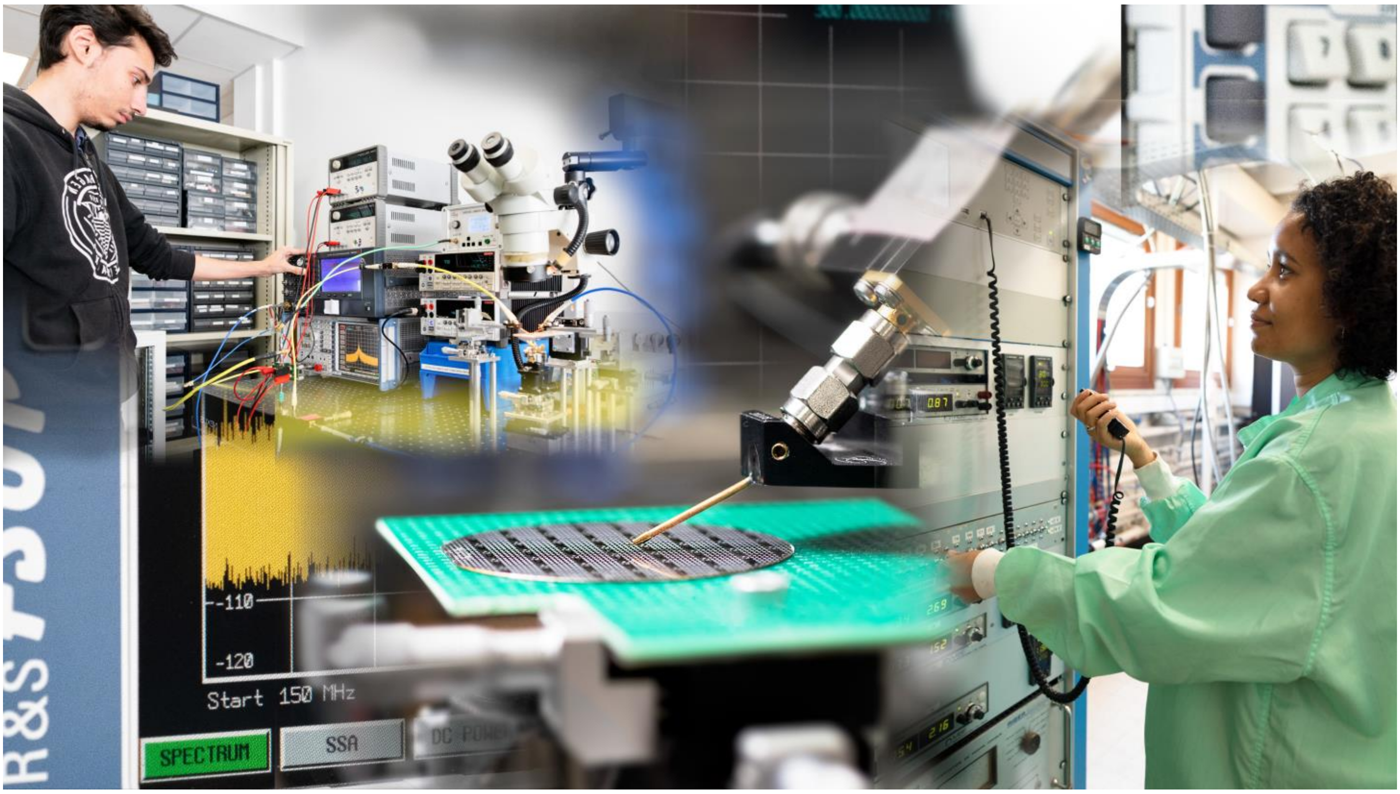
SPINTRONIQUE et TECHNOLOGIE des COMPOSANTS

Master Thesis Projects

2023



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SPINTEC IN BRIEF

SPINTEC is one of the leading spintronics research laboratories in the world, positioned at the crossroads of science and technology. SPINTEC is hosted on the MINATEC campus in Grenoble. The international city of Grenoble is located in the French Alps and surrounded by an exceptional natural environment. It is also an extremely rich ecosystem formed by public research organisations (CEA, CNRS, ESRF, ILL) and the University of Grenoble Alpes (UGA), as well as numerous high-tech companies.

SPINTEC was created 20 years ago and has grown rapidly to now exceed 100 people, including 47 permanent staff from CEA, CNRS and the University of Grenoble-Alpes, and working cooperatively in an open structure organized around focused research topics.

SPINTEC's mission is to act as a bridge between academic research and technological applications in the field of spintronics, which is both a very rich source of new condensed-matter-magnetism physics, and recognized today as one of the major innovation routes for future microelectronics industries, sensing technology and bio-applications. As such, we are at the cross-roads of nanosciences and technology, conducting our activities in collaboration with academic and industrial partners from all around the world. As such, the laboratory's markers are not only high-rank publications and communications in international conferences, but also the creation of a consistent patent portfolio and the implementation of relevant functional demonstrators and device nanofabrication. The laboratory has launched four start-ups in the last 15 years, with a few others in the pipes. This synergy has placed SPINTEC at the forefront of spintronics research, with a crucial contribution to the discovery of new key fundamental effects. These underpin the emergence in the industry of spintronic memories called MRAM, on which the laboratory holds key patents.

The research activity of SPINTEC covers the whole spectrum from theory to demonstrators, including the development of innovative functional materials, the experimental validation of novel concepts in physics, up to the realization of test structures. Academic research concerns spinorbitronics, spintronics in 2D materials, microwave components, antiferromagnetic spintronics, and exotic spin textures. The application-oriented topics are: magnetic random access memories, artificial intelligence, design of spin-based integrated circuits, sensors, biotechnology.

SPINTEC FOR YOUR MASTER OR PHD PROJECT

With the objective to train tomorrow's researchers in an active and growing research field, SPINTEC proposes every year topics for (paid) Master projects. The majority of the Master projects lead over to a PhD thesis project with financial support coming from a variety of funding sources, either from research institutions (bourses "*ministère*", CFR CEA, local foundations), academic contracts (ANR, EU) or industrial partners (bourses CIFRE).

At SPINTEC, you will find a dynamic and multicultural environment, which provides all facilities to advance your research project, and get yourself known in the academic world via participation at international conferences, and develop a wealth of personal skills through collaborative work. One year after defending their PhD, close to 95% of our students have a position, with equal shares in the academics and in the industry, half of them with an indefinite-term contract.

Come and join us to be part of those who like to revolutionize condensed-matter research and unlock new microelectronics applications!

