximum of AMR was observes at 0 and 180 degrees and at 90 almost there wasn't AMR component.

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1. INTRODUCTION

Magnetoresistance (MR) is a phenomenon in which the electrical resistance of the material varies as a function of the application of an external magnetic field.

This phenomenon is intertwined with Spintronics, which is electronics based on the spin of the electron. The electron is a fundamental particle characterized by its charge and mass, however, the charge is not the only degree of freedom that causes the properties of electronic transport to change, and so we introduce another fundamental degree of freedom called spin that relates with magnetism.

In this report we will address three ways of changing the resistance of the material, naming: Anisotropic Magnetoresistance (AMR), Giant Magnetoresistance (GMR) and Tunnelling Magnetoresistance Effect (TMR).

1.1. Anisotropy Magnetoresistance (AMR)

Anisotropy is the tendency of the change in direction of the material physical properties, just as the magnetic properties direction dependence. The AMR effect can be described as the change in scattering due to atomic orbitals, caused by the direction of the magnetic field. This takes origin in the spin-orbit coupling, in the 3d orbitals; this coupling allows the occurrence of scattering with spin inversion, and in this way, the minority electrons can be scattered by d minority states, increasing the resistance. This diffusion is different if the direction of magnetization is parallel or perpendicular to the electric current, figure (1).

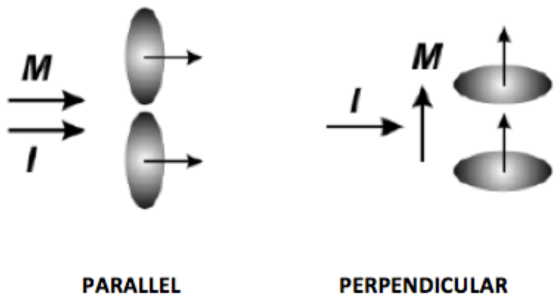

Figure 1 - Direction of magnetization to the electrical current.

In general, the effects of the magnetic field can be determined from the measurements of conductivity:

$$\sigma_{ij} = \frac{J_i(B)}{E_j}$$

Since $J_i(B)$ is the current density in the i direction, in the presence of the electric field applied in direction j and magnetic field B. Another usual equation is:

$$MR = \frac{\Delta R}{R} = \frac{R(B) - R(0)}{R(B)}$$

Where $R(B)$ is the resistance of the sample with applied field B, and $R(0)$ is the resistance of field equal to zero.

In most materials, the resistance is at a maximum when they are parallel and at minimum when they are perpendicular. That is:

$$R(\theta) = R_{\perp} + (R_{\parallel} - R_{\perp}) \cos^2(\theta)$$

Where R is the film resistance and $R_{\perp}$and $R_{\parallel}$ are, respectively, the resistances for $\theta = 90º$ and $\theta = 0º$. Or through the resistivity:

$$\rho = \rho_0 + \Delta\rho \cos^2 \theta$$

1.2. Giant Magnetoresistance (GMR)

The GMR is a quantum phenomenon that comes from the interaction of the electric current spins with the magnetization of the layers of the ferromagnetic material, that is, it results from the scattering difference of the spin in the regions with different directions of magnetization. The phenomenon can be described as follows: when the current of electrons with polarized spins goes through a ferromagnetic material, some of these electrons with antiparallel spin configurations to the magnetization will be scattered, which increases the electrical resistance of the device.

A simplified structure of a device exhibiting these characteristics can be build by superimposing three layers: a ferromagnetic, a non-ferromagnetic and a ferromagnetic material with an antiparallel configuration to the first layer. The change in the resistance of the device comes from the application of a magnetic field capable of aligning the magnetic moments of the layers of the ferromagnetic material, figure (2).

