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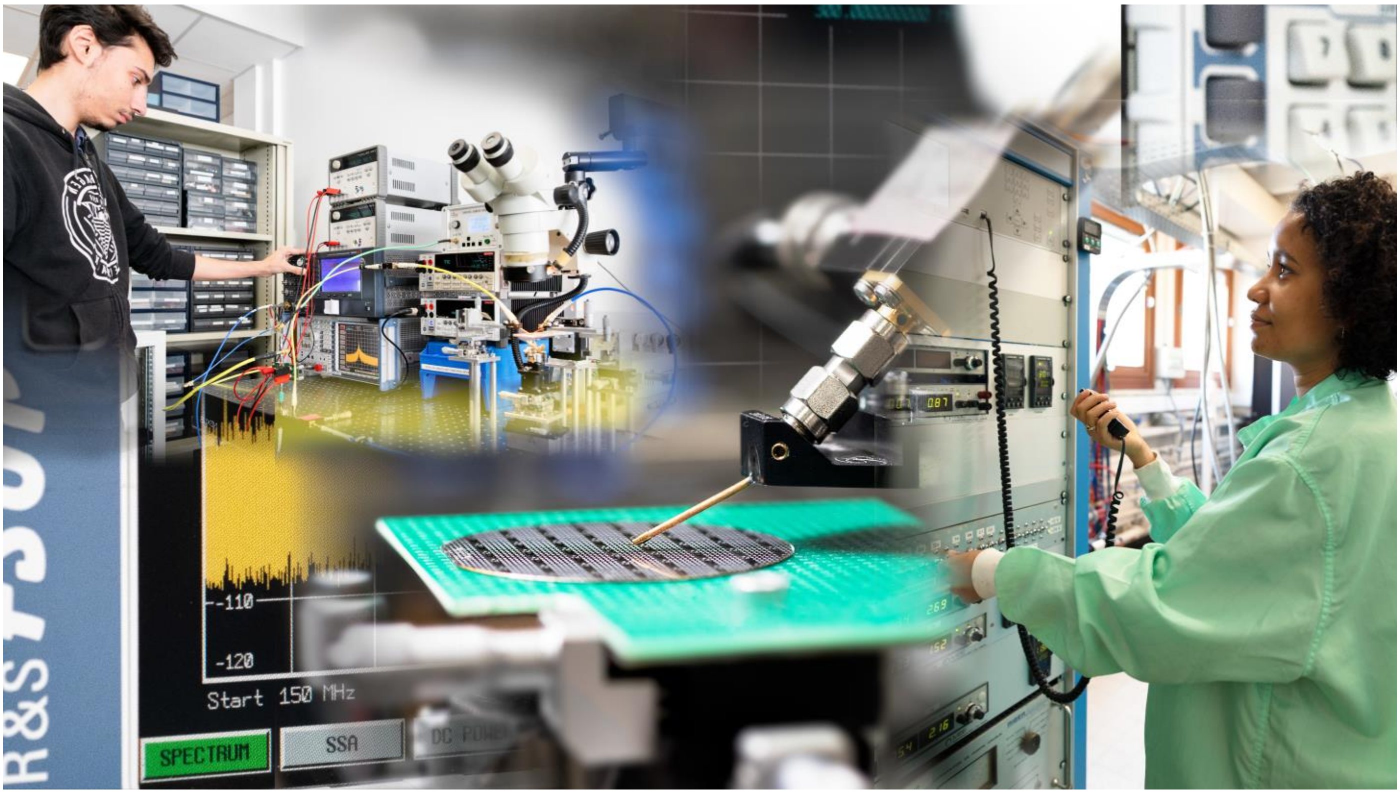
SPIN IN ELECTRONICS

SPINTRONIQUE et TECHNOLOGIE des COMPOSANTS

Master Internship Booklet

2025



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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 53 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, information and communication technologies, sensing technology and bio-applications. As such, we are at the cross-road 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, non-linear magnetization dynamics and magnonics, antiferromagnetic spintronics, and exotic spin textures. The application-oriented topics are: magnetic random access memories, artificial intelligence, microwave components, design of spin-based integrated circuits, sensors, and 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!

List of proposals

The laboratory is constantly seeking undergraduate and summer students with high potential and a taste for research at the frontier between fundamental physics and technology. Individuals with cutting edge scientific skills, strong motivation, the taste for teamwork and a good sense of humor are welcome.

Below is the list and description of projects that are proposed for the Master-2 level, most of them are intended to continue to a PhD, and several are also open to Master-1 level students. In the framework of French universities the typical period for M2 internships is from March to June / July, but we welcome equally students from foreign universities and different timeframes for carrying out their internship.