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LIST OF MASTER THESIS PROJECTS

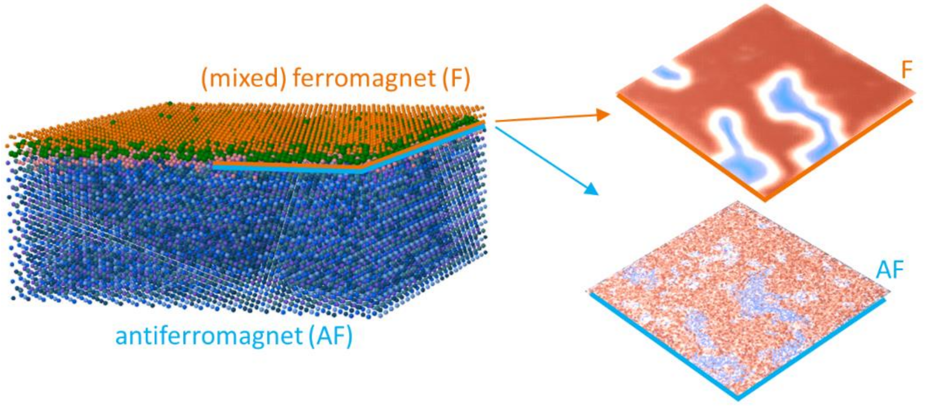
1. Atomistic simulations of antiferromagnetic skyrmions
2. Harnessing the Thz dynamics of antiferromagnets
3. Design for ultralow-power memory/logic devices
4. Ferroelectric control of the spin-orbit coupling
5. Magnetic interactions between two-dimensional magnets
6. Proximity effects between 2D materials and ferroelectrics
7. Manipulation of magnetic skyrmions for neuromorphic computing
8. Magneto-elastic properties of suspended garnet disks
9. Spin transfer torque based magnetic field sensors
10. MRAM for security applications: robustness and vulnerability analysis
11. Spintronics-based non-volatile FPGA development for space applications
12. In-Memory Computing based on Ferroelectric devices
13. Curvilinear magnetism and spintronics in core-shell nanotubes
14. MRAM: new routes toward sub-10nm scalability and improved thermal retention
15. Stochastic computing based on spintronic devices
16. Multi-platform Image processing for Quantitative Magnetic Imaging

Atomistic simulations of antiferromagnetic skyrmions

Context

Skyrmions (Sk) are local topological magnetic textures. They are attracting a lot of attention due to their rich spin physics and high potential for storage and logic computing. **Antiferromagnetic (AF) Sk** encompass various advantageous properties over their ferromagnetic (F) counterparts, including a vanishing net magnetization which provides robustness against perturbations by external magnetic fields and a vanishing net topological charge, which prohibits the Sk from acquiring an unwanted transversal velocity **[1]**. However, since they lack net magnetization, the nucleation of AF Sk is challenging. A way we used to manipulate the order parameter of an AF is to take advantage of the exchange bias interaction between the AF and an adjacent F in order to imprint F configurations into the AF **[2]**. **Our objective for the present project is to investigate theoretically which parameters actually drive the Sk imprint, and how AF Sk influence the field- and current-driven magnetic reversal of the interacting adjacent F and vice versa.** In order to model the dynamics of AFs it is necessary to use atomistic models **[3]** which accurately represent the atomic scale magnetic structure. It makes it possible to model the formation and evolution of exchange bias and the resulting dynamics of coupled spin textures, as well as their fundamental thermodynamic properties **[4]**. This project builds on preliminary results obtained between **SPINTEC and YORK** in the UK **[5]**.

__[1]__ V. Baltz et al, Rev. Mod. Phys. 90, 015005 (2018) - __[2]__ K. G. Rana, R. L. Seeger et al, Appl. Phys. Lett. 119, 192407 (2021) - __[3]__ R. F. L. Evans et al, J. Phys.: Condens. Matter 26, 103202 (2014) - __[4]__ S. Jenkins et al, Phys. Rev. B 100, 220405 (2019) - __[5]__ M. Leiviskä, S. Jenkins et al, in preparation (2022).



(Left) Atomic structure used for the simulations. (Right) Magnetic textures in the F and AF, at the interface - 100 x 100 nm^2.

Work program & Skills acquired during internship

The work will include :

1/ modelling of Sk in single thin films of Fs and AFs and evaluation of the influence of several key parameters like grains sizes, finite size, anisotropy, interfacial DMI, and exchange stiffness on the size, dynamics and thermal stability of the Sk following an exchange bias imprint procedure;

2/ modelling of the influence of AF Sk (single and arrays) **on the dynamic properties of the F in F/AF bilayers, and vice-versa.**

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Requested background: Master 2, solid state physics, numerical simulation, good level of English
Duration: 6 months
Start period: Feb/ March 2023
Possibility of PhD thesis : YES
Proposal number : 1

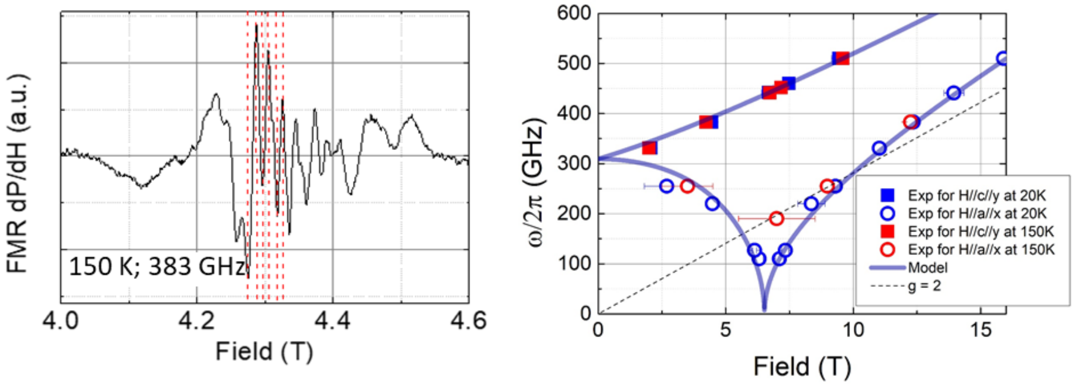
Harnessing the Thz dynamics of antiferromagnets

Context

Several applications - for health, telecommunications, and security - would use the 0.1 to 15 THz range. Spintronic devices based on the dynamics of the antiferromagnetic (AF) order parameter are adapted to handle this range. Indeed, an AF consists of sub-lattices of opposite moments [1]. The sub-THz to THz dynamics is directly related to the internal exchange interactions between the sub-lattices, which is several orders of magnitude larger than the internal fields involved in the GHz dynamics of ferromagnets. **We aim to understand: 1/ how the sub-THz to THz dynamics of AFs can promote spin current emission (spin pumping) and subsequent electric detection** and **2/ how efficiently**, with respect to the damping coefficient (α), exchange field (H_E), the anisotropy fields along the different crystallographic axis ($H_{a,b,c}$), the Dzyaloshinskii-Moriya interaction (H_{DMI}) and the transfer of angular momentum at interfaces.

This project builds on results obtained in a collaboration including **LNCMI Grenoble, CNRS/Thales Paris and SPINTEC [2,3]**. We have taken advantage of the rare capabilities of a quasi-optical bench at LNCMI **[4]**. It combines high-magnetic fields (0 - 16T), high-frequencies (110 GHz and multiples up to 660 GHz) and a wide temperature range (5 - 300K), thus overcoming the obstacles to study the dynamics of AFs. A mapping of the sub-THz properties (α, H_E, $H_{a,b,c}$, H_{DMI}) of selected model AFs (Fe_2O_3, $YFeO_3$) was obtained. We adapted the system to spin pumping experiments by designing a transport module. **Our objective for the present project is to investigate ways to improve the setup in terms of the input power reaching the sample with minimal losses in order to promote the larger spin pumping effect needed to study most AFs.**

*[1] V. Baltz et al, Rev. Mod. Phys. 90, 015005 (2018) - [2] R. Lebrun et al, Nat. Comm. 11, 6332 (2020)- [3] S. Das et al, Nat. Comm. in press (2022) - [4] Y. Li, A.-L. Barra et al, Phys. Rev. B **92**, 140413 (2015).*



(Left) Typical absorption spectrum obtained for a $YFeO_3$ AF. Data analysis allowed estimating α (see text). (Right) Frequency-field dispersion curve obtained from series of absorption spectra. Data fitting returned H_E, $H_{a,b,c}$, and H_{DMI}.

