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Nanodispositivos e Nanoeletrónica

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Magnetic Nanodevices
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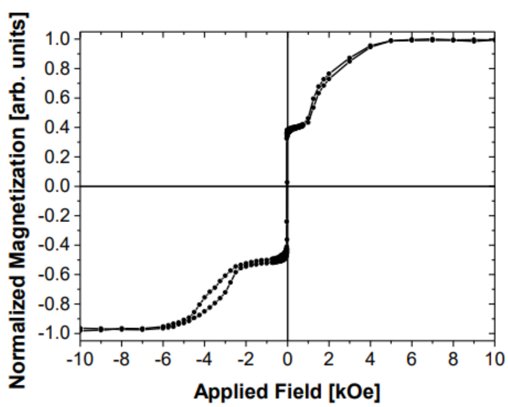
Magnetic Sensors

1. Exercise 1
   (a) In a standard magnetic tunnel junction (MTJ) stack, like the one in the image. What kind of material is each layer?
   (b) In the hysteresis loop which jump corresponds to the rotation of each ferromagnetic layer?
2. Exercise 2
   How do you calculate the sensitivity of a magnetic sensor?



Resolution of Exercise 1 a)

A basic magnetic tunnel junction (MTJ) normally consists of two layers of magnetic metal, separated by an ultrathin layer of insulator. This insulating layer is so thin that electrons can tunnel through the barrier if a bias voltage is applied between the two metal electrodes. But the presented MTJ stack consists of several different layers, each of which is composed of combinations of different materials.

Therefore, analyzing the given stack, one obtains the following different layers:

- **Cap**: constituted by Ruthenium (Ru), Copper Nitride Alloy (CuN) and Tantalum (Ta);
- **Free Layer**: constituted by Nickel-Iron (NiFe), Tantalum (Ta) and Cobalt-Iron-Boron (CoFeB);
- **Insulator or Tunnel Barrier**: constituted by Magnesium Oxide (Mg0);
- **Reference Layer (SAF)**: constituted by Cobalt-Iron-Boron (CoFeB), Ruthenium (Ru) and Cobalt-Iron (CoFe);
- **Pinning Layer**:constituted by Iridium fused with Manganese (IrMn);

- **Buffer Layer**: constituted by Ruthenium (Ru) and then several layers of Tantalum (Ta) with Copper Nitride Alloy (CuN) between them.

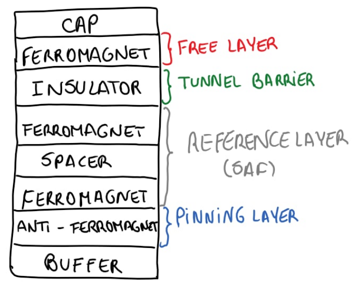


Figure 1: Stack of an MTJ structure with a SAF

Resolution of Exercise 1 b)

We know that a hysteresis loop shows the relationship between the magnetic flux density and the magnetizing field strength. The loop is generated by measuring the magnetic flux coming out from the ferromagnetic substance while changing the external magnetizing field. It was seen in the previous question that there were 3 ferromagnetic layers, which belonged to the following regions: Free Layer and Reference Layer (SAF).This last region has two ferromagnetic layers, so we'll refer to them as the top SAF layer and the bottom SAF layer.

Starting with the lowest values of the magnitude of the applied field (the negative values):

- to the point where, although we continue with negative values, the values are higher, and the applied field is no longer sufficient to keep the layer below the SAF region with the same orientation and therefore the same changes (in the other layers, nothing is affected);
- moving now to positive values of the magnitude of the applied field, the free layer ferromagnet will align with the layer below the SAF. This happens because the magnetization of the free layer rotates coherently with the external field, after reaching the coercive force value;
- lastly, when the field is strong enough, all ferromagnetic layers will align with the field being applied, including the missing one which is the top layer of the SAF.

