

Exploring spin-orbit torque multilayers: Characterisation and modelling of CoFeB films towards magnetic sensors

José Francisco Ribeiro Moutinho

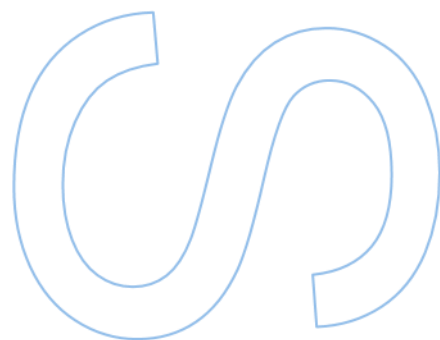
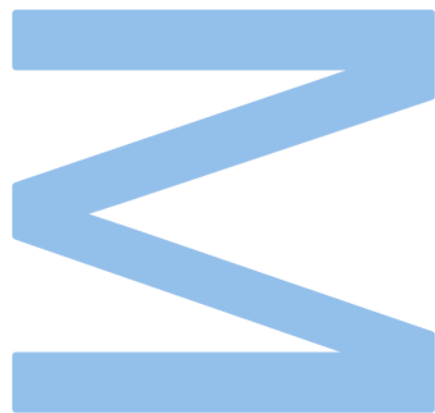
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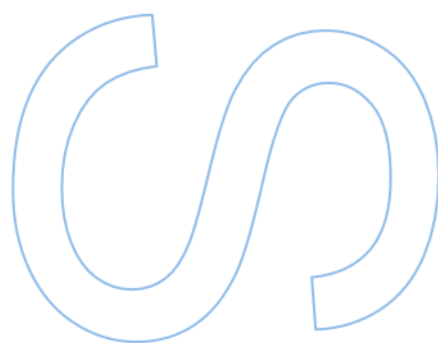
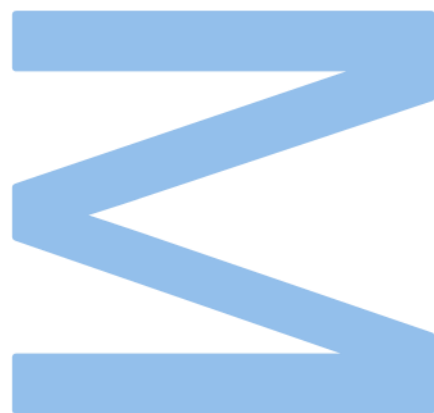
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UNIVERSIDADE DO PORTO

MASTERS THESIS

Exploring spin-orbit torque multilayers: Characterisation and modelling of CoFeB films towards magnetic sensors

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Departamento de Física e Astronomia

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" Sugar and caffeine. My willpower crumbled. "

Percy Jackson, written by Rick Riordan in *The Lightning Thief*

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Abstract

Faculdade de Ciências da Universidade do Porto

Departamento de Física e Astronomia

MSc. Engineering Physics

Exploring spin-orbit torque multilayers: Characterisation and modelling of CoFeB films towards magnetic sensors

by José Francisco Ribeiro MOUTINHO

Magnetic field sensing via spin-orbit torque is explored in this work. This novel technology allows for the determination of all components of a magnetic field in a single element. To do so a Macro-spin model is developed, where there is a field-like term that changes with current density. It is shown that this current term is able to linearize the hysteresis cycle of a magnetic thin-film. Also, the density current necessary to achieve the linearization is heavily dependent on the anisotropy and demagnetisation of the thin-film. Furthermore, the SQUID MPMS®3 is explored and a measurement protocol for thin-films is developed. With that protocol we are able to characterise two multilayered thin-films, Ta(10)/Co₆₀Fe₂₀B₂₀(1.2)/MgO (1.6)/Ta(20) and Ta(5)/Ir(5)/Co₆₀Fe₂₀B₂₀(1.2)/MgO (1.6)/Ta(20) all thickness in nm, obtaining a magnetisation saturation of $M_s = 620.8$ emu/cm³ and $M_s = 1033.5$ emu/cm³, a coercive field of $H_c = 11.2$ Oe and $H_c = 0.5$ Oe and a anisotropy field of $H_K = 952.5$ Oe and $H_K = 1986.3$ Oe, respectively. It is demonstrated that the way to build sensors of this type with different linear ranges is through the manipulation of the heavy metal component, increasing the perpendicular anisotropy of the stack.

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Resumo

Faculdade de Ciências da Universidade do Porto

Departamento de Física e Astronomia

Mestrado em Engenharia Física

Exploração do torque de spin-órbita em multicamadas: Caracterização e modelização de filmes de CoFeB para sensores magnéticos

por [José Francisco Ribeiro MOUTINHO](#)

Neste trabalho é explorada a deteção de campo magnético devido ao torque de spin-órbita. Esta nova tecnologia permite a deteção de todas as componentes do campo magnético num único elemento. Para tal, é desenvolvido um modelo Macro-Spin, onde existe um termo que se comporta como um campo e que muda com a densidade de corrente. É mostrado que este termo de corrente é capaz de linearizar o ciclo histerético de um filme-fino magnético. Para além disso, a densidade de corrente necessária para atingir essa linearização depende fortemente na anisotropia e desmagnetização do filme-fino. Ademais, o SQUID MPMS®3 é explorado e um protocolo de medida de filmes finos é desenvolvido. Com esse protocolo somos capazes de caracterizar duas multicamadas de filmes-finos, Ta(10)/Co₆₀Fe₂₀B₂₀(1.2)/MgO (1.6)/Ta(20) e Ta(5)/Ir(5)/Co₆₀Fe₂₀B₂₀(1.2)/MgO (1.6)/Ta(20), todas as espessuras estão em nanómetros. obtendo uma magnetização de saturação de $M_s = 620.8 \text{ emu/cm}^3$ e $M_s = 1033.5 \text{ emu/cm}^3$, um campo coercivo de $H_c = 11.2 \text{ Oe}$ e $H_c = 0.5 \text{ Oe}$ e um campo de anisotropia de $H_K = 952.5 \text{ Oe}$ e $H_K = 1986.3 \text{ Oe}$, respetivamente. É mostrado que a forma de construir sensores deste tipo com diferentes ranges lineares é através da manipulação da componente do metal pesado, aumentando a anisotropia perpendicular da multicamada.

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Chapter 1

Introduction

Somewhere, something incredible is waiting to be known.

CARL SAGAN

1.1 Motivation and Thesis goals

As the Internet of things (IoT) era develops itself, the usage of sensors gains great importance. In particular, magnetic sensors play an outstanding role in space navigation, automotive electronics, biomedicine, electrical current sensing, and industrial automation[1–5]. In recent years there have been several advances in the development of magnetic sensors, such as quantum interference devices[6], flux gate sensors [7] and graphene Hall sensors[8]. Furthermore, there is, also, the exploring of optical nitrogen vacancies in diamond [9], the Hall effect in semiconductor materials [10] and the spin-dependent resistance effect in magnetic materials [11]. The sensors based on spin-dependent magnetoresistance effects - anisotropy magnetoresistance (AMR)[12], giant magnetoresistance(GMR)[13] and tunnelling magnetoresistance (TMR) [14] - are of particularly interest as they have the advantage of a wide bandwidth, high stability, small size and cost, in addition to excellent resolution, sensibility and linearity [4].

However, a single element of this sensors is not able to determine directly all three components of the magnetic field. Although, some methods were engineered, it is possible to

discretely integrate three element sensors, one in each of the coordinate axis [15] or usage of planar sensors with an attached magnetic flux guide[16]. These techniques are limited by experimental set-up and environmental effects, which leads to non-orthogonality of the three sensing directions, nor is it measured in the same position and at the same time[4]. Furthermore, it brings struggles of large size and planar integration difficulties, in conjunction with complicated adjustments of the subunits, low signal levels, high cross-sensitivities, and numerous electrical connections [5]. Therefore, there is a push in the market for a sensor that can measure the magnetic field vector using only a element.

One solution is presented in [4] and [5], where Spin-orbitronics is used to detect the three components of the magnetic field in a simple element, as will be seen further in section 1.2. These sensors are built with a multilayer of a heavy metal (HM), oxide of manganese (MgO) and a CoFeB layer, HM/CoFeB/MgO/HM. This type of stack has some interesting properties that allows its sensibility to external magnetic fields, its perpendicular magnetic anisotropy and relevant spin-orbit interaction, allows for the linearisation of the hysteresis loop when measuring in the easy axis and in the hard axis, that linearisation will be related to the coercive field of the element of study.

In this Thesis, this type of stacks will be explored and due to its magnetic characterisation we intend to infer about what type of Heavy metal would allow for higher linear range. In order to do so two stacks were deposited, see further in 4, section 4.3, one with the heavy metal being Ta and another with a mix of Ta and Ir. This deposition was made possible by Diana Leitão in the Department of Applied Physics at Eindhoven University of Technology.

As seen above, there is a need to magnetically characterise the multilayers, in order to better understand what type of stack would be ideal for each type of sensor one might want to develop. To perform that characterisation, IFIMUP gave access to its The SQUID MPMS®3. The magnetic characterisation of the stacks proved to be very challenging, as a lot of details were needed to be taken into account, as will be seen further in chapter 4, so part of the objective of this work is to find a measurement protocol to obtain reproducible and accurate results.

In order to guide and verify the materials choice, a Macro-spin model is developed with a component to mimic the effect of a magnetic field created by a charge current. This model is very simple and easy to implement as it assumes the element of study has a single domain, i.e. the magnetisation is uniform in the entire ferromagnet and it changes its direction due to an external applied field. It is important to notice that, although, the model gives qualitative results, as it does not consider the thermal impact on the magnetisation, the exchange interaction is neglected as is the domain wall dynamics, the numerical values obtained might be off.

1.2 State of the art

As soon as the 202 BC a magnetic field sensor was developed, this being non other than the compass [17], made of lodestone, a naturally magnetised stone of iron, although it was not able to give the strength of the magnetic field, it senses its direction, being very helpful for navigation. Then in 1833 Carl Friedrich Gauss, head of the Geomagnetic Observatory in Göttingen, measured the Earth magnetic field [18], it consists on a permanent bar magnet suspended horizontally from a gold fiber, using the difference in oscillations when the bar was magnetised versus when it was not. Gauss was able to measure the absolute value of the Earth magnetic field.

Since then, there have been a lot of evolution in magnetic sensing, so the focus will fall on the most recent ones and the techniques that allow for measurement of the 3 directions of the field.

In 2014, Jeng et al. [19] investigated a three-axis vector magnetometer based on two sets of dual-bridge GMR sensors and a fluxguide. The GMR sensors are built on a printed circuit board with their sensing directions align with the two in plane axis (allowing for a direct measurement of those components), while a cylindrical ferrite fluxguide is put in the centre of the four sensors, with its symmetrical axis normal to the printed circuit plane. The fluxguide deflects the magnetic flux lines of an out of plane magnetic field to generate an in-plane component that is pick-up by the in plane sensors allowing for the measurement of that component. This sensor allows a measurement range of $[-3, 3]$ Oe in all directions.

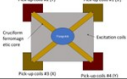
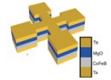
Sensor Design	Linear Range	Source (see figure's caption)
	$[-3,3]$ Oe in all directions	a
	$[-1.5,1.5]$ Oe in all directions	b
	$[0,2]$ T in modulus	c
	$[0,1,1]$ T in modulus	d
	$[-4,4]$ Oe in the out of plane direction $[-10,10]$ Oe in the in-plane directions	e
	$[-20,20]$ Oe in all directions	f

FIGURE 1.1: State of the art summary. Unless otherwise mention, all figures were drawn with heavy inspiration of the cited source. a - [19]; b - [20]; c - [21]; d - [22]; e - Reproduced with permission from Springer Nature [4]; f - [5]

In 2015, Lu and Huang [20] presented a planar fluxgate structure with an orthogonal ferromagnetic fluxguide centrally situated over the magnetic cores as a new form of three axis magnetometer. The proposed tri-axis fluxgate sensor is mainly composed of a bi-axis fluxgate with a cruciform ferromagnetic core, a planar excitation coil and four planar pick-up coils. Thanks to the flux convergence (divergence) of the magnetic fields near the endpoints of the magnetic coils, it is possible to detect the in-plane components of the magnetic field. To detect the out of plane component of the magnetic field, an orthogonally cylindrical ferromagnetic tube is employed to collect or concentrate the magnetic fields and emit or deflect the fields into the the planar cruciform core, acting, therefore as a fluxguide. This sensor allows for a measuring range of $[-1.5, 1.5]$ Oe in all of the sensing axis.

In late 2015, Wouters et al. [21] combined six 1D hall sensors in such a way that each Hall sensor forms one face of a submillimeter-sized cube. Each pair of faces of the cube is sensitive to the same direction of the magnetic field vector. This allows to exploit the high sensibility of the Hall sensor enhancing the precision as each direction is double read. Futhermore, the average value of the pairs for the three components of the magnetic field can be assigned to the same point in space, the cube's centre. This allows for the simultaneous read of the 3 componets of the magnetic field in one point of the space.

However, this cubic assembly leads to a large spacial distribution of the active areas, so in [21], Wouters et al propose a special cuboid design, see figure 1.1. The sensor allows for a linear range of $[0, 2]$ T.

In 2021, Shiogai et al. [22] reported a three-dimensional magnetometer based on a simple Fe-Sn heterostructure Hall device in a planar geometry. The device consists of two Hall-bar channels in series oriented in plane at 45° from each other. The magnetic field in polar coordinates is determined by combining the sizeable anomalous Hall effect, the anisotropy magnetoresistance and the unidirection magnetoresistance. Because of the topology in the Fe-Sn heterostructure, the device has high sensibility at room temperature. This device, reportedly, can archive a linear range of $[0.1, 1]$ T with a sensitivity of $0.4 \text{ V A}^{-1} \text{ degree}^{-1}$ for the angle between the magnetic field and the out-of plane axis, $0.04 \text{ V A}^{-1} \text{ degree}^{-1}$ for the angle between the in plane projection of the magnetic field and the one of the Hall bars channel and $51.3 \text{ V A}^{-1} \text{ T}^{-1}$ for the field amplitude.