Work program & Skills acquired during internship

The work will include : **1/ electromagnetic simulations and sample fabrication** for realizing planar antennas and contacts ; **2/ sub-THz AF resonance measurements** using the current design and comparison with measurements using a newly designed sample and/or sample holder, based on the simulations.

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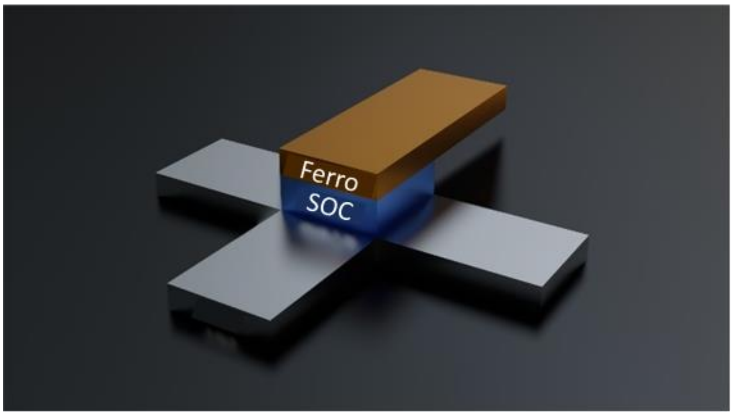
Requested background: Master 2, solid state physics, numerical simulation, good level of English
Duration: 6 months
Start period: Feb/ March 2023
Possibility of PhD thesis : YES
Proposal number : 2

Design for ultralow-power memory/logic devices

Context

Spintronics devices involve ferromagnetic elements with high switching energies. Contrastingly, the polarization of ferroelectrics can be easily switched by an electric field, at energies typically 1000 times lower. As recently demonstrated by Intel, this makes ferroelectrics good candidates for ultralow-power post-CMOS logic[1].

The question of the energy consumption of the information and communication Technologies is becoming an important environmental and geopolitic issue. We recently demonstrated in a Nature article that combined with high spin-orbit coupling elements, ferroelectrics have also a natural potential to generate an electrically-switchable and highly efficient spin-charge interconversion[2]. This effect can be used to develop a new generation of low-power ferroelectric devices. We are currently building a start-up on this topic, through a valorization project based on these discoveries.



Exemple of ultralow-power device developed in our team, with a ferroelectric material with Spin-Orbit Coupling

Work program & Skills acquired during internship

The intern will benefit from the expertise of the Design team of the Spintec Laboratory in developing AI neuromorphic solutions based on innovative spintronics devices. He will also work in close collaboration with the experimental team developing the devices, and in particular with PhDs aiming at using this technology as memories an Artificial Intelligence devices. He will benefit from the existence of a large collective momentum in our teams towards the development and integration of these devices, with ongoing ANR and EU projects, and more importantly with a valorization project aiming at creating a start-up based on this technology.

PhD Funding already secured. Requested qualities: Imagination, inventiveness, interest towards innovative microelectronics applications, and towards intellectual property creation. Possible will to pursue a career in a start-up environment.

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Contacts jean-philippe.attane@cea.fr	Possibility of PhD thesis : YES
laurent.vila@cea.fr	Proposal number : **3**

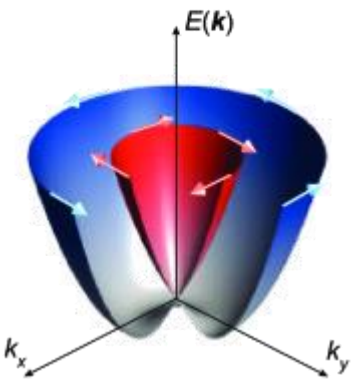
[1] Manipatruni et al., Nature 565.7737 (2019): 35.
[2] Noël, Attané, Vila et al., Nature 580.7804 (2020): 483.

Ferroelectric control of the spin-orbit coupling

Context

Whereas conventional spintronics uses the exchange interaction in a ferromagnetic material to manipulate spin currents, spin-orbit coupling can now be used to generate or detect spin currents, possibly in absence of any ferromagnetic element. We have shown that new spin-orbit coupling quantum materials are exciting candidates for the spin-charge conversion, with in particular the possibility of a control of the spin-orbit properties by ferroelectricity[3].

As recently demonstrated by Intel[4], and by our group[5] in a Nature article, this could lead to the development of ultralow-power post-CMOS logic devices. This is in particular important as the question of the energy consumption of the Information and Communication Technologies is becoming an important environmental and geopolitic issue. We are currently building a start-up through a valorization project based on these discoveries.



Band structure of a Rashba system, with two Fermi contours having opposite spin helicities

Work program & Skills acquired during internship

The M2 internship and following PhD project aims at exploring the possibilities offered by these features. The student will realize the device nanofabrication in order to study the spin-charge interconversion electrically. He will explore the potential offered by the electric-field control of the spin-orbit conversion to create new devices. The student will develop skills in nanofabrication, and in magnetotransport (at room and low temperature) in thin films and in nanodevices. Transport simulations will be performed if necessary, in order to analyse the data.

He/she will benefit from the existence of a large collective momentum in our teams towards the development and integration of these devices, with ongoing ANR and EU projects, and more importantly with a valorization project aiming at creating a start-up based on this technology.

Requested qualities: Taste for experimental condensed-matter physics and collaborative work. Imagination, inventiveness, interest towards innovative microelectronics applications, and towards intellectual property creation. Possible will to pursue a career in a start-up environment.

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laurent.vila@cea.fr	Proposal number : 4

[3] Attané, Vila et al., Nature Communications 4 (2013): 2944. ; Nature Materials 15.12 (2016): 1261. ; Nature Materials, 18(11), (2018) 1187 ; Nature Reviews Materials (2022), 7(4), 258 ; Nature Electronics (2021), 4(10), 740.

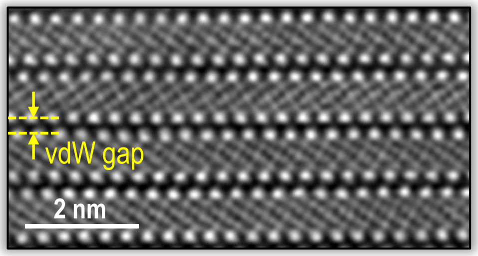
[4] Manipatruni et al., Nature 565.7737 (2019): 35.

[5] Noël, Attané, Vila et al., Nature 580.7804 (2020): 483

Magnetic interactions between two-dimensional magnets

Context

Downscaling of microelectronic and spintronic devices is currently facing major limitations related to the quality of interfaces and the fine control of the electronic structure at the atomic scale. Atomically thin two-dimensional (2D) materials are extremely promising to solve these issues and to develop ultracompact and energy-efficient devices[6]. Moreover, the freedom offered by the stacking of van der Waals materials makes them attractive to study a wealth of physical phenomena at interfaces. The library of 2D materials now extends far beyond pioneering graphene. Recently, 2D magnets emerged as a platform to study low-dimensional magnetism and to incorporate magnetic functionalities in van der Waals multilayers. Our team is pioneering this nascent field of 2D spintronics based on 2D magnets[7]. We are among the few groups worldwide able to grow these materials and to stack them in multilayers by molecular beam epitaxy[8].