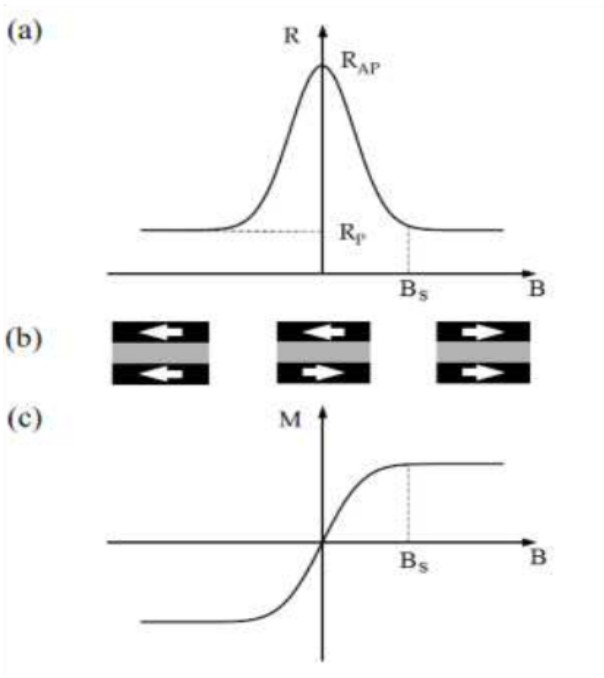

Figure 2 - GMR representation.

MR is measured as follows:

$$MR = \frac{R_{ap} - R_p}{R_p}$$

Where R_{ap} os the maxim resistance equivalent to the antiparallel configuration; R_p is the minim resistance equivalent to the parallel configuration.

Figure 2 caption (a) represents the change in the electrical resistance of the device as a function of the applied magnetic field; b) represents the configuration of the magnetizations of the ferromagnetic layers for different magnetic field values. With a null magnetic field the magnetization configuration is antiparallel, when the value of the magnetic field B is greater than the value of the saturation field B_S , the magnetization configuration is parallel; c) illustrates the magnetization curve for this device.

We can represent the operation of a GMR device through a resistor scheme, in which the spin channels of the current electrons are represented by two parallel circuits whose resistances are associated with the scattering of the electrons, figure (3).

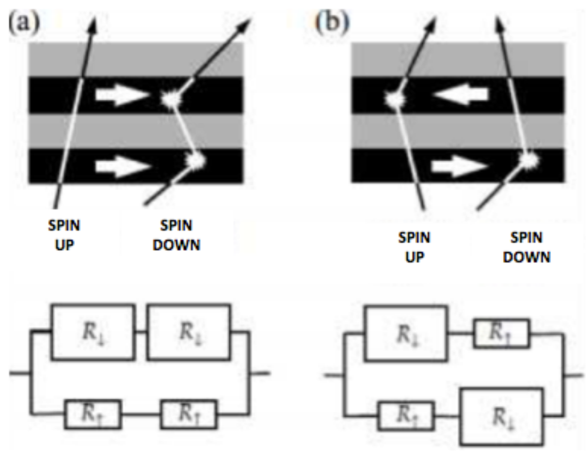

Figure 3 - Schematic Representation of the electron transportation in the parallel and antiparallel configuration.

For the parallel configuration (fig3.a)) the electrons with upward spin suffer small scattering due to the ferromagnetic multilayers whereas the electrons with downward spin suffer a large scattering. If we consider parallel conduction for the two spin channels, the total electrical resistance is low. For the antiparallel configuration (fig3.b)) all the electrons suffer large scattering by the ferromagnetic multilayers, which results in a high electrical resistance.
This way:

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

$$R_{ap} = \frac{R_{\uparrow} - R_{\downarrow}}{2}$$

And considering equation number (5):

$$MR = \frac{(R_{\uparrow} - R_{\downarrow})^2}{2R_{\uparrow}R_{\downarrow}}$$

So, this MR can be calculated through the equivalent resistance of the parallel and antiparallel configuration.

1.3. Tunnelling Magnetoresistance Effect (TMR)

TMR consists of changing the electrical resistance of the device due to the tunnelling of the electric current in the device, which occurs through the insulation layer. Tunnelling is controlled by the configuration of the magnetizations of the electrodes that is generated by an applied magnetic field. The operating principle applied in TMR is similar to the one applied in GMR, described in section 1.2.