Magnetic field sensing using spin-orbit torque is a quite novel technology, it was reported in [4], where using a Hall Cross of Ta(10 nm)/ CoFeB(1.2 nm)/MgO(1.6 nm)/Ta, Ruofan Li et al were able to build a 3D magnetic sensor with a linearity of $[-4, 4]$ Oe in the z axis and $[-10, 10]$ Oe in the x and y direction, for a critical current density of $J = 6.8 \text{ MA/cm}^2$. Following their work, in [5] Zhe Guo et al used a Hall Cross of W(5 nm)/CoFeB(1.1 nm)/MgO(2 nm)/Ta(2 nm) to sense a magnetic field of $[-20, 20]$ Oe in all directions, with a critical current of $I = 40 \text{ mA}$. This sensors rely on the Spin-Hall effect, when a electric current goes through a heavy metal, a spin current is created and it can affect the magnetisation of the ferromagnetic layer. By doing so, there is a movement in the domain wall of that layer and the anomalous hall resistance is changed, when a certain critical current is reached the hysteresis loop for the out of plane magnetic field component closes and a linear range surges, allowing to develop a relationship between it and the magnetic field. A linear range also appears in the in-plane components. This linearity allows to develop a relationship between the anomalous Hall resistance and the three components of the magnetic field.

Chapter 2

Theoretical framework

It is safe to say that nobody understands quantum mechanics.

RICHARD FEYNMAN

2.1 Stoner Wohlfarth model

In 1948, Edmund Clifton Stoner and Erich Peter Wohlfarth published an article [23], where they present their model of ferromagnetism. It included a numerical calculation of the integrated response of randomly orientated magnets. They used hand calculations and trigonometric tables, as it was published before computers being widely available.

In the Stoner-Wohlfarth model, a single domain is considered, meaning that the different possible domains of the ferromagnet are not considered. Therefore, the magnetisation rotates with the variation of an external magnetic field, H_a , that can only vary in a single plane. The ferromagnet is assumed to have uniaxial magnetic anisotropy. As the magnetic field changes, the magnetisation is restricted to the plane containing both the easy axis and the magnetic field. This transforms it into a two-dimensional problem. Meaning that the change in the magnetisation direction can be represented only by an angle, θ .

Considering the scenario presented in the last paragraph, the Stoner-Wohlfarth model consists in calculating the local minima of energy for each applied field, allowing to draw the Magnetisation *vs* Applied field loop.

2.1.1 Zeeman energy

When a body with magnetisation, $\mathbf{M}$, is considered and an magnetic field is applied, $\mathbf{H}_a$ to it, the potential energy that will result from this interaction is given by the Zeeman energy [24], equation 2.1.

$$\varepsilon_z = -\mu_0 \mathbf{M} \cdot \mathbf{H}_a \quad (2.1)$$

This energy is said to be unidirectional as it is only minimised when both the magnetisation and the applied magnetic field are parallel. So, the external magnetic field is *trying* to align the magnetisation with it.

2.1.2 Perpendicular magnetic anisotropy

The natural direction of the magnetization of a microscopic ferromagnetic domain is usually constrained to lie along one or more easy axes. Since magnetism is associated with circulating electron currents, time reversal symmetry requires that a state with magnetization, $\mathbf{M}$, needs to have the same energy as a state with energy $-\mathbf{M}$, along the same axis. This tendency is represented by the anisotropy energy density, ε_K , which is given by equation 2.2[24].

$$\varepsilon_K = K_u \sin^2 \theta \quad (2.2)$$

Where θ is the angle between the magnetisation and the easy axis and K_u is the energy density factor. The anisotropy energy is at its minimum when $\theta = n\pi$ for n integer, this means that the magnetisation is aligned with the easy axis independently of if it is pointing in the positive or negative direction, because of that, this energy term is called uniaxial.

When considering that the anisotropy is perpendicular, the easy axis will be the axis perpendicular to the plane of the element of study, summarising the perpendicular magnetic anisotropy *wants* to put the magnetisation on the perpendicular axis.

2.1.3 Demagnetising Field

When a magnetic field is applied to a ellipsoid shaped object a Demagnetising Field, $\mathbf{H}_d$, appears as a response. This response is always contrary to the applied magnetic field and it depends on the material shape, mathematically described by the demagnetising factor

tensor, $\bar{\bar{N}}_d$, and the materials saturation magnetisation. It can, therefore, be described as equation 2.3[24].

$$\mathbf{H}_d = -\bar{\bar{N}}_d \mathbf{M} \quad (2.3)$$

When considering a thin film in the xOy plane, the x and y directions can be taken as infinite and therefore the only non null component in the tensor $\bar{\bar{N}}_d$ is the $N_d^{zz} = 1$. That will give a demagnetising field of $\mathbf{H}_d = -M_z \hat{\mathbf{z}}$. If the angle between the magnetisation and the z axis is called θ , then the energy density due to the demagnetising field can be obtained by equation 2.4.

$$\varepsilon_d = -\mu_0 \mathbf{M} \cdot \mathbf{H}_d = \mu_0 M_s^2 \cos^2 \theta \quad (2.4)$$

Just like the perpendicular anisotropy field, the demagnetising energy density has a squared term so the energy will be uniaxial as it will have a minimum for $\theta = n\frac{\pi}{2}$, i.e. the energy is minimum when the magnetisation is align with the plane of the thin film, regardless of the direction being positive or negative. Therefore, this energy term must compete directly with the perpendicular anisotropy energy term.

2.1.4 Execution of the Macro-Spin model

Following in the footsteps of Stoner-Wohlfarth, instead of a simple external magnetic field let there be an external magnetic field and an extra field that depends on the current density as depicted in equation 2.5. This field will be orthogonal to both the normal of the plane of the thin-film and the current density applied. Assuming the current density is applied in the x axis and the normal to the plane is the z axis, then the field will be in the $-y$ direction.

$$\mathbf{H}_J = -A \frac{J_c}{\mu_0 M_s t} \hat{\mathbf{y}} \quad (2.5)$$

Where t is the thickness and A a constant.

The energy density will consist of four different energies, the anisotropy energy density, the demagnetising energy, and the two Zeeman energies due to the two different magnetic fields. The total energy density of the system schemed in figure 2.1 is given by equation

2.6. The equilibrium magnetisation will be given when the energy density is minimum with respect to the angle between the magnetisation and the magnetic field, θ .

$$\varepsilon = K_u \sin^2(\alpha - \theta) + \frac{\mu_0 M_s^2}{2} \cos^2(\alpha - \theta) - \mu_0 M_s H_a \cos \theta - A \frac{J_c}{t} \cos \left(\frac{\pi}{2} + (\alpha - \theta) \right) \quad (2.6)$$

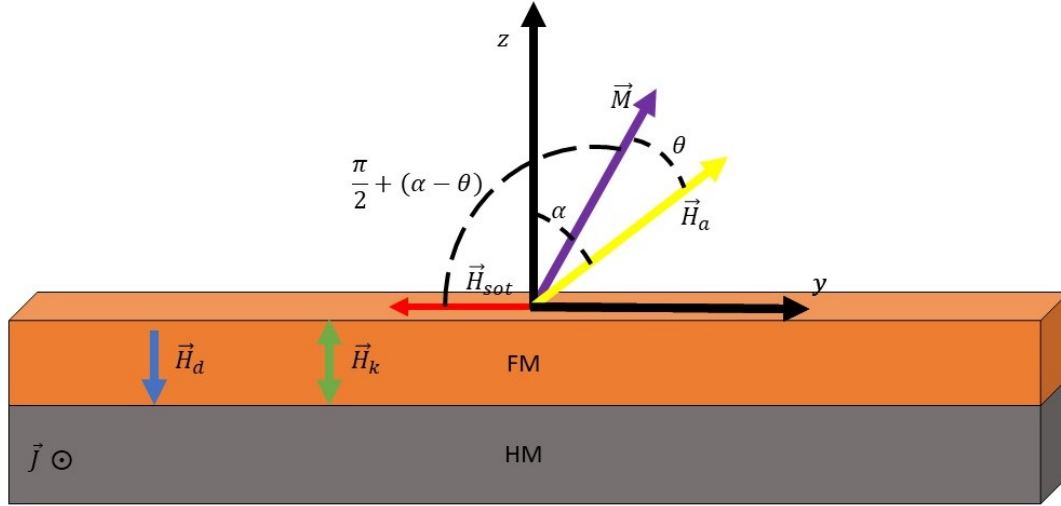


FIGURE 2.1: Schematic of the thin film multilayer in study with the different anisotropies represented. HM - heavy metal; FM - ferromagnet; $\vec{M}$ - magnetisation vector; $\vec{H}_a$ - applied magnetic field; $\vec{H}_{SOT}$ - spin-orbit torque effective field; $\vec{H}_k$ - perpendicular magnetic anisotropy field; $\vec{H}_d$ - demagnetising field; $\vec{J}$ - current density

2.2 Using Spin-orbit torque for magnetic field sensing

2.2.1 Spin-orbit interaction

Considering an electron orbiting the nucleus, this electron will feel an electric field $E = -\nabla\phi$ that keeps it in its orbit with a velocity, $\boldsymbol{\vartheta}$. However, from the reference frame of the electron, it sees a positive charge moving around it, and whenever there is a moving charge, there is a corresponding magnetic field. Therefore, using the Lorentz transformations, one can calculate the magnetic field in the electron's reference frame, $\mathcal{B}$ [25].

$$\mathcal{B} = \gamma_L \left(\mathbf{B} - \frac{1}{c^2} \boldsymbol{\vartheta} \times \mathbf{E} \right) \quad (2.7)$$

Where, $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic field in the laboratory reference frame and $\gamma_L = \left(1 - \left(\frac{\vartheta}{c} \right)^2 \right)^{-1/2}$ is the Lorentz factor, c is the speed of light.

The electron also has a magnetic dipole, μ , [24]

$$\mu = -g_s \frac{\mu_B}{\hbar} \mathbf{S}, \quad (2.8)$$

where g_s is the g-factor of the electron's spin, μ_B is the Bohr magneton, $\hbar$ is the reduced Planck constant and $\mathbf{S}$ is the spin vector operator. This magnetic dipole in the presence of a magnetic field originates a torque such that, [25]

$$\frac{d}{dt} \mathbf{S} = -g_s \frac{\mu_B}{\hbar} \mathbf{S} \times \mathcal{B} \quad (2.9)$$

However, this equation does not take into account that when there is an electric field perpendicular to the velocity of a particle, it generates an acceleration that is also perpendicular to the particle's velocity. This means that the particle will undergo rotation. This phenomenon particularly affects electrons, causing the electron's reference frame to become non-inertial. Consequently, the change in spin with respect to time needs to be rewritten as equation 2.10 [25]

$$\frac{d}{dt} \mathbf{S} = -g_s \frac{\mu_B}{\hbar} \mathbf{S} \times \mathcal{B} - \boldsymbol{\omega} \times \mathbf{S} \quad (2.10)$$

where $\boldsymbol{\omega}$ is the angular velocity of the rotation. Using this equation we can define a magnetic-like field, $\mathcal{B}_L$, so that

$$\frac{d}{dt} \mathbf{S} = -g_s \frac{\mu_B}{\hbar} \mathbf{S} \times \left(\mathcal{B} + \frac{\hbar}{g_s \mu_B} \boldsymbol{\omega} \right) = -g_s \frac{\mu_B}{\hbar} \mathbf{S} \times \mathcal{B}_L \quad (2.11)$$

The Hamiltonian of this interaction will, therefore, be define as

$$\mathcal{H}_{SO} = -\mu \cdot \mathcal{B}_L \quad (2.12)$$

which can be rewritten as

$$\mathcal{H}_{SO} = g_s \frac{\mu_B}{\hbar} \mathbf{S} \cdot \left(\mathcal{B} + \frac{\hbar}{g_s \mu_B} \boldsymbol{\omega} \right). \quad (2.13)$$

Through Lorentz Transformations [25] it is possible to show that $\boldsymbol{\omega} = \frac{\gamma_L^2}{\gamma_L + 1} \frac{\mathbf{a} \times \boldsymbol{\vartheta}}{c^2}$, where $\mathbf{a}$ is the electron's acceleration, and acknowledging that the electron velocity is much smaller than the speed of light, $\boldsymbol{\vartheta} \ll c$, $\gamma_L \sim 1$ and therefore, $\boldsymbol{\omega} = \frac{1}{2} \frac{\mathbf{a} \times \boldsymbol{\vartheta}}{c^2}$. This $\frac{1}{2}$ is the so called Thomas precession factor. Furthermore, the electron's velocity can be written as a function of its linear momentum, $\boldsymbol{\vartheta} = \frac{\mathbf{p}}{m}$, and its acceleration as a function of the

laboratory referential electric field, $\mathbf{a} = -\frac{e}{m}\mathbf{E}$, assuming the Bohr model for the atom, $\mathbf{E} = -\frac{Ze}{4\pi\epsilon_0}\frac{\mathbf{r}}{r^3}$, where Z is the atomic number, so with all that being said,

$$\mathcal{H}_{\text{SO}} = \frac{Ze^2}{8\pi\epsilon_0 m^2 c^2 r^3} \mathbf{S} \cdot (\mathbf{r} \times \mathbf{p}) \quad (2.14)$$

Finally, acknowledging that the orbital momentum, $\mathbf{L} = \mathbf{r} \times \mathbf{p}$, the equation 2.14 gives us

$$\mathcal{H}_{\text{SO}} = \frac{Ze^2}{8\pi\epsilon_0 m^2 c^2 r^3} \mathbf{S} \cdot \mathbf{L} \quad (2.15)$$

The equation referenced as 2.15 yields intriguing outcomes. Firstly, it becomes apparent that the electron's orbital motion couples its spin angular momentum and orbital angular momentum. However, this energy term can often be negligible in most scenarios. It is crucial to discern when this term becomes non-negligible. If we consider that the expected value $\langle \frac{1}{r^3} \rangle \propto Z^3$, then $\langle \mathcal{H}_{\text{SO}} \rangle \propto Z^4$, signifying that this effect magnifies with an increase in atomic number. Consequently, the spin-orbit coupling manifests more prominently in elements with higher atomic numbers, characterised by robust electron-nucleus interactions, such as heavy metals. Furthermore, the establishment of spin-orbit coupling devices necessitates the presence of ferromagnetic order. This implies that the optimal approach to achieve robust spin-orbit coupling involves creating a device that either forms an interface between a ferromagnet and a heavy metal or introduces doping of a ferromagnet with heavy metal.