Our objective is to develop low-power spin-charge conversion devices and magnetic tunnel junctions that incorporate 2D magnets. A first milestone, aim of the current project, is to control and understand the magnetic exchange interaction between these 2D magnets.

High-resolution transmission electron microscopy image showing the perfect atomic arrangement of Fe_5GeTe_2*, a room-temperature 2D magnet fabricated in our team.*

Work program & Skills acquired during internship

The intern will explore various possible magnetic interactions between 2D magnets in specially designed multilayers. These interactions can be direct, through the van der Waals gap, or indirect through quantum tunneling, RKKY coupling or interlayer chiral exchange.

The student will grow magnetic van der Waals multilayers by molecular beam epitaxy and investigate the magnetic coupling with relevant techniques available in the team (SQUID, MOKE or Hall measurements). She/he will develop skills in ultra-high vacuum techniques, growth of thin films, cryogenics and magnetic measurements. The student will benefit from a collaborative environment within the team, with support from several ongoing French and European projects.

The internship will be followed by a PhD thesis with a stronger focus on microfabrication of spin devices and magnetotransport experiments.

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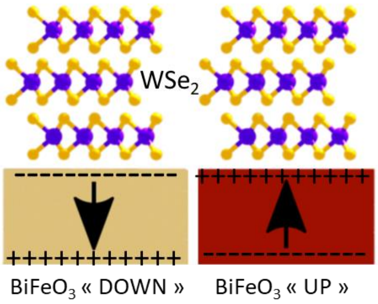
Requested background: Master 2, good knowledge of solid-state physics and magnetism, strong taste for experimental work
Duration: 6 months
Start period: Feb/ March 2023
Possibility of PhD thesis : YES
Proposal number : 5

[6] Lin et al., Nature Elec. 2, 274 (2019)
[7] Gilbertini et al., Nature Nanotechnol. 14, 408 (2019) ; Savero-Torres, Bonell et al., MRS Bull. 45, 357 (2020) ; Galceran, Bonell, Jamet et al., APL Mater. 9, 100901 (2021)
[8] Ribeiro, Bonell, Jamet et al., npj 2D Mater. Appl. 6, 1 (2022) ; Vélez-Fort, Bonell, Jamet et al., ACS Appl. Elec. Mater. 4, 259 (2022)

Proximity effects between 2D materials and ferroelectrics

Context

For their atomic thinness and exceptional electronic properties, 2D materials like graphene and transition metal dichalcogenides (TMD) are promising materials to build new compact and energy efficient electronic and spintronic devices [*Science* ***353****, 6298 (2022); Nature* ***606****, 663 (2022)*]. A key property of those materials is their two dimensional character which makes them highly sensitive to their environment. Thus, it offers the key opportunity to tune their electronic properties by proximity effects when the 2D material is put in contact with another functional material. In particular, the non-volatile electric field generated by a ferroelectric film will strongly affect the electronic properties of a 2D material in proximity. As shown in the figure, we could recently demonstrate a giant effect on the electronic structure of WSe_2, a 2D semiconductor, in contact with $BiFeO_3$, a well-known ferroelectric material (*under review in Nano Letters*). In spintronics, the application of an electric field to modify the spin-orbit coupling or ferromagnetic properties would represent a real breakthrough for the development of ultralow power consumption magnetic memories. Though it is almost impossible with bulk materials used today in spintronic devices, it is feasible with 2D materials in proximity with a ferroelectric material. **During this internship**, our goal is to study the proximity effect between a 2D material and a ferroelectric material. More specifically, we will investigate the modification of spin-orbit coupling in $PtSe_2$ and the modification of ferromagnetic properties in $CrTe_2$ by proximity effects with a ferroelectric material ($BiFeO_3$ or $LiNbO_3$). For this purpose, the 2D spintronics team of Spintec has developed a unique platform to grow 2D materials on large areas by molecular beam epitaxy as well as a method to transfer them on ferroelectric materials. This double competency is unique worldwide.



3 layers of WSe_2 in contact with $BiFeO_3$.

Work program & Skills acquired during internship

The student will grow 2D materials ($PtSe_2$ and $CrTe_2$) by molecular beam epitaxy on mica substrates and transfer them onto ferroelectric films with well-defined electrical polarization. Then, she/he will investigate the modification of spin-orbit coupling in $PtSe_2$ by magnetotransport and spin pumping measurements as well as the ferromagnetic properties of $CrTe_2$ by MOKE, SQUID and Hall measurements. All these equipments are available in the lab. She/he will develop skills in ultra-high vacuum techniques, growth of thin films, cryogenics, electrical and magnetic measurements. The student will benefit from local, national and European collaborative environments.

The internship will be followed by a PhD thesis with an extension to the fabrication of 2D ferroelectric materials to build "all 2D" heterostructures and to insulating 2D ferromagnetic materials like $Cr_2Ge_2Te_6$ to enhance the proximity effects. The internship and thesis will be in very close collaboration with the Unité Mixte CNRS-Thales in Palaiseau (France).

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Requested background: Master 2, good knowledge of solid-state physics and magnetism, taste for experimental work and exploration of new materials
Duration: 6 months
Start period: Feb/ March 2023
Possibility of PhD thesis : YES
Proposal number : **6**

Manipulation of magnetic skyrmions for neuromorphic computing

Context

Magnetic skyrmions are texture composed of spins that whirl closely to form a topologically stable, chiral structure (see Fig.1 (a-b)). Their size can be as small as a few nanometers. Skyrmions can also be manipulated by electric currents, which has led to novel concepts of non-volatile magnetic memories and logical devices where skyrmions in nanotracks encode the information. The nanometer size of skyrmions, combined with the low current density required to induce their motion, opens a path for devices that combine high storage density, high speed execution and low energy consumption. A first step toward application was made in Spintec with the first direct observation of magnetic skyrmions at room temperature in ultra-thin Pt/Co(1nm)/MgO multilayer nanostructures [1] and the demonstration of their fast (>100 m/s) manipulation using electrical currents [2].

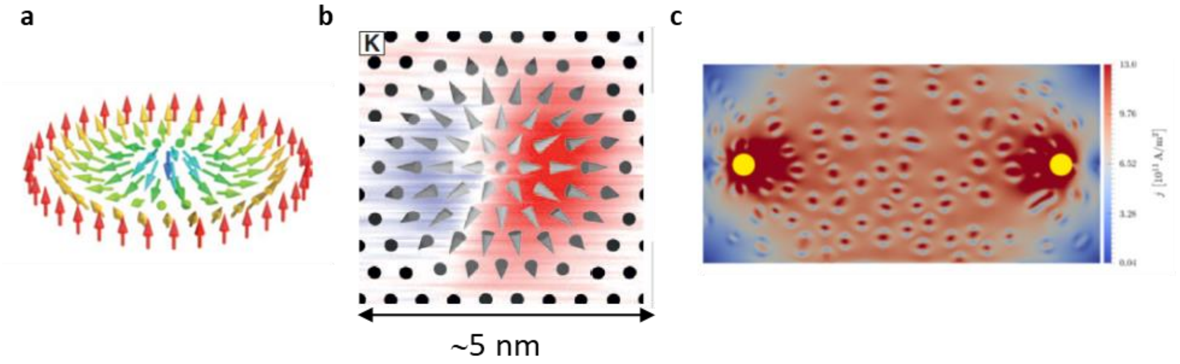

Figure 1a Schematic representation of the spin texture of a magnetic skyrmion b. Spin polarized scanning tunneling microscopy (SP-STM) of a magnetic skyrmion in FePd(2ML) on Ir(111) at 4.2 K [3]. c Proposal of skyrmion reservoir computing device: the current injected in the magnetic film at the position of the yellow dots, leads to oscillation of the skyrmion texture. The resulting changes in the device resistance can be used to recognize temporal pattern for speech recognition. [4]

Recently, unconventional computing schemes, such as neuromorphic or reservoir computing, have been proposed where skyrmions are used to solve standard complex machine learning problems (classification, prediction) with very low energy consumption [4]. The nanometer size of magnetic skyrmions and their non-volatility would allow gains of several orders of magnitude in computing speed and delay compared to current neuromorphic computing devices.