Please do not hesitate to contact us any time if you are a student and wish to join, either through the lab directors or directly through the permanent staff whose e-mail you find at the end of the corresponding description of the research projects.

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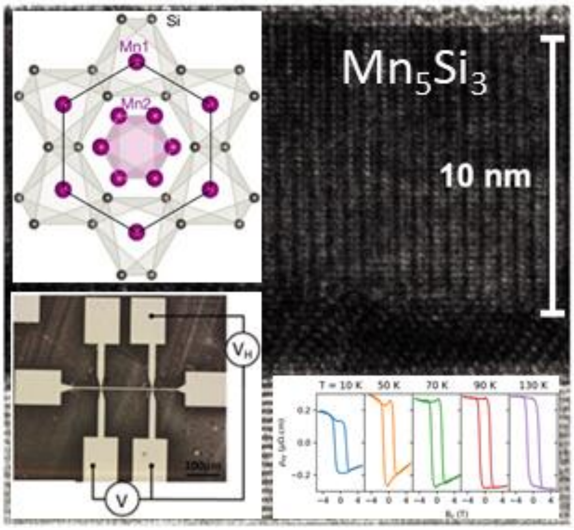
A new altermagnetic material with remarkable properties for spintronics

Context



Recent discoveries have revealed a third class of magnetic materials known as altermagnet. They have attracted considerable attention, opening up new research paths in several fields of condensed matter physics. For future applications, altermagnets, by combining the advantages of ferromagnets (spin polarization of an electric current) and antiferromagnets (robustness to magnetic fields and response to ultra-fast teraHertz frequencies), would enable the production of spintronic devices with higher performance, because they are faster and denser.

We selected Mn_5Si_3 as our workhorse altermagnetic material[1-3], because: (1) it is composed of light-elements with weak relativistic spin-orbit coupling, making it possible to unequivocally link its altermagnetic character to non-relativistic spin physics; (2) it is made of abundant and non-toxic elements and (3) it is compatible with conventional Si-based semiconductor technology.

Up to now, Mn_5Si_3 has mostly been prepared by molecular beam epitaxy. While this method yields almost perfect films, it would not be applicable in larger-scale commercial context.

The objective of this project is to establish the growth of Mn_5Si_3 altermagnetic layers utilizing a PVD sputtering deposition technique at high-temperature, compatible with conventional semiconductor industry. We will further functionalize and characterize the incomparable spin-dependent transport properties of devices once the Mn_5Si_3 layer is embedded in relevant heterostructures.

Work program & Skills acquired during internship

The candidate will contribute to the following tasks :

- Carry out the growth of Mn_5Si_3 thin films by high-temperature co-sputtering & post-anneal the films
- Characterize the crystallography of the films by X-ray diffraction
- Fabricate mesoscopic devices & measure the spin-dependent transport properties of the films
- Analyze, interpret & present the results

The candidate will acquire skills in growth, nanofabrication, structural and electrical characterization of magnetic thin films and devices. He/she will discover many facets of spintronics and nanomagnetism. This internship will be carried out within the "Antiferromagnetic spintronics" team, in close collaboration with the "Materials" team. The candidate will benefit from a strong international environment. Our consortium's (France, Germany, Czech) collaborative work forms the foundation of the present offer, see e.g. Refs 1-3.

[1] I. Kounta et al., PRM. 7, 024416 (2023), https://amu.hal.science/hal-04009609; [2] H. Reichlova et al., Nat. Commun. 15, 4961 (2024), https://hal.science/hal-03092623v1; [3] M. Leiviskä et al., PRB 109, 224430 (2024), https://hal.science/hal-04376117v1

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Requested background: Master 2
Duration: 6 months
Start period: Feb/ March 2025
Possibility of PhD thesis : YES

Orbital Angular Momentum Transfer between Magnon and Phonon

Context

The conservation of angular momentum in solids has long been recognized as a powerful mean to transport information, where the extensively studied notion of angular momentum transfer by conduction electrons is only part of the story. The same rational applies also to bosons e.g. photon, phonon or magnon, which are classically represented by circularly polarized vector fields propagating in continuum media with helical or rotational wave fronts. In certain cases, this angular momentum can be separated into spin and orbital components [see Figure below] However, most of these works have focused on the spin component, which reflect the circularly polarized character of vector fields: $n_S=\pm1$, either clockwise or counterclockwise, while leaving the orbital component mostly unexplored. This can be seen in the context of the general difficulty of direct coupling to waves with large orbital index. Our project is to develop a new approach to mechanically modulate large orbital angular momentum by scattering the circular magnetization dynamics on an anisotropic magneto-elastic tensor. We plan to achieve this conversion in micron-sized single crystal magnetic garnet disks. We also want to go beyond uniformly magnetized state and exploit the ability to continuously morph the equilibrium magnetic texture in the azimuthal direction as a means of engineering the selection rules and thus coherently access otherwise hidden mode symmetries