2.2.2 Spin-Hall effect

In the interface between an heavy metal and a ferromagnet, there is a phenomenon that occurs named Spin-Hall effect. This effect basically transforms a charge current, J_c , into a spin current J_s , this current will be simultaneously perpendicular to the spin polarisation, σ and the charge current.

To explain this phenomenon, consider figure 2.2 where a current flows in the heavy metal, as the heavy metal is a thin film, it does not have inversion symmetry (due to the difference in the normal direction to the plane), and because of that and because of the spin-orbit coupling there is a transference in orbital angular momentum from the lattice to the electrons of the charge current. This leads to the diffusion of spins in the heavy metal and accumulation of the latter in the lateral boundaries, each boundary with a different

type of spin (up or down), leading to a spin-current that is perpendicular to the applied current [26].

In this thesis, the materials and devices explored have perpendicular magnetic anisotropy, therefore the spin polarisation will be given by the normal to the surface, this means that the current generated will be always in the same plane as the thin film.

The spin current density can, therefore, be defined as [26]

$$\vec{J}_s = \frac{\hbar}{2e} \Theta_{SH} (\vec{J}_c \times \hat{z}) \quad (2.16)$$

where Θ_{SH} is the Spin-Hall angle.

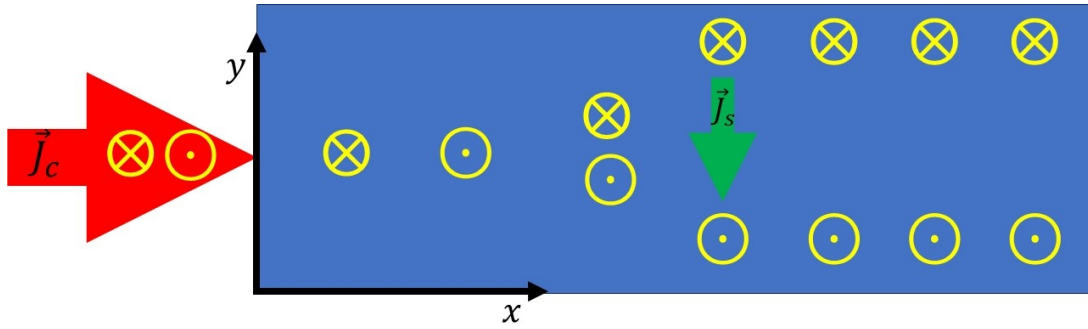


FIGURE 2.2: Scheme of the Spin Hall effect. The $\odot$ represents spin up electrons and the $\otimes$ represents spin down electrons

The current that is generated will be responsible for inducing a torque in the ferromagnetic layer's magnetisation, leading to movement of the domain wall in the ferromagnetic layer as will be seen in section 2.2.4

This phenomenon is currently explained by three theories; **1 - Skew-scattering** When an electron scatters due to an impurity or phonon the spin-orbit coupling gives an effective field gradient along the scattering vector, resulting in a spin dependence of the scattering[27]. **2 - Side-jump** The spin-orbit coupling results in an effective field gradient along the incoming and outgoing direction, which upon repeated scattering leads to an accumulation at the lateral boundaries [28]. **3 - Intrinsic** due to the band-structure and the spin-orbit coupling a transverse velocity is generated in between scattering events, which leads different spin electrons in different directions. [29]

2.2.3 Landau–Lifshitz–Gilbert equation

The Landau–Lifshitz–Gilbert equation (LLG), equation 2.17, is the equation that describes the magnetisation dynamic's phenomenologically,[30]

$$\frac{d}{dt}\mathbf{m} = -\gamma\mathbf{m} \times \mathbf{H}_{eff} + \alpha\mathbf{m} \times \frac{d}{dt}\mathbf{m} \quad (2.17)$$

where $\mathbf{m}$ is the magnetisation's versor, γ is the electron's gyromagnetic ratio, α is the damping factor and $\mathbf{H}_{eff}$ is the Magnetic effective field (will be discussed further soon).

Equation 2.17 represents two types of torques, one given by the effective field and the other perpendicular to it. It is important to distinguish these two types of torque. In the one hand, the torque given by the effective field will cause the magnetisation to precess around the direction of the given field. On the other hand, the damping torque will try to align the magnetisation with the effective field direction. There is, therefore, two types of alignment of the magnetisation competing with each other, figure 2.3.

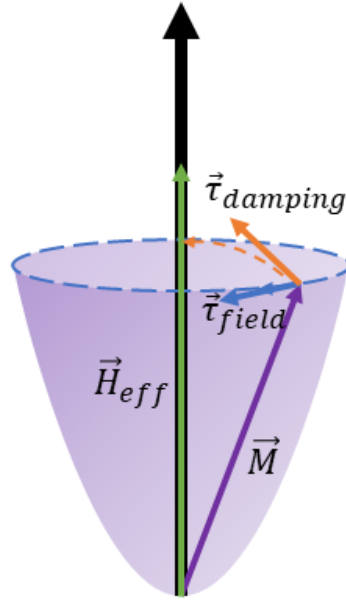


FIGURE 2.3: Two types of competing torques due to a magnetic field and their effect on the magnetisation

The effective field in equation 2.17 is the main responsible for the magnetisation dynamics. This field takes into account the exterior and interior interactions of the system being studied, for instance an external magnetic field applied (external interaction) or the anisotropy of the material (internal interaction). The effective magnetic field relates itself

with the energy density, ε , of the system as,

$$\mathbf{H}_{eff} = -\frac{1}{\mu_0 M_s} \nabla_m \varepsilon \quad (2.18)$$

where $\nabla_m = [\frac{\partial}{\partial m_x} \quad \frac{\partial}{\partial m_y} \quad \frac{\partial}{\partial m_z}]$ is the gradient with respect to the magnetisation coordinates and ε is the energy density of the material being studied.

In any ferromagnetic material, the main terms in the energy density are the exchange, magnetic anisotropy, and the magneto-static energy. Any external field, $\mathbf{H}_a$, will give its contribution to the energy due to the Zeeman energy. That being said, in the presence of an external magnetic field the energy density of the system is given by equation 2.19

$$\varepsilon = A \sum_{i=1}^3 |\nabla m_i|^2 + K_u \sin^2 \theta + \mu_0 M_s^2 \cos^2 \theta - \mu_0 M_s \mathbf{m} \cdot \mathbf{H}_a \quad (2.19)$$

where A is the exchange correlation constant, K_u is the anisotropy energy density factor, $\mu_0 M_s^2 \cos^2 \theta$ is the demagnetising energy density, θ is the angle between the magnetisation and the $\hat{z}$ axis, and M_s is the saturation magnetisation. It is important to notice that the magnetisation is being defined as $\mathbf{M} = M_s [\cos \phi \sin \theta, \sin \phi \sin \theta, \cos \theta]$, equation 2.19 takes into account perpendicular magnetic anisotropy and demagnetisation in thin films. These interaction are both uniaxial, which means that they try to align the magnetic field with an orientation of an axis, being independent of its sense, that is why they are described by a squared term, furthermore, the signal of this terms needs to be contrary to each other, because, as the perpendicular anisotropy wants to align the magnetisation off-plane, the demagnetising field wants to align it in plane.

As seen in section 2.2.2, the Spin-Hall effect gives origin to a spin-current and spin accumulation in the borders of the heavy-metal, this will be responsible for a transference of angular momentum to the ferromagnetic layer, allowing its switching or tilting. Whenever there is a transference in angular momentum, it can be mathematically described by a torque, in this case, the spin-orbit interaction gives birth to two different torques, on commonly known as *field-like* and another known as *damping like*.

$$\boldsymbol{\tau}_{SO} = \gamma (\tau_{FL} (\mathbf{m} \times \mathbf{u}_{SOT}) - \tau_{DL} \mathbf{m} \times (\mathbf{m} \times \mathbf{u}_{SOT})) \quad (2.20)$$

where, generally, $\tau_{FL} = \eta_{FL} \frac{\hbar J_c}{2e\mu_0 M_s t} \ll \tau_{DL} = \eta_{DL} \frac{\hbar J_c}{2e\mu_0 M_s t}$, [31][30], t is the ferromagnetic layer thickness and $\mathbf{u}_{SOT} = \frac{J_c}{J_c} \times \mathbf{z}$. [30].

The spin-orbit interaction can originate another interaction, which does not depend on the applied current. It is called the interfacial Dzyaloshinskii-Moriya interaction (DMI), which arises from the spin-orbit coupling at interfaces. Assuming in-plane isotropy (as is the case for this film), the energy of this interaction is described by equation 2.21 [30]

$$\varepsilon_{DMI} = D (m_z \nabla \cdot \mathbf{m} - (\mathbf{m} \cdot \nabla) m_z) \quad (2.21)$$

where D is the DMI constant.

Finally considering all the effects above mentioned it is possible to rewrite equation 2.17, considering the effective field as defined by 2.18. Furthermore as seen, there is an extra torque due to the current applied, this torque must also be included in the LLG, therefore it is rewritten as equation 2.22.

$$\begin{aligned} \frac{d}{dt} \mathbf{m} = & \frac{\gamma}{\mu_0 M_s} \mathbf{m} \times \left(2A \nabla^2 \mathbf{m} - 2m_z (K_u - \mu_0 M_s^2) \hat{\mathbf{z}} + \mu_0 M_s \mathbf{H}_a - D [(\nabla \cdot \mathbf{m}) \hat{\mathbf{z}} - \nabla m_z] \right) + \\ & + \frac{\gamma}{\mu_0 M_s} \mathbf{m} \times \eta_{FL} \frac{\hbar J_c}{2et} \mathbf{u}_{SOT} + \alpha \mathbf{m} \times \frac{d}{dt} \mathbf{m} - \gamma \eta_{DL} \frac{\hbar J_c}{2e \mu_0 M_s t} \mathbf{m} \times (\mathbf{m} \times \mathbf{u}_{SOT}) \end{aligned} \quad (2.22)$$

2.2.4 Hall cross sensing

Thus far a simple multilayer has been considered, from now on a Hall Cross will be used to explain how the sensor operates. As seen in subsection 2.2.2 a current flowing in the heavy metal can create a magnetic field due to spin-orbit torque and Spin-Hall effect, this magnetic field will be responsible for the domain wall dynamics.

Without any magnetic field being applied the magnetisation will be perfectly align with the out of plane axis, due to the perpendicular magnetic anisotropy. In conjunction, the system response to the spin-orbit torque is perfectly symmetric to changes in the current sign. However, when an external magnetic field is applied in plane the magnetisation is tilted and the spin-orbit torque response becomes asymmetric. So when no magnetic field is being applied, the domain wall is at the centre of the ferromagnetic layer, resulting in a anomalous Hall resistance of $\sim 0 \Omega$.

By applying a magnetic field in the plane of the Hall Cross is possible to align the magnetisation inside the domain wall with it. In particular, when this field is applied with a

parallel current it is possible to induce a movement of the domain wall perpendicular to the current. On the other hand, if the field is applied in the out of plane direction, the spin-orbit torque will still ensure some alignment of the domain wall spins in its direction (transverse to the current being applied and in plane), but as seen in the above paragraph, the response of the Hall Cross would be symmetric with respect to the current sign. In summary, whenever a magnetic field is applied out plane or parallel to the applied current, there is movement of the domain wall in the direction simultaneously perpendicular to the current and the normal to the plane, see figure 2.4. [4]

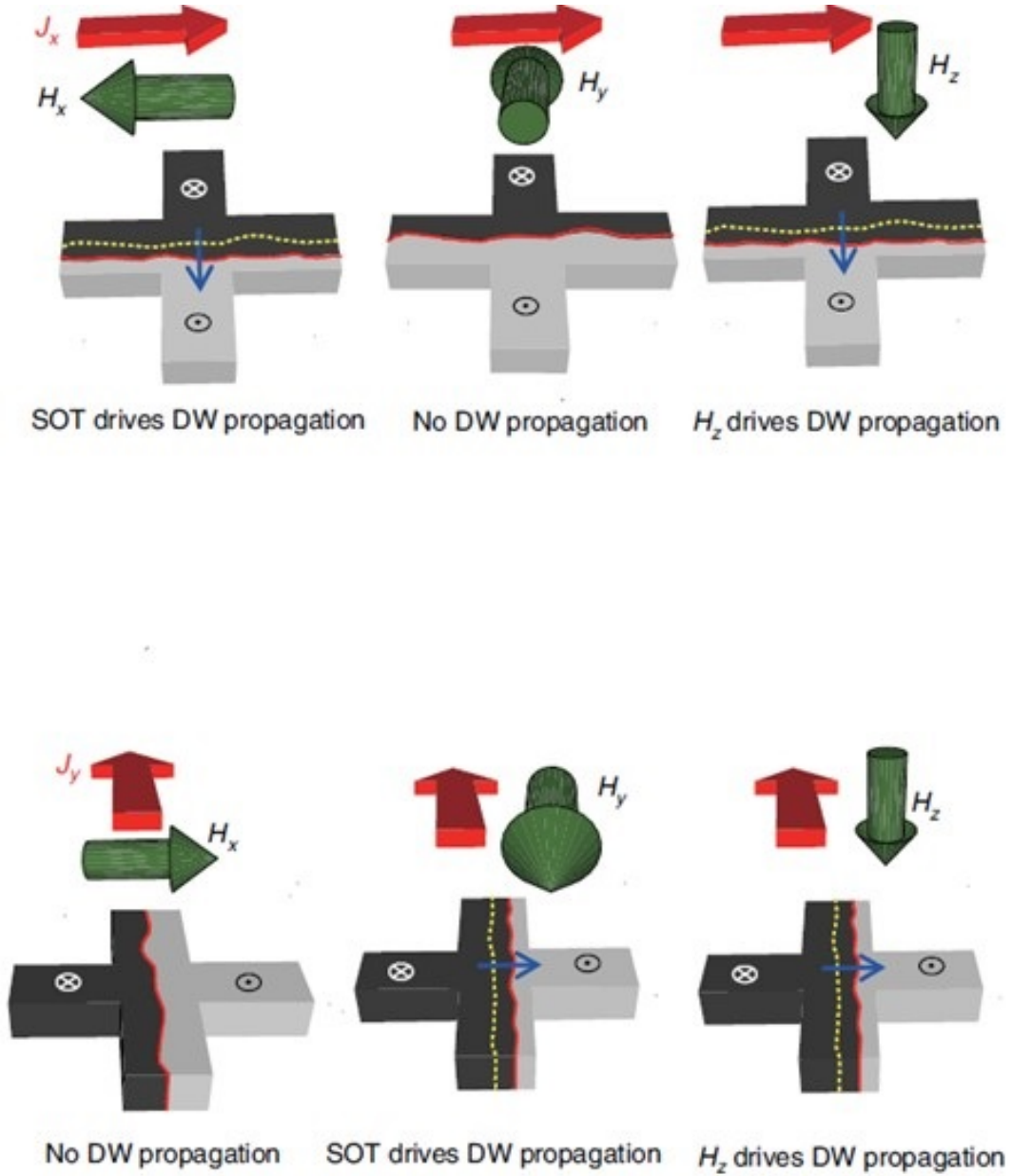


FIGURE 2.4: Different conditions for domain wall movement induced by magnetic field and current application. Reproduced with permission from Springer Nature [4]

When a 3D magnetic field is applied, the domain wall motion will vary with the current sign and the planar field. However, the movement due to the out-of plane field will only depend of the magnetic field's sign and not the current's. Because of this, this two phenomena can be separated and characterised through the domain wall dynamics[4].