In this internship, we propose to demonstrate the potential of magnetic skyrmions for neuromorphic computing by showing the basic functionalities of logic devices based on the manipulation of magnetic skyrmions for non-conventional computing. The first step will be to fabricate neuromorphic devices based on the manipulation of skyrmions and demonstrate their basic functionalities. The final objective will be the demonstration of the resolution of standard learning problems, for instance voice recognition.

Work program & Skills acquired during internship

The internship will be based on all the methods and experimental techniques used for the development and characterization of spintronic devices: sputtering deposition of ultra-thin multilayers and the characterization of their magnetic properties by magnetometry methods, then nanofabrication of nanostructures by electron beam lithography and ion etching. The nanofabrication will be performed at the PTA nanofabrication platform located in the same building as the Spintec laboratory. The manipulation of the skyrmions in the nanostructures will then be characterized by Kerr effect optical magnetic microscopy (MOKE). The data will then be analyzed using neural network algorithms in order to achieve pattern recognition tasks.

Reference [1] O. Boulle et al., Nat Nano 11, 449 (2016). [2] R. Juge et al., Phys. Rev. Applied 12, 044007 (2019). [3] N. Romming et al., Science 341, 636 (2013). [4] D. Pinna et al., Phys. Rev. Applied 14, 054020 (2020).

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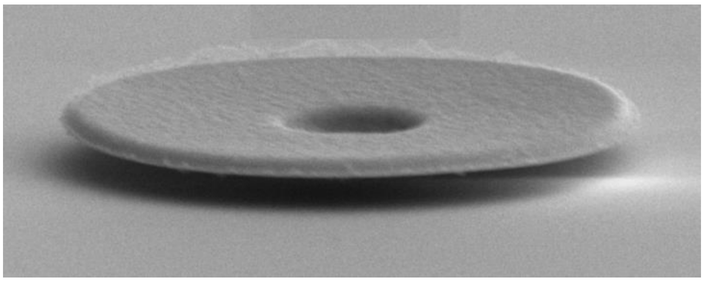
Requested background: Master 2
Duration: 6 months
Start period: Feb/ March 2023
Proposal number : 7

Magneto-elastic properties of suspended garnet disks

Context

A joint European research program coordinated by the Université Grenoble-Alpes seeks to appoint a creative and motivated experimental M2 student to participate in an ongoing project on magneto-elastic properties of suspended garnet disks. The position will be funded by the Horizon Europe PathFinderOpen program, which brings together leading European experimental and theoretical groups working on magneto-acoustic effects in magnetic garnets. The appointed candidate will be responsible for designing and characterizing magnetic and acoustic resonators and the coupling between magnons and phonons at microwave frequencies. S/he will carry out process development, documentation of processes, and implement the required steps to investigate and maximize the interaction between selected magnon and photon modes. The objective of this master project will be to evaluate how these suspended structures perform as magnon-phonon transducers. This will be achieved by coupling these slabs to microwave antenna or interdigited piezoelectric transducer. S/he will collaborate with the other members of the Consortium focused on related topics on ferromagnetic resonance and microwave spectroscopy.



Microscopic image of a suspended drum-like garnet disk resonator of micron-size in diameter.

Work program & Skills acquired during internship

The work program will consist of performing magnetic resonance spectroscopy on individual micro-mechanical devices prepared by nano-lithography and comparing the spectral signature to finite element simulations. The skills acquired are microwave technology, magnetic and elastic eigen-response to oscillatory excitation and finite element simulations. The project will result in a thesis project for which funding is already available.

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Requested background: Master 2
Duration: 6 months
Start period: Feb/ March 2023
Possibility of PhD thesis : YES
Proposal number : 8

Spin transfer torque based magnetic field sensors

Context

Magnetic non-volatile memory (MRAM) is a technology being developed at Spintec. MRAM cell resistance changes that can be greater than 100%, and switching depends on the application of a current pulse and the presence of a magnetic field. It is thus possible to write a bit '1' or '0' according to the polarity of the applied current if the current density. To detect a magnetic field, it is possible to apply a measurement procedure patented by our laboratory. The purpose of the internship will be to validate the operating principle and determine the material space parameters and how they affect the resolution of the memory in field sensor mode. We will optimize the measurement procedure to optimize it in terms of speed and sensitivity. The temperature dependence of the sensor characteristics will also be studied. Potential applications of this concept would be for example in the high precision alignment of dye-wafer required for 3D assembly, widely used in microelectronics to reduce the surface area of chips in smartphone devices.

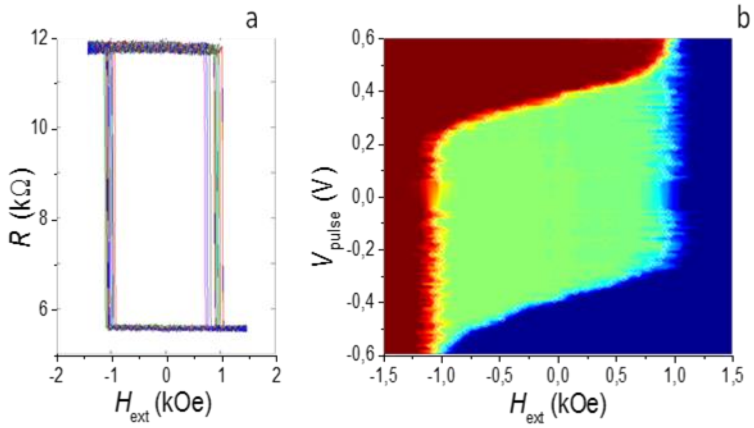

Figure 2 a) *Magneto-Resistive (MR) hysteresis cycle measured on a perpendicular anisotropy tunnel junction showing the variation of the resistance and two distinct resistance sates [1]. b) A state-phase diagram plot of the same junction when applying current pulses. The color code shows the resistance state, blue for low and red for high resistance, with green being the bi-stable region for memory cell.*

Work program & Skills acquired during internship

Different material stacks as well as the size of the memory element so that the magnetization of the storage layer remains stable against thermal fluctuations, while allowing for the accurate sensing of magnetic. The physics involved is well understood so that the modeling of these structures by simulation will be possible. The experiments will consist of depositing magnetic multilayers, nano-fabrication (lithography, etching) in a clean room and then characterizing their magnetic and electrical properties.
Requested student profile: Master 2 in nanophysics/solid state physics, knowledge of instrumentation programing (Matlab/Python), interest in microelectronics. It will be possible to follow a PhD thesis on this subject after the internship.