2. EXPERIMENTAL PROCEDURE

In this experiment the geometry of the current in the plane (CIP) was used, and the resistance was measured the through the four contacts method. These contacts are parallel and are at the same distance as shown in figure (4). A current is then applied to the external contacts and the voltage is measured at the internal contacts. Since the applied current is constant, according to Ohm's law, if the resistance varies, the voltage will change as well.

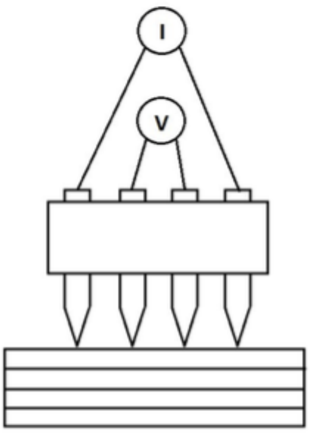

Figure 4 - Resistance Measurement Method (4 contacts).

To vary the resistance (through magnetoresistance), the sample was placed on a platform located between two Helmholtz coils, as in Figure (5), in order to obtain a magnetic field as uniform as possible. These coils are connected to a source, which is connected to a signal generator, modulating the power applied in order to control the field in the sample. These devices are connected to the computer by GPIB and are controlled through a program in *LabView* designed for this purpose.

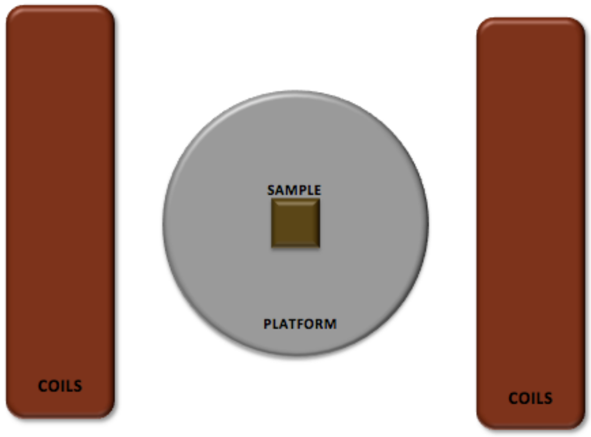

Figure 5 - Experimental Setup.

For the measurement of the Giant Magnetoresistance (GMR), a sample of Ta(5nm)/ CoFe(2nm)/ NiFe(1,5nm)/ Cu(2nm)/ MnIr(7nm)/ Ta(5nm). To begin with, the current value to be used was estimated by measuring the resistance of the sample with a multimeter (obtaining $R = 40\Omega$), obtaining a current value of $I = 0{,}0025A$. However this current had to be adjusted throughout the experiment since there was a lot of noise. The current was increased to $I = 0{,}001A$ or $I = 0{,}002A$ in the knowledge that the consequence could be the heating of the sample. A maximum field of $1000\ Oe$ with a step of $10\ Oe$ was also used. The angle from 0 degrees to 180 degrees was varied in 30 degrees steps.

For the Anisotropic Magnetoresistance measurement (AMR) a thin film of Ta (5nm) / NiFe (20nm) / Ta (5nm) was used. This sample had the easy axis at 45 ° from the major axis. A similar procedure as above was used, with $I = 0{,}4A$, and maximal field of $500\ Oe$ or $1000\ Oe$ with a step of, respectively, $25\ Oe$ or $50\ Oe$.

For the measurement of the Tunnelling Magnetoresistance Effect (TMR), it was used a sample of Ta (5nm) / Ru (18nm) / Ta (3nm) / MnPt (20nm) / CoFe (2: 2nm) / (Ru (0: 9nm) / CoFeB (2nm) / MgO (1nm) / CoFeB (3nm) / Ru (5nm) / Ta (5nm). In this case the current must pass through an insulator. The thickness of this isolator must be very small so that the electrons could pass through the barrier without suffering collision. The sample was very small and we had to use a microscope to fix the tips in the respective blades. However, no results were obtained for this experiment so they are not presented in the next section.

3. RESULTS ANS DISCUSSION

3.1. Giant Magnetoresistance

Figure 6 shows the results obtained for the field strength in the case of Giant Magnetoresistance, for the different angles measured, considering that the 0 degrees indicates that the magnetization is perpendicular to the field. The conclusions drawn below can be seen more easily in the chart in the Annex.