The domain wall dynamics is followed by a change in the out of plane magnetisation. Meaning that the anomalous Hall resistance will be altered with the domain wall motion. While the current is being applied in the x direction the Hall voltage can be measured in the y axis, allowing to calculate the anomalous Hall resistance, R_{xy} , or doing the reverse to calculate R_{yx} .

As shown in [4], when measuring the R_{xy} (the same happens for R_{yx} , but the current must be in y) with a current in the x axis, the coercive field of the loop decreases as J_x increases, until there is a given current that allows R_{xy} to be approximately linear with H_z , figure 2.5a. This happens because the hard axis of the ferromagnet change, as the in plane spin-orbit torque effective field is strong enough to make the out-of plane axis the hard axis. On the other hand, for that current, if we measure the R_{xy} versus H_x loop, figure 2.5b, there is also a linear zone, for each current sign.

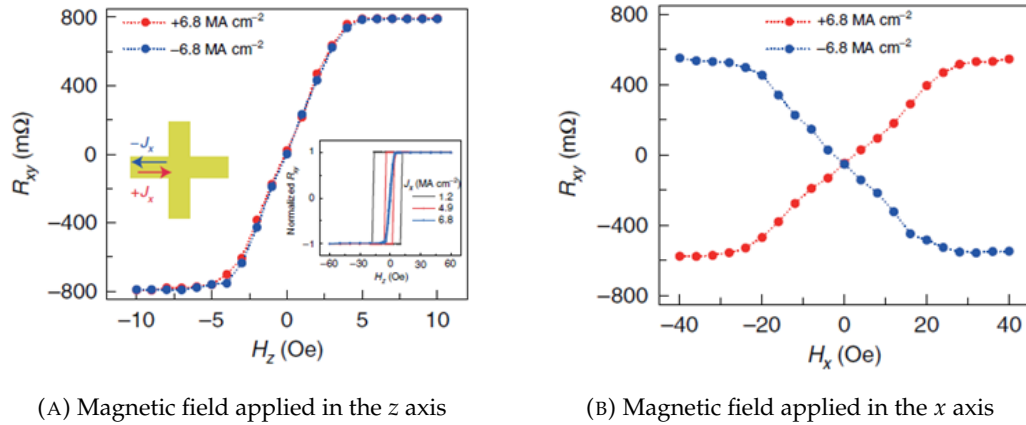


FIGURE 2.5: Experimental data showing the loop R_{xy} with respect to the applied magnetic field. Reproduced with permission from Springer Nature [4]

Due to the different responses to the current polarisation, it is possible to measure two different resistances for each of the current polarisation. In the example being used,

is possible to measure $R_{xy}(J_x)$ and $R_{xy}(-J_x)$ and taking advantage of the symmetric behaviour, to relate them as shown in equations 2.23 and 2.24.[4]

$$R(H_x) = \frac{R_{xy}(J_x) - R_{xy}(-J_x)}{2} \quad (2.23)$$

$$R(H_z) = \frac{R_{xy}(J_x) + R_{xy}(-J_x)}{2} \quad (2.24)$$

Note that, by doing the subtraction the component due to H_z is eliminated and, similarly, by doing the addition the H_x component is eliminated.

2.3 Final Remarks

In this chapter, two different ways of describing magnetic dynamics are presented one Macro, section 2.1, and another Micro, section 2.2. These two approaches have different advantages and disadvantages. On the one hand, micromagnetism in the form of the LLG leads to results considering all the interactions of the magnetic moment, giving a description of the magnetisation with respect to time and even allows for the determination of the spin of different domains in the ferromagnet, leading to a description of the domain wall dynamics. However, this approach is hard to compute and to build an intuition on, as it relies heavily in mathematically hard operations. On the other hand, the macromagnetic approach is simpler to compute and build intuition on, as it is built mostly around additions of energies. This simplicity is also a problem, as due to the single domain approach all interactions between magnetic domains is neglected, furthermore, there is no temperature dependence of the magnetisation. That being said, the model built in chapter 3 will be done using the Macro-spin approach, although some bridges are made between the two models as seen ahead.

In the LLG equation there is a term that behaves like a Magnetic field and has a dependence of the current density, it supports the idea of considering a magnetic field dependent of the current in the Macro-Spin model.

Furthermore, with section 2.2.1, it was shown that the spin-orbit interaction is greater for materials with high atomic number, that shows the importance of the usage of the heavy metal in the sensor. That conclusion lead to the idea of using Iridium as a heavy metal as it has a atomic number of $Z = 77$, the results will be seen in chapter 4.

Chapter 3

Macro-spin model Results

Things should be made as simple as possible, but not any simpler.

ALBERT EINSTEIN

3.1 Comparison guidelines

In the supplementary material of [4] the figure 3.1 is found. The objective of this model is to try to mimic both the figure 3.1 when no current is being applied and figure 2.5a when there is current.

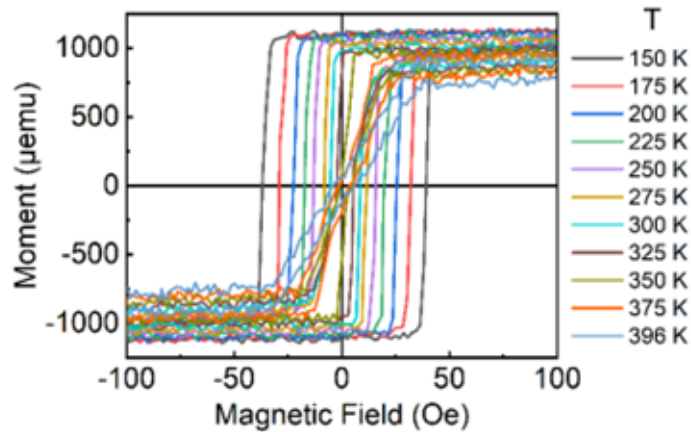


FIGURE 3.1: M-H curve for CoFeB. Reproduced with permission from Springer Nature [4]

In order to find the magnetisation for each magnetic field, the minimum of energy, equation 2.6, needs to be found. A python routine was built, which can be consulted in

Appendix B. This routine starts by defining the normalised energy as seen in Appendix A, then a initial guess of minimisation angle is defined, one in the first quadrant and another in the second, following that the function *minimize* imported from *scipy.optimize* is used to calculate each of the local minimums in the neighbour of the initial guess for each magnetic field. Finally when the magnetic field is increasing the minimum in the first quadrant is chosen, while when it is decreasing it is chosen the one in the second quadrant. When the normalised magnetisation is calculated it is multiplied by M_s and the other normalisations are reversed, obtaining the graphs that will be seen ahead.

3.2 Exploring the competing anisotropies

This simulations are trying to demonstrate the results obtained in [4] and then help to conclude about the best parameters to change in order to obtain higher field sensors as the ones reported.

The first simulation that will be done will be for $\alpha = 0$, the magnetic field out of the plane, the current will not be applied, $J_c = 0$, and using the values of saturation magnetisation, $M_s = 890 \times 10^3$ A/m and perpendicular magnetic anisotropy, $K_u = 1.34 \times 10^5$ J/m³ given by [4]. So equation 2.6 is rewritten as equation 3.1. In 3.1 it was taken into account that as the demagnetising energy density is superior to the anisotropy energy, to better see that they are competing, the $\sin^2 \theta = 1 - \cos^2 \theta$.

$$\varepsilon = K_u + \left(\frac{\mu_0 M_s^2}{2} - K_u \right) \cos^2 \theta - \mu_0 M_s H_a \cos \theta \quad (3.1)$$

Doing the numerical simulations the graph of figure 3.2 is obtained.

By analysing the results in Figure 3.2, it is possible to conclude that the easy axis of the sample would be in-plane. However, in [4], figures 3.1, it seems that the easy axis of the sample is the axis perpendicular to the plane. What is happening is most likely the value of saturation magnetisation given in the paper is too big and not the one of a thin film. Usually, the values for thin films are smaller. If that is not true, just by a simple calculation, it is possible to realise that the demagnetising energy density will be larger than the magnetic anisotropy energy density, so the latter would win as they compete. Therefore, the magnetisation would prefer to be aligned with the plane rather than out of the plane as expected.

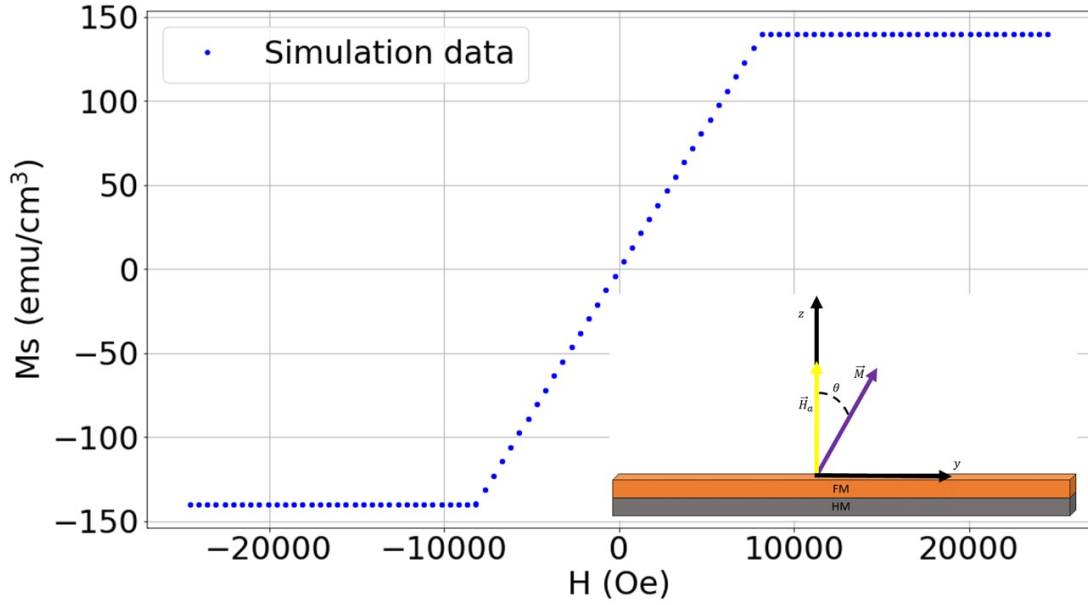


FIGURE 3.2: Simulation of the M-H curve for the sample described in [4]

3.3 Ensuring the dominance of the out-of plane magnetic anisotropy

From now on the value of the magnetisation saturation to be used will be $M_s = 3.00 \times 10^5$ A/m, in order to satisfy $K_u > \frac{\mu_0 M_s^2}{2}$. This time, as $K_u > \frac{\mu_0 M_s^2}{2}$ let us instead consider $\cos^2 \theta = 1 - \sin^2 \theta$ allowing to rewrite equation 2.6 as equation 3.2. Running the simulation the graph presented in figure 3.3 is obtained.

$$\varepsilon = \left(K_u - \frac{\mu_0 M_s^2}{2} \right) \sin^2 \theta - \mu_0 M_s H_a \cos \theta + \frac{\mu_0 M_s^2}{2} \quad (3.2)$$

As predicted analytically, the easy axis is the out of plane axis. However, the values given numerically by the simulation are not the ones expected experimentally as seen in [4]. The Stonner-Wolfhart Model, as explained in section 2.3, takes a lot of approximations and simplifications, as for example, the effect of temperature is not taken into account, the single domain approximation leaves out some important interactions, all this permits the values obtained to be way higher than what is to be expected when a measurement is done, as will be seen in chapter 4 or in figure 3.1.