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Requested background: Master 2
Duration: 6 months
Start period: Feb/ March 2023
Possibility of PhD thesis : YES
Proposal number : 9

MRAM for security applications: robustness and vulnerability analysis

Context

Connected devices have been primarily designed and deployed based on cost and power consumption characteristics, leaving security as a secondary requirement. Recent successful attacks have proven that security of “Internet of Things” will become a major concern requiring technical solutions to strengthen security, including countermeasures against physical attacks. MRAM as a non-volatile memory is best suited for IoT, however its robustness and vulnerability to attacks still needs to be addressed. The purpose of the internship is to investigate MRAM devices to determine their thermal stability based on alternative measurement procedures, which will then be compared to different models.
The thesis goal is to identify the best model corresponding to the observed behavior. In second step, predict the effectiveness of possible electromagnetic attacks depending on the sensitivity of the reversal mechanism. The final objective is to identify these vulnerabilities to design secure MRAM cells.

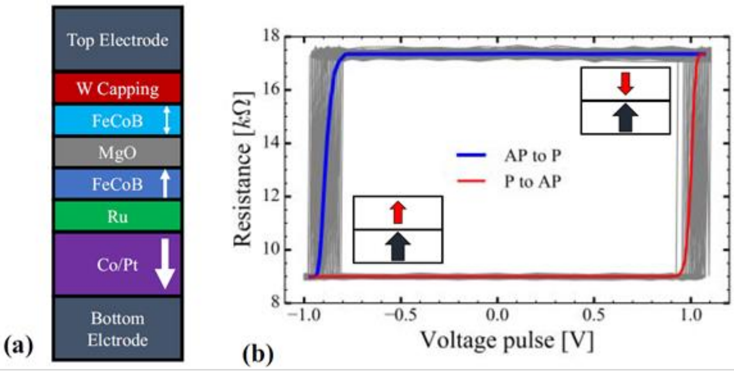

Figure 3 a) Typical magnetic stack of a perpendicular anisotropy magnetic tunnel junction MRAM cell.
b) Voltage loop switching between high and low resistance states [1].

[1] L. Tillie et al., ‘P-STT-MRAM thermal stability and modeling of its temperature dependence’, in 2018 International Symposium on VLSI Technology, Systems and Application (VLSI-TSA), Apr. 2018, pp. 1–2, doi: 10.1109/VLSI-TSA.2018.8403857.

Work program & Skills acquired during internship

Typical electrical characterization of MRAM bitcells consists in measurements of tunnel magnetic resistance (TMR) under voltage pulses resulting in spin transfer torque (STT) switching. Switching voltage and thermal stability of single cells provide designers with target values for the measured parameters.
The intern will validate the different methods to extract these parameters, and verify the compatibility of the fabricated devices with memory specifications. This characterization provides data of writing current density, pulse voltage as well as temperature dependence. Physical simulation of the fabricated cells using magnetic simulation codes developed at Spintec will allow understand the influence environment parameters from external magnetic fields (static or AC) and short heat pulses. Changes in the physical layer stack can also be evaluated, based on the simulation results, evaluating the trade-off between fabrication and stack complexity and risk mitigation performance.

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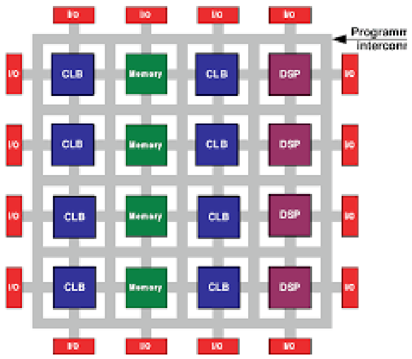
Requested background: Master 2
Duration: 6 months
Start period: Feb/ March 2023
Possibility of PhD thesis : YES
Proposal number : 10

Spintronics-based non-volatile FPGA development for space applications

Context

In microelectronics one can distinguish two integrated circuit families. The first one is related to ASIC (Application Specific Integrated Circuit) and the second family, on which we are focused on for this internship, is related to **FPGA** (Field Programmable Gate Array) which is dedicated to digital electronics. The main advantage of FPGA is the fact they are **reprogrammable**. These circuits are composed of several elementary programmable logic cells interconnected with each other through a programmable system of interconnections. An FPGA is thus mainly composed of memory elements to program the functionality of the circuit, rendering them particularly sensitive to radiations, since a fault occurring in the memory changes the operation of the FPGA permanently. Traditional FPGAs are based on SRAM or Flash.



FPGA schematic

On the other hand, **Magnetic RAM (MRAM)** memories are widely studied and developed worldwide in the electronics domain. They are intrinsically non-volatile and low sensitive to radiations. They also have the advantage to be very dense, to have a high endurance and a low power consumption compared to other non-volatile emerging memories.
The purpose of this internship is to evaluate the use of MRAM as a configuration memory for FPGAs and in particular as a way to improve/simplify the implementation of standard hardening techniques for space applications.

Work program & Skills acquired during internship

This master thesis proposes to **combine the use of MTJ into FPGA architecture** trying to improve the performance and radiation robustness and validate through electrical simulations.
During the internship, a **first bibliography phase** is necessary in order to have a clear overview of the current state of the art. Then, an **architectural design phase** will enable to propose innovative structures that will be evaluated / validated by **electrical simulations**. **Particle perturbation** will be injected to evaluate the global robustness.
This internship has **clearly the ambition to pursue in a Ph. D.** in which all these aspects will be studied exhaustively in depth, in parallel to electrical simulation model development and integration into radiation specific simulations tools for space application.
The candidate should have a **master degree or equivalent, from university or engineer school**. Skills should cover microelectronics **full-custom/circuit level design** preferably using Cadence. **Digital design notions** would be an asset. The level of English should allow the candidate to read and write **scientific articles**, as well as attending **technical discussions** that could be in English.

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Possibility of PhD thesis : YES
Proposal number : 11

In-Memory Computing based on Ferroelectric devices

Context

Typical computing system are based on the Von-Neumann architecture, where the logic and memory parts are separated. In this approach, the main limitation in terms of speed and energy comes from the communication between both, often referred as “memory wall”. One of the solutions to solve this issue consists in performing the computations close to the memory (Near Memory Computing) or inside the memory (In Memory Computing, IMC). For the implementation of IMC architectures, emerging resistive memory technologies are very interesting, since their resistive nature allows Current Mode Logic (CML) implementation. Among these emerging technologies, spintronics, which consist in mixing magnetic and standard electronic devices, offers a unique set of performance and functionalities.
However, spintronic devices involve ferromagnetic elements with high switching energies, that can limit their use for high performance/low-power logic circuits. Contrastingly, the polarization of ferroelectric devices can be easily switched by an electric field, at energies typically 1000 times lower than standard spintronic devices. As recently demonstrated by Intel, this makes ferroelectrics good candidates for ultralow-power post-CMOS logic [Nature 565.7737 (2019): 35]. At spintec, we recently demonstrated that combined with high spin-orbit coupling elements, ferroelectric devices have also a natural potential to generate an electrically-switchable, highly efficient spin-charge interconversion [Nature 580.7804 (2020): 483-486] that can be used to develop new ferroelectric devices. **The aim of the internship consists in evaluating innovative IMC architectures based on emerging ferroelectric-spintronic devices.**