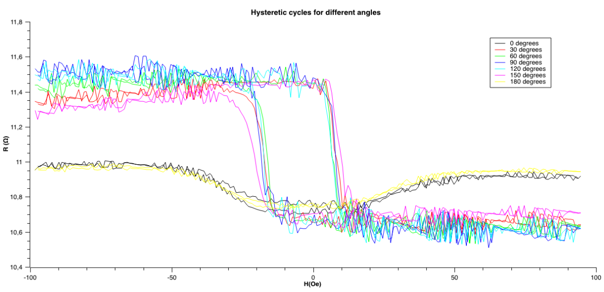

Figure 6 - Resistance in function of the magnetic field for GMR.

For the 0 degrees and 180 degrees, the observed curves are softer, which corresponds to a lower resistance. This is due to the fact that the applied magnetic field is positioned perpendicularly to the easy axis of the free layer. The magnetization of the fixed layer is approximately perpendicular to the applied magnetic field, so for larger fields, the magnetization tends to be perpendicular to the magnetization of the fixed layer; Even for null fields, the ferromagnetic coupling causes that the magnetization of the free layer tends to be parallel with the magnetization of the fixed layer.

For 90 degrees, the applied magnetic field is approximately parallel to the easy axis of the fixed layer. For magnetic field in the positive direction, the magnetization of the free layer must be parallel to the fixed layer and therefore the resistance is minimal (for negative direction, the result is analogous, and the resistance is maximum).

At the other angles, after 90 degrees, the magnetization of the fixed layer moves away from the direction of the applied magnetic field, so for the field in the negative direction, the magnetizations of the fixed layer begin to become less antiparallel in relation to the magnetizations of the free layer, and the resistance is reduced. For the magnetic field applied in the positive direction, the conclusion is analogous: the magnetization of the free layer tends to line up in this field, and the magnetizations between layers become more and more antiparallel, increasing the resistance.

The percentage of giant magnetoresistance of the material was evaluated by the following equation:

$$\frac{\Delta R}{R}(\%) = \frac{R_{max} - R_{min}}{R_{min}} 100$$

From which the graph in figure 7 was obtained, which contains an evaluation for different angles.

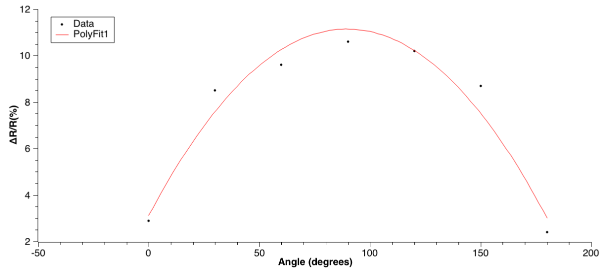

Figure 7 - Resistance Variation from 0 to 180 degrees.

It is observed that the maximum percentage of magnetoresistance is approximately 11%, corresponding to the angle 90º, that is when the magnetization of the fixed layer is parallel to the magnetization of the free layer. On the other hand, the percentage is minimal for the 0º and 180º angles, that is, when the magnetization of the fixed layer is perpendicular to the applied magnetic field.

3.2. Anisotropic Magnetoresistance

Figure 8 shows the results obtained for Anisotropic Magnetoresistance, for different angles.

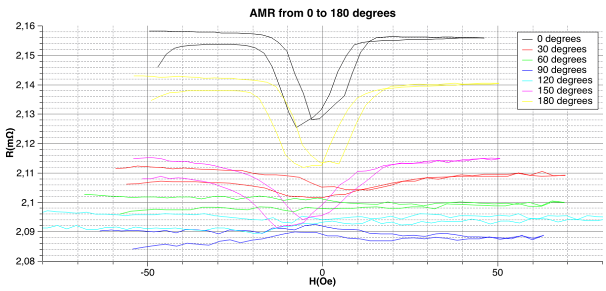

Figure 8 - AMR from 0 to 180 degrees.