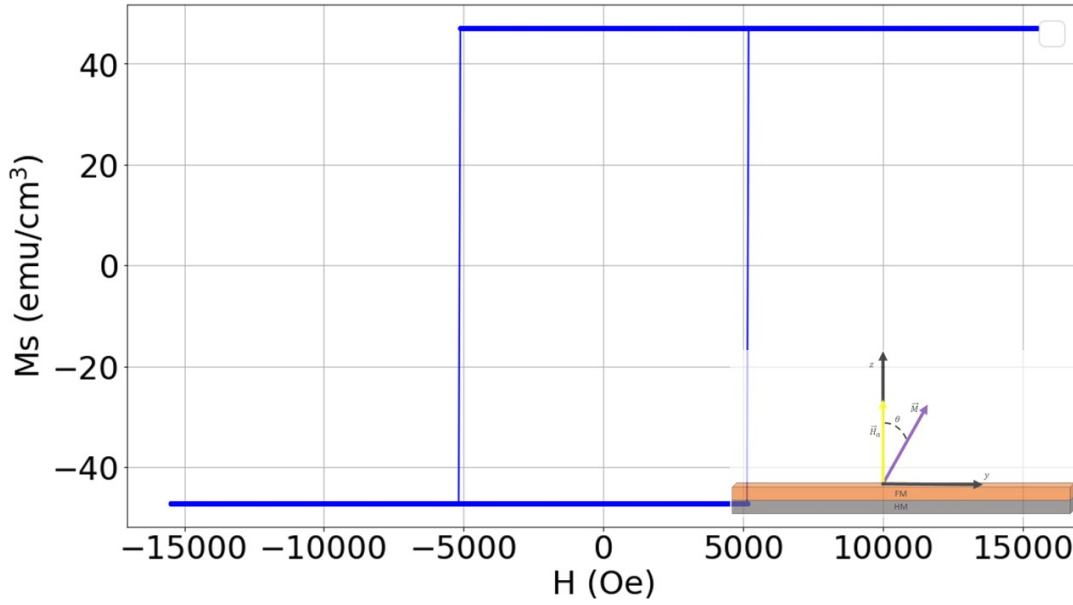


FIGURE 3.3: M-H loop simulated ensuring perpendicular magnetic anisotropy

3.4 Model with different values of current density

Once the predicted result for the current-less case is obtained, it is time to turn the current switch on! The hysteresis loop was made for different current inputs and the objective is to try and find the current that would linearize the hysteresis as reported in [4]. The equation 2.6 takes then the form of equation 3.3. The numerical simulation was made, being presented in figure 3.4.

$$\varepsilon = \left(K_u - \frac{\mu_0 M_s^2}{2} \right) \sin^2 \theta - \mu_0 M_s H_a \cos \theta - A \frac{J_c}{t} \cos \left(\frac{\pi}{2} - \theta \right) + \frac{\mu_0 M_s^2}{2} \quad (3.3)$$

In figure 3.4, once again the numerical values obtained differ from the ones found in figure 2.5a, putting in full display one of the Stonner-Wolfhart model limitations. Nevertheless, there is a linearization of the hysteresis loop as the current density increases just like what was expected. It is a smoother linearization, as the linear range is just between $M \in [-20, 20]$ emu/cm³, and not the full range of the magnetisation. Also, it is possible to verify that before the critical current is achieved, the current contributes to decreasing the coercive field, just like what is reported in figure 2.5a. Furthermore it is also shown that just like in figure 2.5a the sign of the current does not change the behaviour of the out-plane magnetisation.

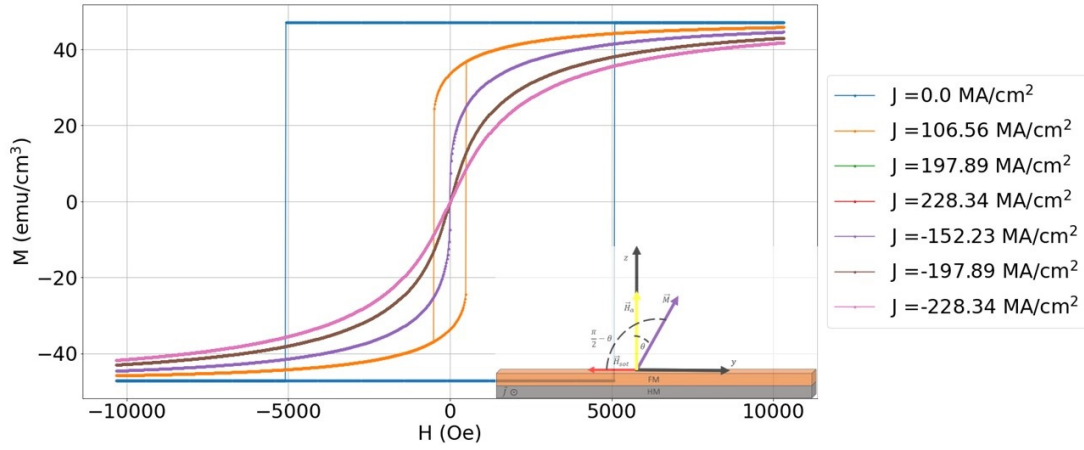


FIGURE 3.4: Simulation of the M-H curve for the sample, changing $M_s = 3.00 \times 10^5 \text{ A/m}$ and for different values of current density

3.5 Optimisation of parameters

As only the anisotropy field and the saturation magnetisation values are changed, the equation of the energy that needs to be minimise is the same as 3.3

Although the model cannot give accurate predictions of the values of both coercive field and critical density currents, it is possible that it might give the correct relationship between them. To verify that, it is possible to define a effective uniaxial field, H_u^{eff} , that is the field that ensures $\frac{\mu_0 M_s H_u^{\text{eff}}}{2} = K_u - \frac{\mu_0 M_s^2}{2} = \frac{\mu_0 M_s H_k}{2} - \frac{\mu_0 M_s^2}{2}$. The saturation magnetisation can be achieved simply by $M_s = H_k - H_u^{\text{eff}}$. Starting by considering $H_k = 5000 \text{ Oe}$ and the $H_u^{\text{eff}} = 30 \text{ Oe}$ to obtain an coercive field of the same order of the article 2.5a, it will give an saturation magnetisation of $M_s = 3.96 \times 10^5 \text{ A/m}$. So, applying this parameters to the model it gives the graph in figure 3.5.

The graph of figure 3.5 clearly shows that when the coercive field is in the same order of the one given in the article [4] the current density will be the one given experimentally. Therefore, although the Stonner-Wolfhart model does not give the values measured experimentally the relationship between those quantities is correct. It is important to notice that the saturation magnetisation used is superior than the one used in figure 3.4, the anisotropy energy density is smaller, $K_u = 0.989 \times 10^5 \text{ J/m}^3$. With this values, the potential barrier, $K_u - \frac{\mu_0 M_s^2}{2}$, that must be beaten to close the hysteresis loop is smaller than the previous one and therefore the current needed to do so, is also smaller, the value of the barrier is reduced by 99% (calculated for the coercive field), just like the energy due to the

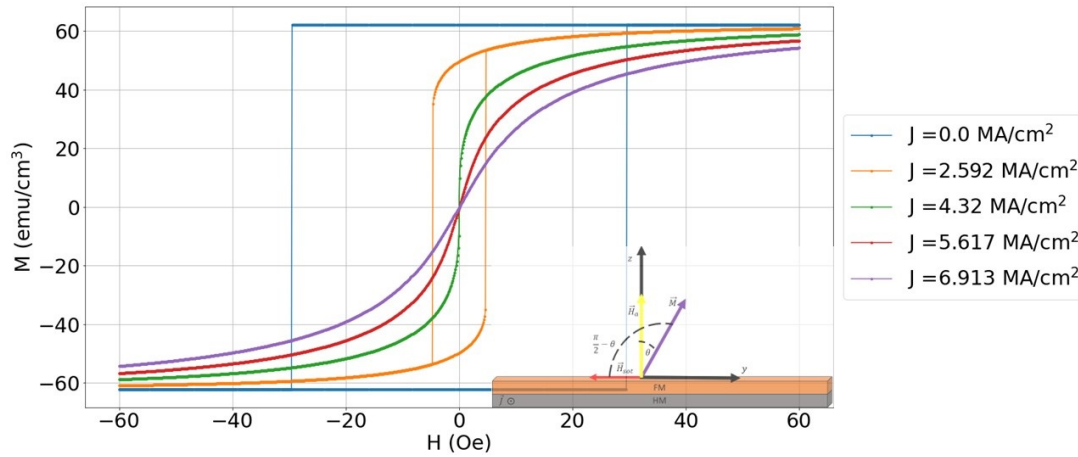


FIGURE 3.5: Simulation of the M-H curve for the sample, changing: $M_s = 3.96 \times 10^5 \text{ A}/\text{m}$ and $H_K = 5000 \text{ Oe}$ for different values of current density

applied magnetic field, the energy of the spin-orbit torque field is reduced in 97% (calculated for the linearization current), as the difference in energy reduction is really close, this helps sustain that both the critical current density and the coercive magnetic field are related.

3.6 Perspectives

The major conclusion that is possible to draw from this study is that, as expected, the anisotropy and demagnetisation are the define factors to the linear range of the magnetisation of the thin film. That being said, it is clear that they impact both the coercive field and the critical current density. This is happening because when the anisotropy and demagnetisation is changed, the energy barrier that the magnetic field and current density need to beat is also changed. To obtained a sensor with a linear range for higher magnetic fields, it is expected to be necessary to increase the perpendicular anisotropy (as the demagnetisation competes with it, should be the lesser possible), but in doing so the current density necessary would also increase.

Chapter 4

Magnetic multilayer characterisation

I have not failed. I've just found 10000 ways that won't work.

THOMAS EDISON

4.1 The SQUID MPMS®3

The SQUID (Superconducting QUantum Interference Device) magnetometer MPMS®3 by Quantum Design offers different types of measurements. By consulting the SQUID datasheet [32], it is noticeable it utilises a 7 T superconducting, helium vapour-cooled magnet and an hybrid digital/analog magnet power supply. Optimised for precise and quiet control of the magnetic field. It also allows for control of the chamber temperature that ranges from T_e [1.8, 400] K, the temperature control insert utilises a vacuum-insulated chamber into which helium is drawn through a variable flow valve. The sophisticated software and finely tuned flow impedance allows for continuous operation at 1.8 K, while the heaters allow for operation up to 400 K, where the thermal shield minimises liquid helium loss when operating at high temperatures.

As show in figure 4.1, the SQUID MPMS®3 consists of a gradiometer tightly coupled to an inductor, called the Input Coil, this inductor is responsible to receive the current from the pick-up coils and transform it in magnetic flux that will be coupled to the SQUID magnetometer.[33]

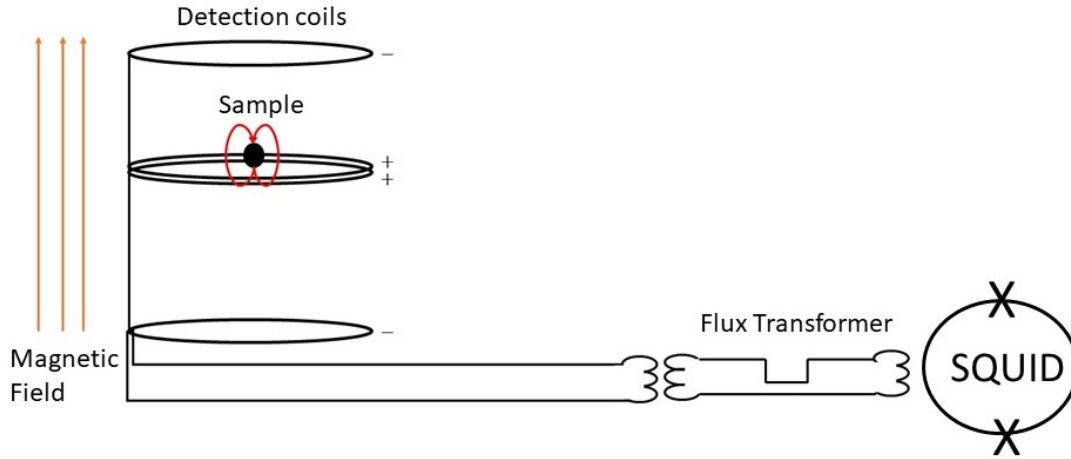


FIGURE 4.1: SQUID detection diagram cryogenic insert, inspired by [34]

4.1.1 SQUID magnetometer

The DC SQUID was invented by Robert Jaklevic, John J. Lambe, James Mercereau, and Arnold Silver of Ford Research Labs in 1964 [35]. It has two Josephson junctions [36][37] in parallel with a superconducting loop, figure 4.2. In the absence of an external magnetic field, the input current, I splits uniformly into the two branches. However, if a small external magnetic field is applied to the superconducting loop, a screening current, I_s , begins to circulate in order to cancel the external field. Therefore, an additional Josephson phase arises which is proportional to the external magnetic field. In one of the branches, the screening current is in the same direction as the input current, and in the other, it is in the contrary direction. As soon as the current in either branch reaches the critical current of that Josephson junction, a voltage appears across the junction.

When the external magnetic flux exceeds half the magnetic flux quantum $\Phi_0/2$, now instead of opposing it, the SQUID energetically prefers to increase the flux to Φ_0 , has the flux enclosed in a superconducting loop needs to be an integer of the magnetic flux quantum [38]. Therefore, the screening current will change its direction, decreasing as the flux approaches Φ_0 , then when it is reached the screening current would be zero, $I_s = \vec{0}$. Now, if the external magnetic flux is once again increased this process will be repeated. Thus the current changes direction periodically, reaching its maximum on every half integer of Φ_0 and being zero for every integer of Φ_0 .

When the input current is slightly larger than the critical current of the SQUID (the sum of the critical current of each Josephson Junction), the latter will be in the resistive

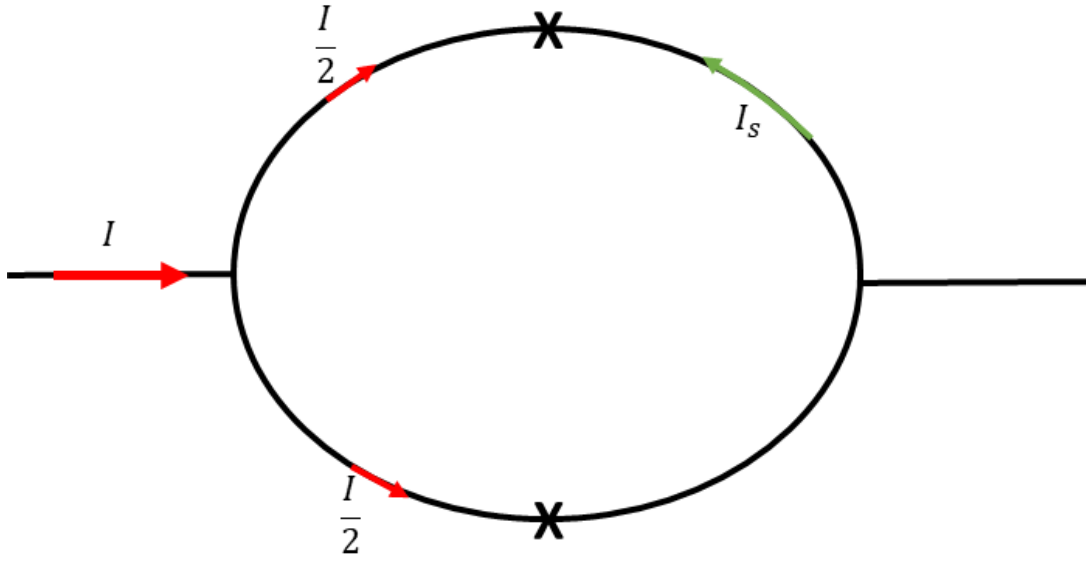


FIGURE 4.2: SQUID scheme. The X represents the Josephson junctions

mode. The voltage across the SQUID will then be a function of the applied field, with a period equal to a flux quantum . Using Ohm's law, the relationship between the variation in voltage and flux can be approximately calculated. As the variation in critical current is twice the variation of the screening current, and the screening current is equal to the applied flux, $\Delta\Phi$, divided by the loop self inductance, L , it can be defined as equation 4.1 [38]

$$2I = 2 \frac{\Delta\Phi}{L} \quad (4.1)$$

As the resistance of the SQUID is half the resistance of one of the junctions, than by Ohm's Law and equation 4.1,

$$\Delta V = \frac{R}{L} \Delta\Phi \quad (4.2)$$

knowing the self inductance and the resistance, R , of the ring, it is possible to relate the voltage difference with the variation of magnetic flux.