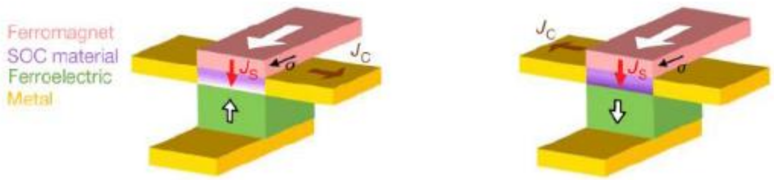

Figure 4: Scheme of Spintec’s *new hybrid ferroelectric spintronics device, that can be connected to perform memory and logic operations. The data is coded within the ferroelectric polarization state.*

Work program & Skills acquired during internship

During this internship, the candidate will have to imagine new IMC architectures taking advantage of these emerging devices. Compared to standard resistive devices, ferroelectric/spintronic devices offer logic capabilities, paving the way towards new IMC implementations. For that purpose, it will be necessary to understand the physical operation of the various device flavors and design circuits embedding these devices then design/characterize innovative architectures of smart memory arrays. Due to the preliminary stage of development of the devices, a constant feedback between the design and the technology will be required to adapt the operation of the device to the one of the circuit and vice versa.
The candidate should pursue a master degree or equivalent, from university or engineer school. Skills should advantageously cover microelectronics full-custom/circuit level design, preferably using Cadence. The level of English should allow the candidate to read and write scientific articles, as well as attending technical discussions that could be in English. An attraction for research and multidisciplinary topics are very important for this internship.

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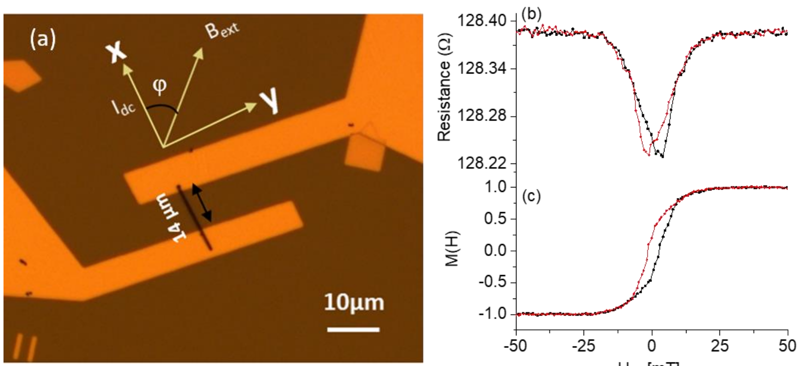
Possibility of PhD thesis : YES
Proposal number : 12

Curvilinear magnetism and spintronics in core-shell nanotubes

Context

The physics of nanomagnetism and spintronics has been mainly developed based on planar structures, making use of thin-film deposition and clean-room patterning technology. This concerns interfacial magnetic anisotropy, magnetoresistance effects, spin-transfer torques, magnonics etc. **3D nanomagnetism and spintronics emerged recently as a new research direction**. A number of fundamentally-new effects are expected, related to 3D spin degrees of freedom, closed boundary conditions in cylindrical nanostructures, and more generally curvature-induced effects. This a fast-developing topic, bringing together experts in chemical synthesis, nanofabrication, imaging and simulation, all developing ever-flexible tools.

This field is the background of the Spin Textures research team of SPINTEC. We have recently developed several key systems, consisting of core-shell magnetic nanotubes and nanowires. These are of crucial interest to translate spintronics in a 3D geometry, as spintronic effects are provided by interfaces. Besides, cores and shells with different functions can be brought together. Here, we propose to make use of such core-shell systems to investigate the physics of domain-wall motion and magnonics, *i.e.*, spin wave propagation, in curved systems. In both cases, we will seek to evidence signatures of the impact of curvature on magnetism, predicted however so far not reported experimentally.



(a) Single magnetic nanotube contacted electrically using laser lithography. Magnetization probed by (b) anisotropic magnetoresistance, converted to (c) a hysteresis loop, revealing the unexpected azimuthal direction of magnetization.

Work program & Skills acquired during internship

The chemical synthesis, combining several cutting-edge techniques, is conducted by several international collaborators. The candidate will be in charge of handling core-shell nanotubes and nanowires, contact them electrically, characterize them in dc and ac electrical measurements, and use a combination of several magnetic microscopies to investigate domain-wall motion under nanosecond pulses of electric current, and the controlled excitation of spin waves. This may involve both in-lab measurements and stays at synchrotron-radiation facilities. The work is conducted jointly with colleagues from the theory group, providing a quick and effective support. Besides direct monitoring, the candidate benefits from weekly meetings in a collaborative environment including experts in electric measurements, advanced magnetic microscopy, and numerical/analytical micromagnetism.

The candidate will learn nanofabrication techniques, electrical measurements and magnetic imaging, as well as a deep physical understanding of nanomagnetism and spintronics, providing a solid and broad basis to start a scientific research career, which we aim to be extended with a PhD project.

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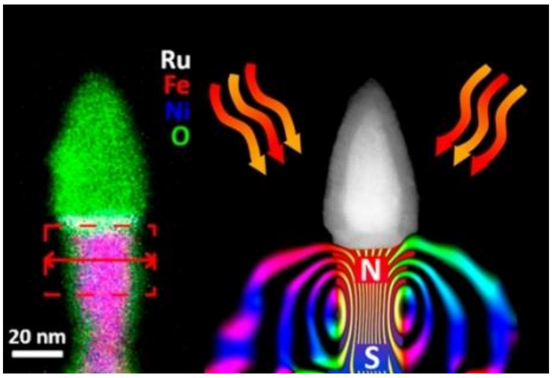
Possibility of PhD thesis : YES
Proposal number : 13

MRAM: new routes toward sub-10nm scalability and improved thermal retention

Context

Magnetic random access memories (MRAM), based on magnetic tunnel junctions storing and reading bits of information, are emerging key ICT components. They are of immediate relevance for low-power and high-speed processor and mass-storage cache memory. However, limits of downward scalability have already been identified related to scientific or technological bottlenecks, This issue, shared with all standard microelectronics approaches, pushes upstream research to design three dimensional devices and thus allow long-term scalability in terms of areal density or thermal stability.



Left: chemically-resolved TEM image of a single magnetic nanopillar (pink). Right: electron holography measuring the lines of magnetic induction field, revealing the perfect vertical direction of magnetization in the pillar, and the resulting stray field in its vicinity.

The scalability of single vertical MRAM cells below 10 nm lateral size has been demonstrated recently at SPINTEC – see figure. Such extreme features are obtained combining ion-beam etching at normal incidence as in usual patterning processes for the aspect ratio, and lateral trimming at grazing incidence to achieve these low dimensions. We have demonstrated the high thermal stability of these cells thanks to the vertical aspect ratio, as well as their magneto-electric functionalities, both reading and writing the cell with a spin-polarized current. However, we evidenced two bottlenecks. First, the fabrication involving grazing incidence etching is not compatible with integration in closely-packed devices. Second, the writability of the cell is hampered by the large volume of the cell, compared to the standard ultrathin MRAM cells.

Work program & Skills acquired during internship

The purpose of the internship is to address the two bottlenecks that appeared in the proof-of-concept experiments: suitability for device integration, and hampered writability. We will address the first by using semiconductor vertical interconnects, a mature technology, to be filled with a magnetic material to serve as a storage cell. We will address the second by implementing new strategies to switch magnetization reversal, while maintaining the thermal stability of the pillar, making use of additional of graded sources of anisotropy (RKKY, magnetostatic etc.).