It is immediately observed that these results are weak, since the hysteretic cycles do not close. This is probably due to the Joule effect caused by the increase in current, provoked in an attempt to reduce signal noise.

For angles 0º and 180º the current is parallel to the applied magnetic field and the scattering of the electrons in this direction causes the resistance to be at maximum.
As the angle approaches the 90º, the current tends to be perpendicular to the magnetic field and the scattering of the electrons must be minimum, reason why the resistance tends to the minimum.

Observing the figure 9 in which the resistances for the 0° and 90° are represented, it is concluded that there is a decrease and increase of resistance, respectively. However, for 90 degrees the results are not the best because it should be verified a much greater resistance variation.

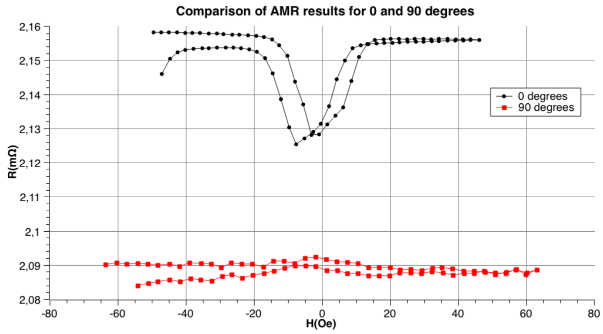

Figure 9. - AMR Comparison for 0 and 180 degrees

In figure 10, the variation of the resistance as a function of the angle was analysed. It is possible to observe that the maximum variation is very small, in the order of 1.4%, and occurs for the 0º and 180º, that is, when the current and the magnetic field are parallel; and minimum for the 90º, when the field Is perpendicular to the applied current. This leads us to conclude that the easy axis is in the 90º, where there was almost no anisotropy magnetoresistance.

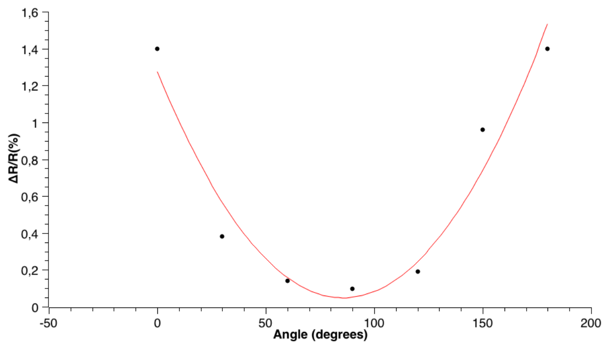

Figure 10 - AMR Variation from 0 to 180 degrees.

4. CONCLUSION

With this experiment, it was concluded that the spin valve (sample used in GMR analysis) has a giant magnetoresistance and that this is at most 11% occurring when the angle is 90 degrees. On the other hand, GMR is minimum for 0 degrees (or 180º).

For the NiFe sample, it was concluded that it has AMR and that it has a maximum of 1.4% when the angle is 0 degrees (or 180º), and that it has almost no AMR when the angle is 90 degrees.

5. References

[1] Sarah M Thompson, The Discovery, development and future of GMR: The Nobel Prize 2007, J. Phys. D:Appl.Phys.41 093001 (2008)

[2] “Spintronics”, 2015

[3] T. R. McGuire and R. I. Potter, Anisotropic Magnetoresistance in Ferromagnetic 3d Alloys, IEEE Transaction on Magnetics. Vol. AMg-11, No 4, July 1975.

6. Annex

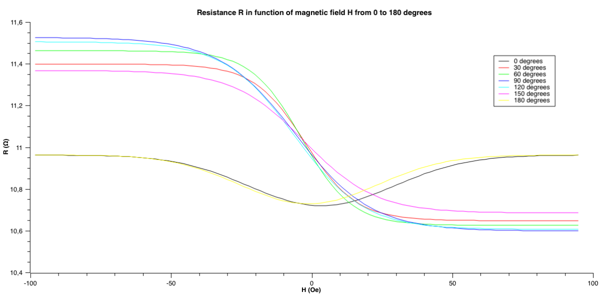

Figure 11 – Some kind of fit for GMR analysis,