4.1.2 DC measurement *vs* VSM measurement

In order to understand the difference between the two types of measurement, it is important to understand how they are performed. In the introduction of this section, section 4.1, it was seen that the pick-up coils will produce an electromotive force, the important part now is understanding how is it formed.

In the DC measurement, the sample is firstly at rest in the centre of one of the pick-up coils. Then, the sample is quickly extracted from that pick-up coil to the centre of the other, generating an electromotive force.

By consulting the datasheet of the SQUID MPMS®3 [32], this measurement has a sensitivity of $< 5 \times 10^{-8}$ emu for magnetic fields under or equal to 2500 Oe and a sensitivity of $< 6 \times 10^{-7}$ for magnetic fields superior to 2500 Oe. Allowing for a maximum moment measurement of 2 emu.

The VSM measurement, on the other hand, consists of vibrating a sample in an applied magnetic field. This vibration will have a known amplitude and a known frequency. As predicted by Faraday's law of induction [39], the magnetic flux variation with time will produce an electromotive force that can be measured directly.

Consulting the datasheet of the SQUID MPMS®3 [32], the VSM measurement has a sensitivity of $< 1 \times 10^{-8}$ emu for magnetic fields under or equal to 2500 Oe and a sensitivity of $< 8 \times 10^{-8}$ for magnetic fields superior to 2500 Oe. Allowing for a maximum moment measurement above 100 emu.

As the magnetisation to be measured is in the order of 10^{-5} emu for magnetic fields of up to around 10000 Oe, the choice of measurement was the VSM measurement, as it allows for improved sensitivity all around.

4.1.3 Magnet Reset

The superconductor solenoid of the SQUID MPMS®3 does not show resistance to the movement of electrons, and therefore, it keeps picking up magnetic flux, making it challenging to achieve a true zero field. This means that even though there are no currents or potential differences in the magnet, there are small residual currents in the superconducting material.

One way of minimising the magnetic field or the magnetic field gradient in the chamber is to use the *Magnet Resect* option [32]. The software will bring the solenoid to the

supposed zero field and then heat it up above its critical temperature, stopping its superconductivity, allowing for the elimination of these residual currents. After that, a few more minutes are required to cool down the solenoid back to its operating temperature.

This process is very costly in terms of helium consumption due to boil-off. However, as the magnetic moments to be measured are on a very small scale, this measure becomes essential to provide clearer results around the magnetic field close to zero.

4.1.4 Vibration Amplitude of VSM

As seen in subsection 4.1.2, the VSM measurement is the one to be used. Therefore, one of the more important parameters to determine is the vibration amplitude of the sample.

By consulting the *Application Note 1500-013* of Quantum Design [40], it is found that in contrast to former VSM measurements, which are linear with amplitude, the signal of the SQUID VSM scales quadratic with this parameter. Thus, by changing the signal amplitude, one can control the scale of the signal.

The larger the amplitude of motion, the greater the sensitivity of the measurement, and the lower is the dependence on geometrical factors. However, larger amplitude measurements can lead to several problems. Namely, higher noise signals and temperature instability (due to the increasing friction). So, if a sample is very sensitive to small changes in the magnetic field, a lower amplitude is recommended. By reducing the vibration of the sample, it is possible to minimize the edge effects of the superconducting magnet.

As a "rule of thumb," Quantum Designs recommends the usage of higher amplitudes unless it is verified that the lower amplitude results in better measurement quality.

In this thesis, the two samples to be studied and characterised have a thickness of about 32.8 nm and a length of around 3 mm. As the out-of-plane measurement is required for small fields and is more volatile, the amplitude chosen was 2 mm, which is clearly superior to the thickness of the samples, allowing for a good signal but not too big that it introduces a lot of noise. On the other hand, this choice for the in-plane measurement would be poor, as the length of the sample would be superior to the length of the motion.

Therefore, for the in-plane measurement, an amplitude of 6 mm will be implemented, allowing for a better signal with less noise.

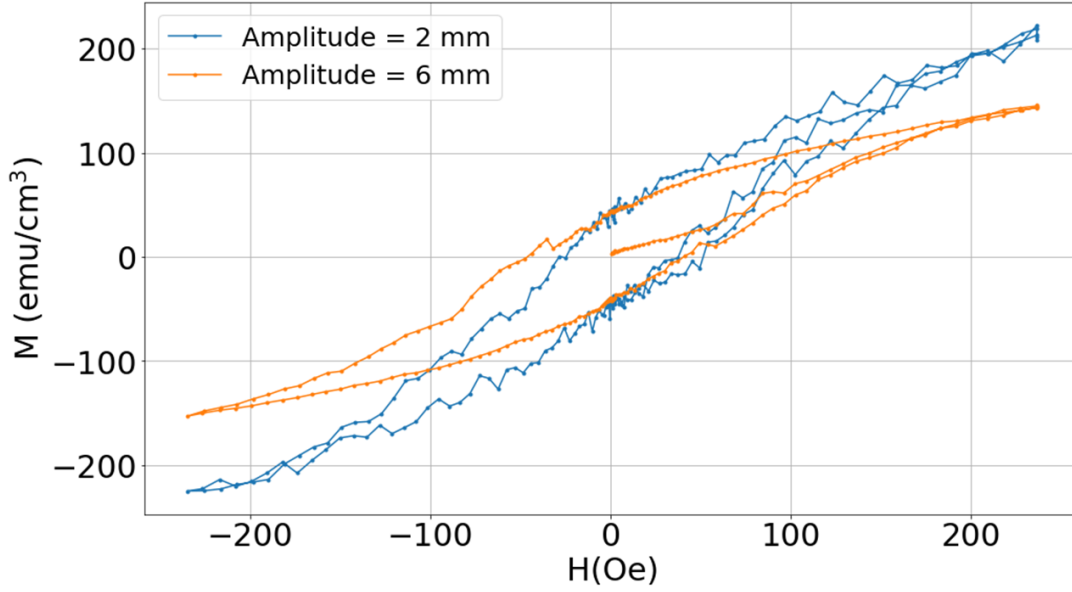


FIGURE 4.3: VSM with the magnetic field in-plane for different amplitudes, and for sample CF2. Note: this measurement was done while the protocol of section 4.2 was still in development, because of that the maximum magnetic field is too small.

4.1.5 Correction of the Applied field with Pd standard

Due to flux trapping and pinning, superconductive magnets although capable of producing high magnetic fields, can present additional challenges when generating below 10 Oe magnetic fields [41]. This can result in errors when measuring samples with low coercive fields, often resulting in an "inverted" loop, where the switching field along the descending (ascending) branch of the hysteresis loop occurs for positive (negative) fields.

In order to minimise this problem, it is possible to utilise a Pd sample at 298 K, temperature in which its susceptibility is well known, $\chi = 5.25 \times 10^{-6} \text{ emu Oe}^{-1} \text{ g}^{-1}$, and performed the exact routine that will be performed in the samples to be studied. As Pd is a paramagnetic material, by applying a magnetic field it will respond linearly, allowing to determine the true field, H_{true} , using equation 4.3,

$$H_{true} = \frac{M_{measured}}{\chi m} \quad (4.3)$$

where, $M_{measured}$ is the magnetisation measured and $m = 0.2593 \text{ g}$ is the sample mass.

4.2 Measurement protocol

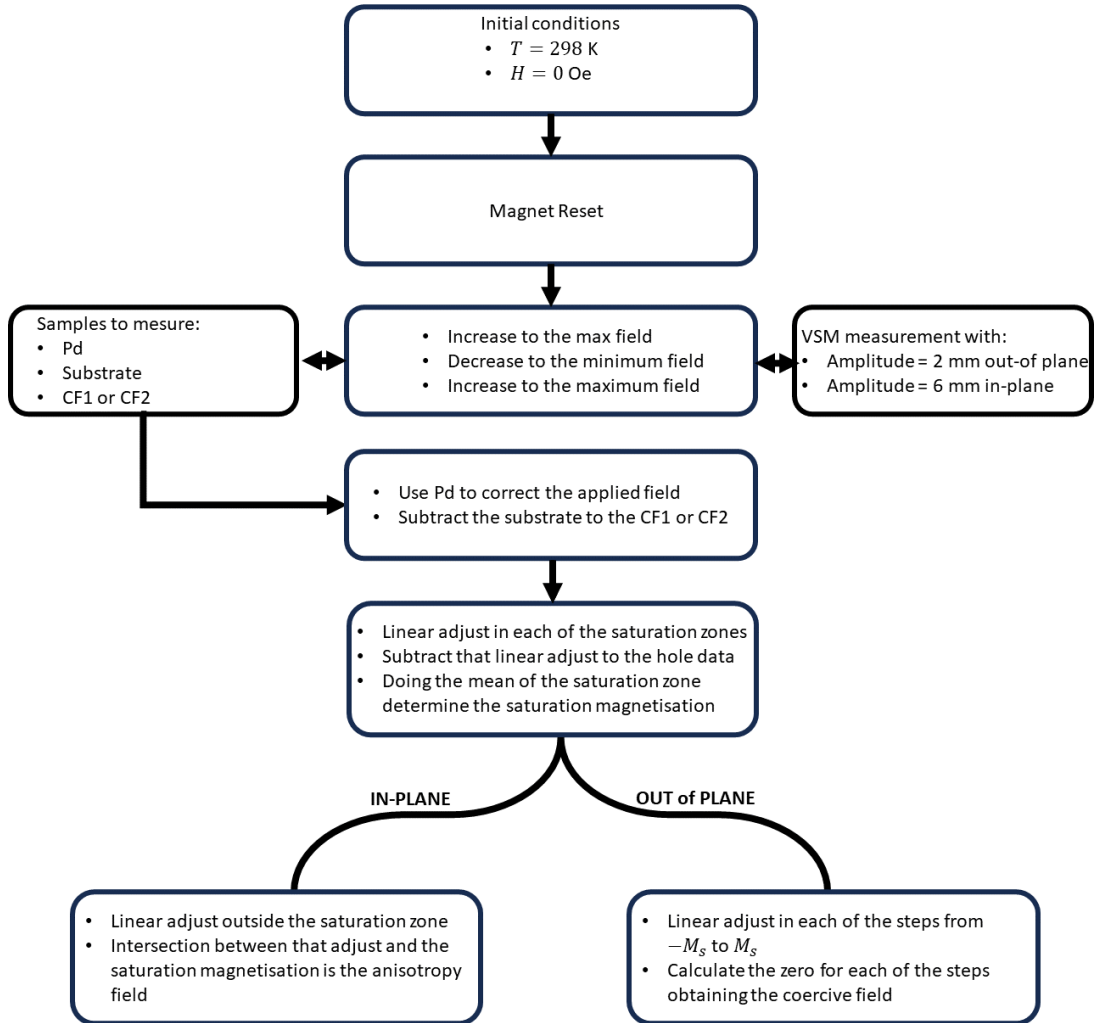


FIGURE 4.4: Measurement protocol

A measurement protocol was developed to measure the magnetisation of each sample with regards to the magnetic field applied. This protocol is very similar for either the in-plane measurement and the off-plane measurement, the main difference will be the maximum magnetic field applied and the amplitude of the sample movement, as seen in subsection 4.1.4.

The type of measurement will be an VSM measurement as seen in subsection 4.1.2, where the amplitude of the sample movement will be 2 mm for the out-plane and 6 mm for the in-plane measurement. Furthermore, while the magnetic field applied for the out-plane measurement will be of a maximum of 200 Oe, as we are dealing with samples

with low coercive field; in the in-plane measurement the maximum applied field will be 10000 Oe in order to better define the saturation zone and to facilitate the calculation of the anisotropy magnetic field.

The measurement starts by setting the temperature to 298 K, as seen in subsection 4.1.5. Following it, a magnet reset is done, as described in subsection 4.1.3. After that, the hysteresis cycle will be measured starting from zero.

After the measurements are done, the first step in the analysis is to make use of equation 4.3 and apply the correction to the applied field, as explained in section 4.1.5.

The sample is fixed using a Kapton tape, so the magnetisation of the sample holder and the Kapton tap with a piece of the background where the film is deposited was measured, this prove to be necessary, because the signal obtained from it is in the same order to the signal obtained when measuring the sample, see figure 4.5. Therefore, before every measurement, it is necessary to measure the background and exchange the background sample with the sample to be measured, but the Kapton tape remains the same (because it alone due to impurities shows relevant magnetisation). Then, when analysing the results, the background is removed and the magnetic field corrected. After all that, if any vestiges of para or diamagnetism are found in the saturation zone, its must be remove with a fitting linear function.