In the framework of an internship, the first steps consist in the structural, magnetic and electric characterization of such interconnects. Magnetic measurements will be those standard for MRAM cells, consisting of VSM and MOKE hysteresis curves under perpendicular and in-plane field to determine the stability of each stack, targeting stability up to 400°C. In parallel, magnetic simulation codes developed at Spintec will be used to understand the influence of material design on the magnetic stability, and outline directions for improved writability with no compromise on thermal stability.

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Possibility of PhD thesis : YES
Proposal number : 14

Stochastic computing based on spintronic devices

Context

The widely increasing amount of data to be processed today in more and more complex applications is currently reaching the limits of the standard Von-Neumann architectures of computing systems, where the bottleneck comes from the communication between the logic and memory parts which are separated. To try to push forward this limit, new computing schemes are intensively investigated. Stochastic computing is one of the possible solutions since it allows a strong reduction of the hardware complexity. In particular, Ising machines are particularly efficient to solve optimization problems. They rely on probabilistic bits (pbits) acting as a tunable True Random Number Generators (TRNG). Thanks to their stochastic behavior due to the thermal fluctuations of their magnetization, spintronics devices have been studied as a promising implementation of pbits [Nature, 573(7774), 390-393], Figure 5. Preliminary demonstrations at device/circuit level have been shown, but no study evaluating the benefits of using spintronics devices for Ising machines at application level has been proposed so far. **The aim of the internship consists in proposing a flow allowing to integrate the pbit in a full design flow for evaluation of Ising machines based on spintronic pbits for specific applications.**

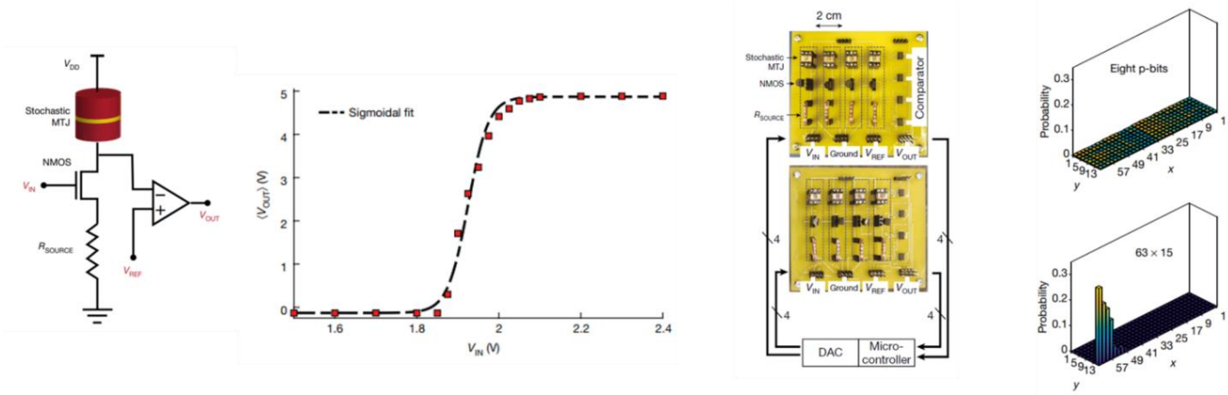

Figure 5: experimental demonstration of a spintronics-based pbit and factorization function

Work program & Skills acquired during internship

During this internship, the candidate will have to understand the operation of the pbit implementation that has been proposed in the lab. He will then have to accurately and intensively characterize it at circuit level using electrical simulations. This will allow to provide a behavioral model of the pbit using Verilog or VHDL language (for digital simulations) and a liberty file (.lib) containing the time and power consumption response of the pbit (for synthesis operation). Given the specific nature of the probabilistic computing, the description of the behavioral model as well as the synthesis should be considered (in particular to force the synthesis tool to use the stochastic functions rather than standard ones). Once the flow has been setup, it will be validated by running a simple application like solving the traveling salesman problem.

The candidate should pursue a master degree or equivalent, from university or engineer school. His skills should cover microelectronics full-custom/circuit level design (electrical simulation) and digital design (digital simulations and synthesis). The level of English should allow the candidate to read and write scientific articles, as well as attending technical discussions which could be in English. An attraction for research and multidisciplinary topics are very important for this internship.

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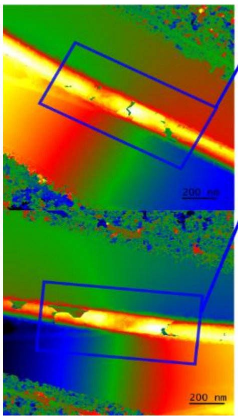
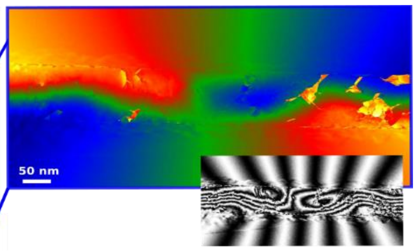
Requested background: Master 2
Duration: 6 months
Start period: Feb/ March 2023
Possibility of PhD thesis : YES
Proposal number : **15**

Multi-platform Image processing for Quantitative Magnetic Imaging

Context

Nanoscale characterization in the direct space (*i.e.*, imaging) is not only an observation at the nanometer scale, but allows a mapping of physical and functional properties. As regards magnetic imaging, several cutting-edge methods are used in SPINTEC to obtain quantitative magnetic information in objects relevant for future devices (domain walls in nanowires, skyrmions in patterned media, nano-magnets for non-volatile memories). Two prominent techniques are Electron Holography and X-ray Magnetic Dichroism. Both require to acquire multiple images with variations in the sample orientation or the incoming beam, and then to recombine them into a final image revealing the magnetic information. The ultimate spatial resolution and physical sensitivity can only be achieved through advanced sub-pixel realignment, to avoid artifact and obtain a reliable quantification. In addition, the emergence of *in situ* methods enable to quickly change the magnetic state, resulting in a large number of images to process in a careful way, up to video mode. The aim of this internship is to develop a robust and multi-platform flow for image realignment, resulting in a Python library and user-friendly interface. This platform will be implemented both on desktop and directly on microscopes, to provide a live processing to assist the experimentalists during acquisition.





A cobalt-nickel wire imaged with Electron Holography. Left : two acquisitions with Electron Holography (Phase images) acquired before and after flipping the sample by 180° top to split structural and magnetic contrast. The color codes the phase shift of electron waves. Top: zoomed image obtained by the registered subtraction of the two blue areas in the original image. One can now see the fine structure of the magnetic domain wall that can be highlighted showing only iso-phase variations (B&W image in the inset)

Work program & Skills acquired during internship

The internship will be devoted to experimental image processing using a Python ecosystem developed in the electron microscopy platform. Various tasks will be conducted:

- **hdf5** harmonisation (automatic generation, reading & sorting) of various magnetic images
- **Image registration** procedures in multiple steps (automatic & manual steps)
- Open access display via **Jupyther noetbook** of experimental results
- Implementation (translation or adaptation) of magnetic imaging libraries.

The main activity will then be dedicated to physical studies using **correlative microsopies** (association of various techniques on the same object) by taking part to experimental acquisition of data (either in front of or remotely) of TEM (Electron holography) and STXM (Ptychography). A PhD extension would extend to linking quantitatively experimental images and the output of micromagnetic simulations.

<u>The candidate will gain various research skills such as :</u> image processing, **electron microscopy**, **transmission x-ray microscopy**, team work, physic modeling, **micromagnetism**, spintronic, advance python programming

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Possibility of PhD thesis : YES
Proposal number : 16