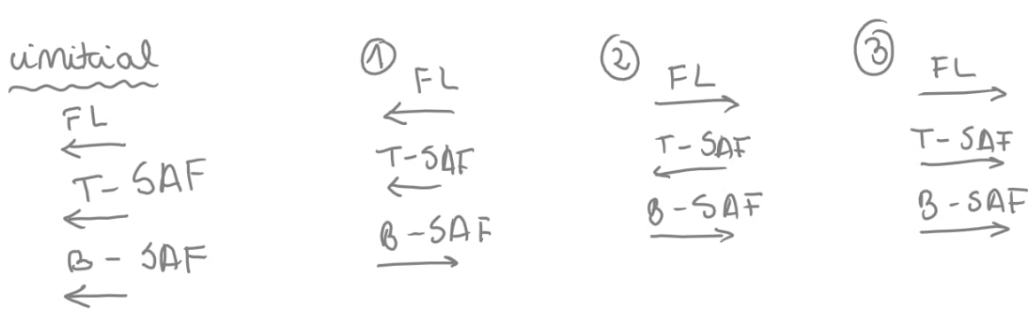


Figure 2: Demonstration of the variation in the direction of each ferromagnetic layer where initially it is more or less up to the value of -5kOe; 1) corresponds to the first point described above and corresponds to the interval from -5kOe to 0kOe; 2) corresponds to the second point described above and is the interval from 0kOe to 1kOe; 3) corresponds to the third point described above and is for applied field values greater than 4kOe.

As a conclusion, we can say that in a typical MTJ structure, exist two possible responses to an external field: the magnetization of the free layer rotates coherently with the external field and we see that there is a linear change in resistance and we have a square response in which the MTJ is either in the maximum or minimum resistance states.

Resolution of Exercise 2

For any type of sensors, including magnetic ones, sensitivity is one of the most important parameters to consider. It is known that having a good sensitivity means that for a small input variation, you have a large output variation. Hence, for these magnetic sensors, you take a portion of the transfer curve, and you see the slope of the linear part of that same portion. This provides a description of how the sensor responds to various changes in the field around its axis.

Magnetic Tunnel Junctions

Using the Julíère model estimate the TMR, polarization, and percentage of electrons polarized along the magnetization from the transfer curve in Figure 1.

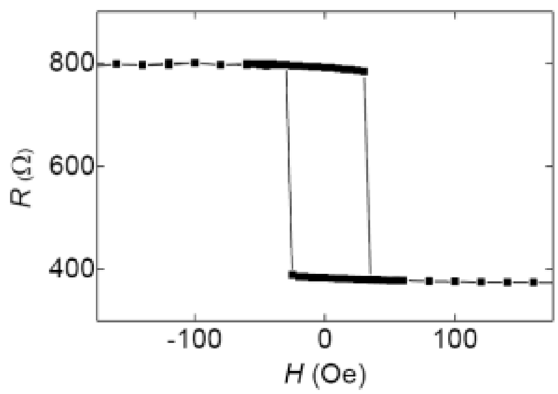


Figure 3: Transfer curve of a MTJ nano-oscillator

Resolution of "Magnetic Tunnel Junctions"

The TMR is estimed by using the Julíère model. So, we have that:

$$TMR = \frac{R_{anti-parallel} - R_{parallel}}{R_{parallel}} \Leftrightarrow TMR = \frac{R_{max} - R_{min}}{R_{max}}$$

Analyzing the given graph, it can be seen that $R_{max} \approx 800\Omega$ and $R_{min} \approx 400\Omega$. Substituting, we have that:

$$TMR = \frac{R_{max} - R_{min}}{R_{max}} \Leftrightarrow TMR = \frac{800 - 400}{400} \Leftrightarrow TMR = 100\%$$

Now, the link between the TMR value and the spin polarization of the two electrodes is:

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

So, we have that (assuming that $P_1 = P_2 = P$):

$$1 = \frac{2 \cdot P^2}{1 - P^2} \Leftrightarrow 1 - P^2 = 2 \cdot P^2 \Leftrightarrow 1 = 3 \cdot P^2 \Leftrightarrow P = 57.7\%$$