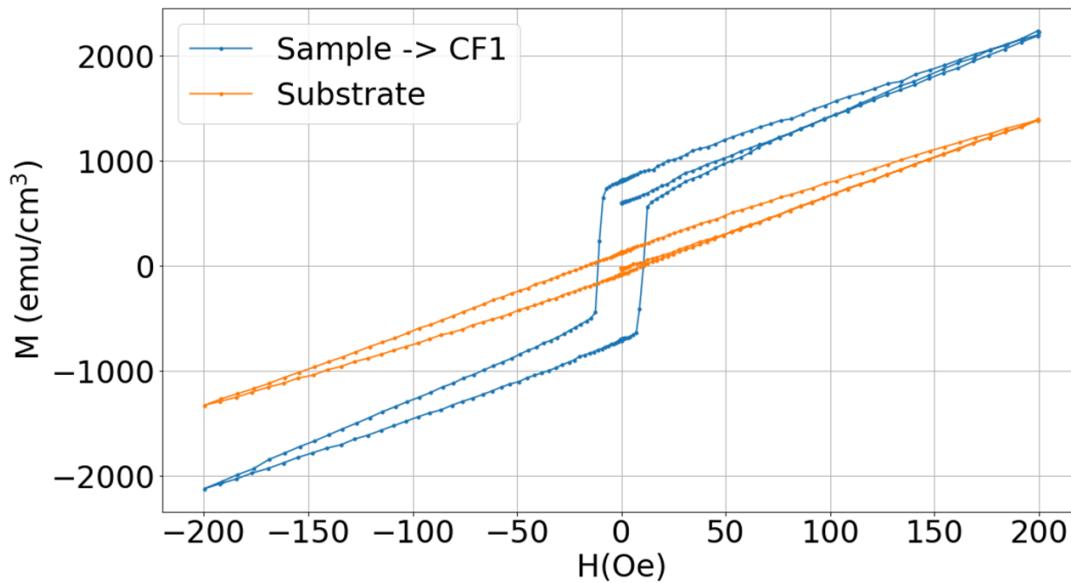


FIGURE 4.5: VSM of the substrate and the sample CF1. The amplitude used is 2 nm.

When this protocol is done the measurements are ready to be analysed and the relevant magnetic properties to be determined, as will be seen in section 4.4.

4.3 Sample Deposition

There will be two samples in study, CF (continuous film) 1 and 2. A schematic of both multilayer samples can be found in figure 4.6

The CF1 sample is constituted of Ta(10)/Co₆₀Fe₂₀B₂₀(1.2)/MgO (1.6)/Ta(20), all thickness in nm. The Ta and Co₆₀Fe₂₀B₂₀ are deposited in Si/SiO₂ substrate via sputtering, while MgO is deposited via electron beam evaporation and finally the second layer of Ta is also deposited via sputtering, during all this fabrication process there is no vacuum break.

The CF2 sample is built by Ta(5)/Ir(5)/Co₆₀Fe₂₀B₂₀(1.2)/MgO (1.6)/Ta(20) all thickness in nm with a similar fabrication method, with the metals being deposited with sputtering and the oxide being deposited by electron beam vapouration, also in a Si/SiO₂ substrate.

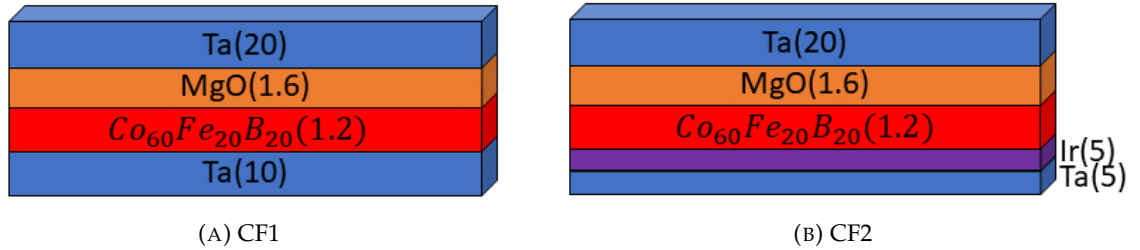


FIGURE 4.6: Schematic of the samples in studied

4.4 Analysis and discussion of results

In order to obtain the graphs in figure 4.7 and figure 4.8, some adjustments were necessary to the raw signal obtained.

The first step was to subtract the background signal to the sample signal and simultaneously using formula 4.3 obtained the real Magnetic field. Following that, as the measurement still presented vestiges of paramagnetism (measurements with the magnetic field being applied perpendicular) or diamagnetism (measurements with the magnetic field

being applied parallel to the sample plane), a linear fitting was made to calculate that vestiges and then, subtract them to the main signal.

After this initial treatment of the data, one can start to try and calculate the saturation magnetisation. To do so, it is necessary to do the mean of both saturation zones (positive and negative). However, contrary of what is expected the values obtained for the saturation magnetisation are different in modulus in the positive and negative part, so the mean between them was made, and in order to better present the graph and correct that error the signal was centred in its magnetisation axis, allowing for the mean magnetisation to be the saturation magnetisation in the positive and negative part of the graph.

Up to this point the treatment of the data is the same for both the in-plane and out-plane measurement. From this point onward the objectives are very distinct, for the measurements out-plane the objective is to calculate the coercive field of the sample, as for the in-plane measurement the objective is to determine the anisotropy field, H_k .

In the out-plane measurements, to calculate the coercive fields, first a linear fitting was made in both branches of the step from $-M_s$ to M_s , then from that linear fit, it was calculated the value that allowed for a zero magnetisation, that being the coercive field . Once, again, however, the data are not perfectly centred, so the coercive fields are different in modulus, to correct that error, the mean of the two coercive fields was made and the data centred around that. This is what leads to the graphs of figure 4.7a and figure 4.8a

For the in-plane measurements, in order to calculate the anisotropy field, a linear fitting was made in both the linear branches, the rising and the decreasing, and then the mean of them was taken. After that, the line originated from that fitting was drawn and the points in which it cross the magnetisation of saturation define the approximation for the anisotropy field. As seen in the graphs of figures 4.7b and 4.8b .

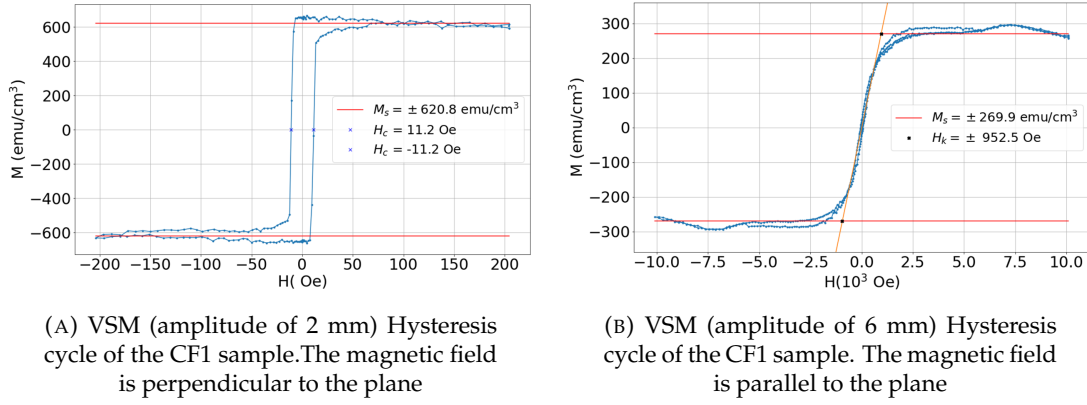


FIGURE 4.7: Hysteresis cycles of the sample CF1

For the CF1 sample it is possible to at first sight verify that the perpendicular magnetic anisotropy is present in this sample as the out of plane measurement gives the typical hysteresis cycle of the easy axis and the in-plane measurement gives the linear zone expected for a measurement in the hard axis.

For the out of plane measurement it is obtained a magnetisation saturation of $M_s = 620.8 \text{ emu/cm}^3$, that being about a difference of 9% of what is reported in [4] for the temperature of $T = 298 \text{ K}$. This difference can come from the different fabrication method of the multilayers, from the fraction of Co, Fe and Br being different of the ones in the paper, as it is not said what they are, and of course from some experimental errors. However, this shows that this method allows for a good determination of the saturation magnetisation as this difference can be considered small. Furthermore, it is obtained an coercive field of $H_c = 11.2 \text{ Oe}$, in the supplementary material of [4], figure 3.1, there is no M-H hysteresis for $T = 298 \text{ K}$, although there is one for $T = 300 \text{ K}$, what is a good approximation of what is supposed to be expected, consulting it, it is clear that the value should be way smaller than 25 Oe, as it is the last mark in the graph, that being said, it appears that the coercive field would be smaller than 10 Oe but not much, so it appears that the value obtained is pretty acceptable. That being said, for the out of plane characterisation, it appears that our protocol is accurate.

Considering now the in-plane measurement, it gives a magnetisation saturation, $M_s = 269.9 \text{ emu/cm}^3$, which is very different from the saturation magnetisation obtained in the out of plane measurement, it is actually normal to happen, because the SQUID MPMS®3 is prepared to measure samples with the magnetic field being applied perpendicular to

it, so when the sample is placed in a way that the magnetic field is in plane, although the The SQUID MPMS®3 gives the right behaviour of the curve, the values of magnetisation are not to be trusted. From this measurement, it is also possible to calculate the anisotropy field, being obtained a value of $H_k = 952.5$ Oe, consulting the supplementary material of [4], it gives a difference of 78%, once again, the anisotropy of a material is very dependent of the way this material is grown, and both samples were fabricated using different methods, that being said, it is not possible to safely said that the method of measurement used was the most correct. However, it allows to clearly see the hard axis measurement, as the behaviour of the curve is exactly what is expected, so it is more likely that not that the measurement was rightly done and that the difference comes from the facts enumerated in the previous sentence.

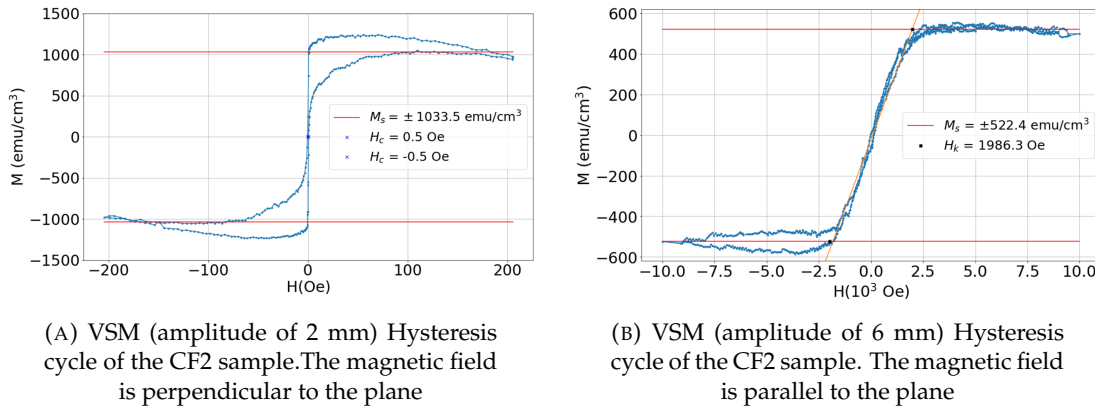


FIGURE 4.8: Hysteresis cycles of the sample CF2

From a critical standpoint, it is easy to realise the hysteresis cycles of the CF1 sample are more *well behaved* than those of the CF2. As the CF2 out of plane measurement does not really saturate as expected, and even in the in-plane, it is possible to see that the negative part of the saturation zone is also not really saturated. On the one hand, as the coercive field is very small, $H_c = 0.5$ Oe, the precision of the measurement in its neighbourhood is not very good, because it was not possible to obtain a lot of points for that small magnetic field, furthermore, even though the magnetic reset is done, there might be some remanent magnetic field in the coils, interfering with the measurement, all this can be interfering with the sensibility of the SQUID MPMS®3, not allowing it to give the proper saturated curve. To fix this, one possible way would be to try and use the ultra-low field option of the SQUID MPMS®3, but that is not the scope of this work, might be a future solution. On the other hand, as there is no saturation, it is possible that the

Iridium interferes, as it increases the Spin-orbit torque interaction, it might be changing the anisotropy of the multilayer, i.e. it is actually removing the perpendicular anisotropy, defining the easy axis slightly tilted from the perpendicular axis to the plane. To further support this theory, the out of plane measurement nearly does not have hysteresis, indicating it might no longer be the easy axis. It is assumed that if this is the case, the tilt must be small because the in-plane measurement still shows that the in-plane axis is way harder than the out of plane, as it shows the expected linear zone.

In the in-plane measurement it is obtained an anisotropy field of $H_k = 1986.3$ Oe, this shows that as predicted in chapter 3, section 3.6, the increase in the spin-orbit interaction must be followed by an increase in the anisotropy barrier. This shows that, although at first sight increasing the spin-orbit interaction, seem like it would be the better way to build sensors for higher magnetic fields, it actually is not that simple. As seen, when the spin-orbit interaction increases the anisotropy barrier increases, but at the same time, the coercive field seems to decrease a lot, or the perpendicular anisotropy is lost. It is expected that, if the anisotropy increases, the coercive field would also increase as the field that would be able to beat the energy barrier needs to be larger, but that is not what is seen. If we consider that it happens because the axis we are measuring is no longer the easy axis, then, another struggle surges as the sensing axis would not be perpendicular to the plane, not allowing to define a conventional referential. In summary, the usage of a layer of Iridium seems to not allow to achieve a sensor for higher magnetic fields.

Chapter 5

Conclusion

5.1 Results summary

In this Thesis, it was shown that using a Macro-spin model it is possible to predict the magnetisation of a thin film in the presence of a charge current density. It was shown, that in order to obtain higher magnetic fields in the linear range it is necessary to increase the magnetic anisotropy of the thin film, which results in the need to apply higher current densities in order to linearize the hysteresis cycle.

Furthermore, a protocol of measurement was developed and applied to two different multilayered samples, this protocol allows to obtain the magnetisation of saturation ($M_s = 620.8 \text{ emu/cm}^3$ for the CF1 and $M_s = 1033.5 \text{ emu/cm}^3$ for CF2), the coercive field ($H_c = 11.3 \text{ Oe}$ for the CF1 and $H_c = 0.5 \text{ Oe}$ for CF2) and the anisotropy field for the said samples ($H_K = 952.5 \text{ Oe}$ for the CF1 and $H_K = 1986.3 \text{ Oe}$ for CF2). By doing so, it was possible to conclude that the Iridium layer indeed increased the anisotropy of the multilayer, but as the coercive field is reduced (contrary to what the Macro-Spin model predicts) it is possible that this particular way of increasing the anisotropy, actually tilts the easy axis. In conclusion, the anisotropy needs to be increased but the perpendicular anisotropy can not be lost.

5.2 Outlook

The Macro-spin model developed in this Thesis is only applicable for placing the external magnetic field in the perpendicular axis to the sample. It would be interesting to in

future work develop the same model but considering the possibility of placing the magnetic field in the plane. It is important to notice that, as [4] states, the magnetic field needs to be perpendicular to the field due to current, and therefore if one wants to put it in the plane then a 3D Macro-Spin model needs to be developed with the simultaneous minimisation of two angles. This will be the next step in developing a complete Macro-Spin model for Spin-Orbit torque based sensors.

Once there is already an measurement protocol, new type of stacks can be easily explored. In conjunction with that, there was no electrical measurements of a sensor prototype, it would be interesting to do that and try and replicate the results of [4]. To do so, it is necessary the usage of the Physical Property Measurement System (PPMS) which will undoubtedly bring its own challenges. After that, the study can continue by trying to develop new sensors with different heavy metals, that seems to be the path to a high field 3D magnetic sensor consisting of a single element.

5.3 Final Thoughts

Although the main objectives of this Thesis are fulfilled, it serves only as the jumping start to the development of a high field 3D magnetic sensor consisting of a single element. A lot of work still needs to be done, as seen in section 5.2. In order to fulfil the desired objective new collaborations are in the horizon as the scientific development always benefits from bringing new heads to the discussion. In the words of the basketball legend the late Kobe Bryant "Job is not finished".

Appendix A

Normalisation of the energy density for the Macro-Spin model

As usual in the model, it is necessary to rewrite the energy density as an adimensional function of adimensional variables, here it will be called, $\zeta(h, j, \theta, \alpha)$, where $h = \frac{\mu_0 M_s}{2 \left(k_u - \frac{\mu_0 M_s^2}{2} \right)} H_a$ and $j = \frac{A J_c}{2 \left(k_u - \frac{\mu_0 M_s^2}{2} \right) t}$. Making use of trigonometry's the fundamental rule the equation that needs to be minimised will be equation [A.1](#).

$$\zeta(h, j, \theta) = \pm \frac{1}{2} \sin^2 (\alpha - \theta) - h \cos \theta - j \sin (\alpha - \theta) \pm \frac{\mu_0 M_s^2}{2 \left(K_u - \frac{\mu_0 M_s^2}{2} \right)} \quad (\text{A.1})$$

This normalisation must account for two cases, if $K_u > \frac{\mu_0 M_s^2}{2}$ then the sign in the first term is $+$, in contrast, if $K_u < \frac{\mu_0 M_s^2}{2}$, the sign in the first term needs to be $-$, this is due to the fact that the minimum is being calculated without taking into account the $K_u - \frac{\mu_0 M_s^2}{2}$ term, but it's sign influences if the easy axis is the perpendicular to the plane or the in-plane.

Appendix B

Python code for minimisation of the energy

```
import numpy as np
import matplotlib.pyplot as plt
from scipy.optimize import minimize
plt.rcParams.update({'font.size': 30})

π = np.pi
cos = np.cos
sin = np.sin

def ε (θ,α,h,j):
    return 1/2 * sin(θ-α)**2 - h * cos(θ) - j * cos(π/2 + (α-θ))

def Mag (j,α):
    X0 = np.array([π/4-2*π/10,3/4*π+2*π/10])
    X = X0 * θ
    M = H_hist * θ
    for i in range (len(H)):
        for ℓ in range(len(X0)):
            X[ℓ] = minimize (ε,X0[ℓ], args=(α,H[i],j)).x
        M[i] = np.cos(X[0])
        M[-i-1] = np.cos(X[1])
    return M
```

FIGURE B.1: Python code to calculate the magnetisation normalised

Bibliography

- [1] S. Marshall, "Vehicle detection using a magnetic field sensor," *IEEE Transactions on Vehicular Technology*, vol. 27, no. 2, p. 65–68, 1978. [Cited on page 1.]
- [2] J. Lenz and S. Edelstein, "Magnetic sensors and their applications," *IEEE Sensors Journal*, vol. 6, no. 3, p. 631–649, 2006.
- [3] K. Tsukada, M. Hayashi, Y. Nakamura, K. Sakai, and T. Kiwa, "Small eddy current testing sensor probe using a tunneling magnetoresistance sensor to detect cracks in steel structures," *IEEE Transactions on Magnetics*, vol. 54, no. 11, p. 1–5, 2018.
- [4] R. Li, S. Zhang, S. Luo, Z. Guo, Y. Xu, M. Song, Q. Zou, L. Xi, X. Yang, J. Hong, and L. You, "A spin–orbit torque device for sensing three-dimensional magnetic fields," *Nature Electronics*, vol. 4, pp. 1–6, 03 2021. [Cited on pages xiii, 1, 2, 4, 5, 17, 18, 19, 21, 22, 23, 24, 25, 37, 38, and 42.]
- [5] Z. Guo, R. Li, S. Zhang, Y. Tian, J. Hong, and L. You, "A three-dimensional magnetic field sensor based on a single spin–orbit-torque device via domain nucleation," *Applied Physics Letters*, vol. 120, no. 23, p. 232404, 06 2022. [Online]. Available: <https://doi.org/10.1063/5.0093949> [Cited on pages xiii, 1, 2, 4, and 5.]
- [6] M. E. Huber, N. C. Koshnick, H. Bluhm, L. J. Archuleta, T. Azua, P. G. Björnsson, B. W. Gardner, S. T. Halloran, E. A. Lucero, and K. A. Moler, "Gradiometric micro-squid susceptometer for scanning measurements of mesoscopic samples," *Review of Scientific Instruments*, vol. 79, no. 5, 2008. [Cited on page 1.]
- [7] P. Ripka, "New directions in fluxgate sensors," *Journal of Magnetism and Magnetic Materials*, vol. 215–216, p. 735–739, 2000. [Cited on page 1.]

- [8] Y. Zheng, L. Huang, Z. Zhang, J. Jiang, K. Wang, L.-M. Peng, and G. Yu, "Sensitivity enhancement of graphene hall sensors modified by single-molecule magnets at room temperature," *RSC Advances*, vol. 7, no. 4, p. 1776–1781, 2017. [Cited on page 1.]
- [9] D. Labanowski, V. P. Bhallamudi, Q. Guo, C. M. Purser, B. A. McCullian, P. C. Hammel, and S. Salahuddin, "Voltage-driven, local, and efficient excitation of nitrogen-vacancy centers in diamond," *Science Advances*, vol. 4, no. 9, 2018. [Cited on page 1.]
- [10] V. Zieren, "A new silicon micro-transducer for the measurement of the magnitude and direction of a magnetic-field vector," *1980 International Electron Devices Meeting*, 1980. [Cited on page 1.]
- [11] J. E. Hirsch, "Spin hall effect," *Physical Review Letters*, vol. 83, no. 9, p. 1834–1837, 1999. [Cited on page 1.]
- [12] D. J. Adelerhof and W. Geven, "New position detectors based on amr sensors," *Sensors and Actuators A: Physical*, vol. 85, no. 1–3, p. 48–53, 2000. [Cited on page 1.]
- [13] N. Pérez, M. Melzer, D. Makarov, O. Ueberschär, R. Ecke, S. E. Schulz, and O. G. Schmidt, "High-performance giant magnetoresistive sensorics on flexible si membranes," *Applied Physics Letters*, vol. 106, no. 15, 2015. [Cited on page 1.]
- [14] N. A. Pertsev, "Magnetic tunnel junction on a magnetostrictive substrate: An ultra-sensitive magnetic-field sensor," *Applied Physics Letters*, vol. 109, no. 13, 2016. [Cited on page 1.]
- [15] S. Kordic, *Sensitivity of the silicon high-resolution 3-dimensional magnetic-field vector sensor*. Proc, 1986. [Cited on page 2.]
- [16] J. Chen, M. Wurz, A. Belski, and L. Rissing, "Designs and characterizations of soft magnetic flux guides in a 3-d magnetic field sensor," *IEEE Transactions on Magnetics - IEEE TRANS MAGN*, vol. 48, pp. 1481–1484, 04 2012. [Cited on page 2.]
- [17] W. Lowrie, *Fundamentals of geophysics*. Cambridge University Press, 2014. [Cited on page 3.]
- [18] C. F. Gauss, *The Intensity of the Earth's Magnetic Force Reduced to Absolute Measurement*. Retrieved 21, Oct. 2009. [Cited on page 3.]

- [19] J.-T. Jeng, C.-Y. Chiang, C.-H. Chang, and C.-C. Lu, "Vector magnetometer with dual-bridge gmr sensors," *IEEE Transactions on Magnetism*, vol. 50, no. 1, p. 1–4, Jan 2014. [Cited on pages [xiii](#), [3](#), and [4](#).]
- [20] C.-C. Lu and J. Huang, "A 3-axis miniature magnetic sensor based on a planar fluxgate magnetometer with an orthogonal fluxguide," *Sensors*, vol. 15, no. 6, p. 14727–14744, Jun 2015. [Cited on pages [xiii](#) and [4](#).]
- [21] C. Wouters, V. Vranković, C. Rössler, S. Sidorov, K. Ensslin, W. Wegscheider, and C. Hierold, "Design and fabrication of an innovative three-axis hall sensor," *Sensors and Actuators A: Physical*, vol. 237, p. 62–71, Dec 2015. [Cited on pages [xiii](#), [4](#), and [5](#).]
- [22] J. Shiogai, K. Fujiwara, T. Nojima, and A. Tsukazaki, "Three-dimensional sensing of the magnetic-field vector by a compact planar-type hall device," *Communications Materials*, vol. 2, no. 1, 2021. [Cited on pages [xiii](#), [4](#), and [5](#).]
- [23] E. C. Stoner and E. P. Wohlfarth, "A mechanism of magnetic hysteresis in heterogeneous alloys," *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, vol. 240, no. 826, pp. 599–642, 1948. [Online]. Available: <https://royalsocietypublishing.org/doi/abs/10.1098/rsta.1948.0007> [Cited on page [7](#).]
- [24] J. M. D. Coey, *Magnetism and magnetic materials*. Cambridge University Press, 2010. [Cited on pages [8](#), [9](#), and [11](#).]
- [25] J. D. Jackson, *Classical electrodynamics*, 3rd ed. New York, NY: Wiley, 1999. [Online]. Available: <http://cdsweb.cern.ch/record/490457> [Cited on pages [10](#) and [11](#).]
- [26] X. Han, X. Wang, C. Wan, G. Yu, and X. Lv, "Spin-orbit torques: Materials, physics, and devices," *Applied Physics Letters*, vol. 118, no. 12, 2021. [Cited on page [13](#).]
- [27] J. Smit, "The spontaneous hall effect in ferromagnetics ii," *Physica*, vol. 24, no. 1–5, p. 39–51, 1958. [Cited on page [13](#).]
- [28] L. Berger and G. Bergmann, "The hall effect of ferromagnets," *The Hall Effect and Its Applications*, p. 55–76, 1980. [Cited on page [13](#).]
- [29] R. Karplus and J. M. Luttinger, "Hall effect in ferromagnetics," *Physical Review*, vol. 95, no. 5, p. 1154–1160, 1954. [Cited on page [13](#).]

- [30] S. A. Nasser, B. Sarma, G. Durin, and C. Serpico, "Analytical modelling of magnetic dw motion," *Physics Procedia*, vol. 75, p. 974–985, 2015. [Cited on pages 14, 15, and 16.]
- [31] S. Koraltan, C. Schmitt, F. Bruckner, C. Abert, K. Prügl, M. Kirsch, R. Gupta, S. Zeilinger, J. M. Salazar-Mejía, M. Agrawal, J. Güttinger, A. Satz, G. Jakob, M. Kläui, and D. Suess, "Single device offset-free magnetic field sensing principle with tunable sensitivity and linear range based on spin-orbit-torques," 2023. [Cited on page 15.]
- [32] "Mpms3 platform measurement options," *Quantum Design : 1500-103 Rev. B0*, 2020. [Cited on pages 27 and 30.]
- [33] "Coupling magnetic signals to a squid amplifier," *Quantum Design : SQUID Application Note 1052-202A*, 2001. [Cited on page 27.]
- [34] "Magnetic property measurement system® mpms 3 user's manual," *Quantum Design : Part Number 1500-100, F1*, Jun 2016. [Cited on pages xiii and 28.]
- [35] R. C. Jaklevic, J. Lambe, A. H. Silver, and J. E. Mercereau, "Quantum interference effects in josephson tunneling," *Phys. Rev. Lett.*, vol. 12, pp. 159–160, Feb 1964. [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRevLett.12.159> [Cited on page 28.]
- [36] B. D. Josephson, "The discovery of tunnelling supercurrents," *Reviews of Modern Physics*, vol. 46, pp. 251–254, 1974. [Online]. Available: <https://api.semanticscholar.org/CorpusID:54748764> [Cited on page 28.]
- [37] B. Josephson, "Possible new effects in superconductive tunnelling," *Physics Letters*, vol. 1, no. 7, pp. 251–253, 1962. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/0031916362913690> [Cited on page 28.]
- [38] T. d. L. E. du, D. Gignoux, and M. Schlenker, *Magnetism: Materials and applications*. Springer, 2003. [Cited on pages 28 and 29.]
- [39] P. Kinsler, "Faraday's law and magnetic induction: Cause and effect, experiment and theory," *Physics*, vol. 2, no. 2, pp. 148–161, may 2020. [Cited on page 30.]
- [40] "Svsm measurement best practices amplitude: "going big"," *Quantum Design : Application Note 1500-013, Rev. A0*, 2011. [Cited on page 31.]
- [41] "Correcting for the absolute field error using the pd standard," *Quantum Design : 1500-021 Rev. B0*, 2020. [Cited on page 32.]