Since this spin polarization quantity is normally used to indicate the imbalance in the DOS at the Fermi level in FM materials, we also have that:

$$P = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}}$$

onde $N_{\uparrow} + N_{\downarrow} = 100\%$

Then, it follows that:

$$P = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} \Leftrightarrow P \cdot (N_{\uparrow} + N_{\downarrow}) = N_{\uparrow} - N_{\downarrow} \Leftrightarrow 0.577 \cdot N_{\uparrow} + 0.577 \cdot N_{\downarrow} = N_{\uparrow} - N_{\downarrow} \Leftrightarrow$$

$$\Leftrightarrow -0.423 \cdot N_{\uparrow} = -1.577 \cdot N_{\downarrow} \Leftrightarrow N_{\uparrow} = 3.728 \cdot N_{\downarrow}$$

How $N_{\uparrow} + N_{\downarrow} = 1$, one has to:

- $N_{\downarrow} = 21.2\%$;
- $N_{\uparrow} = 78.8\%$.

Spin Transfer Torque - Switching energy

Calculate the energy used for switching from AP to P and P to AP for the device shown in Figure 2.

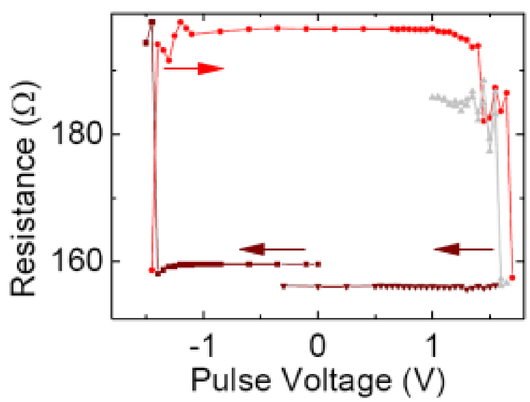


Figure 4: Resistance measured after voltage pulse of 100 s length on a 100 nm diameter MTJ nanopillar.

Resolution of "Spin Transfer Torque - Switching energy"

From the graph it can be removed that:

- we know that switching from AP to P, in terms of resistance, is switching from high to low values of resistance. That happens in $1.9V$;
- already changing from P to AP is the opposite of the previous point, what happens when we have $-1.5V$;
- it also withdraws that: $R_{AP} = 197\Omega$ and $R_P = 160\Omega$;
- the voltage pulse is $t = 100\mu s = 100 \times 10^{-6} s$

We have that the energy used for switching from AP to P is given by $E_{AP} = I_{AP}^2 \cdot R_{AP} \cdot t$ where $I_{AP} = V_{AP}/R_{AP}$. So, we are going to have:

$$E_{AP} = \frac{V_{AP}^2 \cdot t}{R_{AP}} \Leftrightarrow E_{AP} = \frac{1.9^2 \cdot 100 \times 10^{-6}}{197} \Leftrightarrow E_{AP} = 2.0 \times 10^{-6} J = 2.0 \mu J$$

Simillarly, the energy used for switching from P to AP is:

$$E_P = \frac{V_P^2 \cdot t}{R_P} \Leftrightarrow E_P = \frac{(-1.5)^2 \cdot 100 \times 10^{-6}}{160} \Leftrightarrow E_P = 1.0 \times 10^{-6} J = 1.0 \mu J$$

Spin Transfer Torque - Switching probability

How long do we have to wait on average until 1 in 1000 nanopillars switched due to thermal energy at room temperature with half the critical current applied and following characteristic parameters?

- Characteristic switching time: $\tau_0 = 1ns$;
- Thermal stability factor: $\Delta = 30$.

Resolution of "Spin Transfer Torque - Switching probability"

In this exercise, we are going to use the following expression, in order to calculate the average time Δt:

$$P_{SW} = 1 - exp\left(\frac{-\Delta t}{\tau_0} \cdot e^{-\Delta \cdot \left(1 - \frac{I}{I_{CO}}\right)}\right)$$

From the statement, we know that:

- Thermal stability factor: $\Delta = 30$;
- Characteristic switching time: $\tau_0 = 1ns = 1 \times 10^{-9} s$;
- $I = \frac{I_{CO}}{2}$;
- $P_{SW} = 1/1000$.

So, we are going to have that:

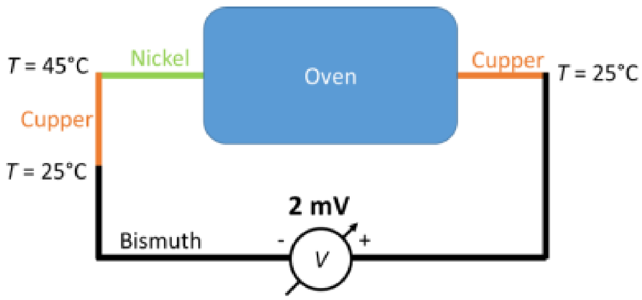
$$P_{SW} = 1 - exp\left(\frac{-\Delta t}{\tau_0} \cdot e^{-\Delta \cdot \left(1 - \frac{I}{I_{CO}}\right)}\right) \Leftrightarrow ln(1 - P_{SW}) = \frac{-\Delta t}{\tau_0} \cdot e^{-\Delta \cdot \left(1 - \frac{I}{I_{CO}}\right)} \Leftrightarrow$$

$$\Leftrightarrow \Delta t = -\tau_0 \cdot \frac{ln(1 - P_{SW})}{e^{-\Delta \cdot \left(1 - \frac{I}{I_{CO}}\right)}} \Leftrightarrow \Delta t = -1 \times 10^{-9} \cdot \frac{ln(1 - 1/1000)}{e^{\left(-\frac{\Delta}{2}\right)}} \Leftrightarrow$$

$$\Leftrightarrow \Delta t = -1 \times 10^{-9} \cdot \frac{ln(1 - 1/1000)}{e^{\left(-\frac{30}{2}\right)}} \Leftrightarrow \Delta t \approx 3 \times 10^{-6} s \approx 3 \mu s$$

Thermovoltages

What is the temperature in the oven if we measure 2 mV on the voltmeter? You can assume the temperature is homogenous in the oven.



	S / μVK^{-1}	S^{abs} / μVK^{-1}
Bi	-50	-55
Co	-25.8	-30.7
Ni	-14.5	-20.4
Pt	0	-4.92
Cu	6.14	1.9
Au	7	2.08
Fe	20	15

Resolution of "Thermovoltages"

We know that in an equilibrium state, we have that:

$$I_{total} = \left(\frac{U_{thermo}}{R} - \frac{-S \cdot \Delta T}{R} \right)$$

So, from here, we can have that:

$$U_{thermo} = -S \cdot \Delta T$$

From the statement, we have several values for S or Seebeck Coefficient for different materials, hence:

- $U_{cupper_1} = -6.14 \cdot (25°C - T) = 6.14 \cdot (T - 293)$;
- $U_{niquel} = -(-14.5 \cdot (-45°C + T)) = -14.5 \cdot (T - 318K)$;
- $U_{cupper_2} = -6.14 \cdot (45°C - 25°C) = -6.14 \cdot 20 = -122.8\mu V$.

As the voltmeter shows that $U = 2mV$, and as we are facing a series circuit, we can conclude that the temperature in the oven is given by:

$$U = U_{cupper_1} + U_{niquel} + U_{cupper_2} \Leftrightarrow 2 \times 10^{-3} = +6.14 \times 10^{-6} \cdot (T - 293K) + 14.5 \times 10^{-6} \cdot (T - 318K) - 122.8 \times 10^{-6} \Leftrightarrow$$

$$\Leftrightarrow 2 \times 10^{-3} = +6.14 \times 10^{-6} \cdot T - 0.001799 + 14.5 \times 10^{-6} \cdot T - 0.004611 - 122.8 \times 10^{-6} \Leftrightarrow$$

$$\Leftrightarrow 0.000021 \cdot T = 0.008533 \Leftrightarrow T \approx 406.333K \approx 133.333°C$$