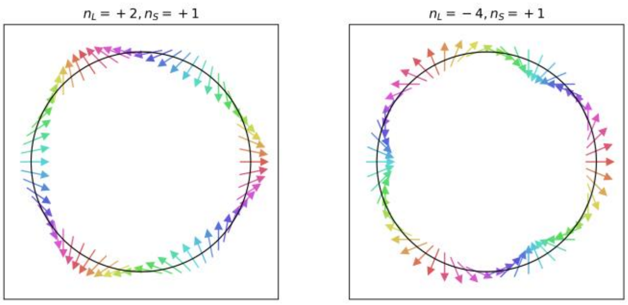

Figure: *Snapshots of the vector pattern formed by two azimuthal spin-wave modes with opposite angular momentum in a normally magnetized disk. The index $n_J=\pm3$ counts the winding number of the phase relative to the radial direction. The index $n_S=\pm1$ indicates the polarization of the circular precession. Modes can be alternatively indexed by n_L the number of turns of the vector in a Cartesian framework, with $n_J=n_L+n_S$.*

Work program & Skills acquired during internship

The work program will consist of i) performing magnetic resonance experiments with a home-built spectrometer on nanolithographically prepared magnetic microdisks and ii) comparing the spectral signature with finite element simulations. The skills required are a basic knowledge of solid state physics and an interest in self-development of experiments. The skills that will be acquired during this training are microwave technology, magnetic resonance, and finite element simulations. The project will lead to a Ph.D. thesis, for which funding is already available.

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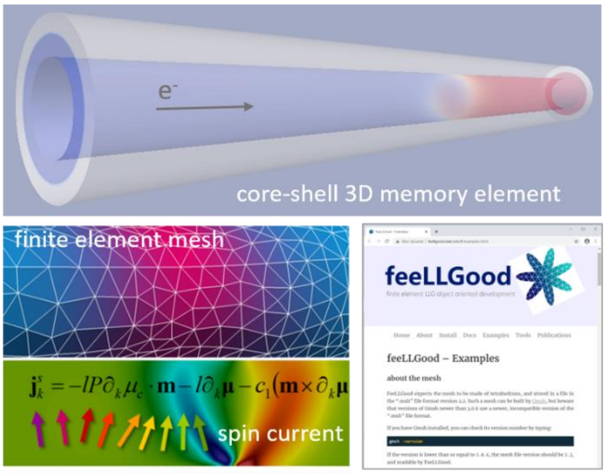
Requested background: Master 2
Duration: 4-6 months
Start period: Feb/ March 2025
Possibility of PhD thesis : YES

Simulation of domain walls and spinwaves in nanowires and nanotubes

Context

Three-dimensional spintronics considers the interaction of local magnetic moments with the spins of conduction electrons in curved 3D systems, cylindrical structures being textbook objects. These both provide a playground for new fundamental properties as well as building blocks for advanced data storage technologies. In particular, information may be encoded in cylindrical structures by magnetic domains separated by magnetic domain walls, addressed by moving the domain walls by applying a spin-polarized current. Domain walls are also expected to emit spin waves, with non-reciprocal dispersion induced by curvature. At SPINTEC and in collaboration with colleagues at Institut Néel (Grenoble) and IMDEA (Madrid), we are currently considering nanowires and nanotubes displaying spontaneously azimuthal magnetization. These give rise to new topologies of domains and domain walls, offering a virgin playground and new challenges for theory and modeling. To simulate non-trivial 3D magnetic textures and the role of current on their dynamics we use the open-source home-developed multi-physics finite-element C++ software *feeLLGood* http://feellgood.neel.cnrs.fr/. In addition to conventional single material wires, the continuous progress in nanofabrication gives rise to a new variety of multi-layered core-shell geometries, which we aim to explore numerically in the framework of this internship.



3D modeling for spintronics using our software *feeLLGood*: from theoretical concept, related spin-dependent equations and volume discretization to exploring of real structures and contribution to the dedicated website.

Work program & Skills acquired during internship

This internship offers the opportunity to be trained on the various aspects of finite element modelling for spintronics starting from the numerical experiments design to the contribution to the dedicated website and tight interaction with experimentalists. We are looking for a motivated candidate and contribute to:

- Carry out the pre-study of typical physical structure using the COMSOL software;
- Generate non-regular finite element meshes using GMSH software;
- Conduct comprehensive simulations on our calculation server in the UNIX environment;
- Post-treat and visualize obtained data with Paraview software and home-made Python scripts;
- Contribute to the dedicated website and take into account the feedback from experimentalists

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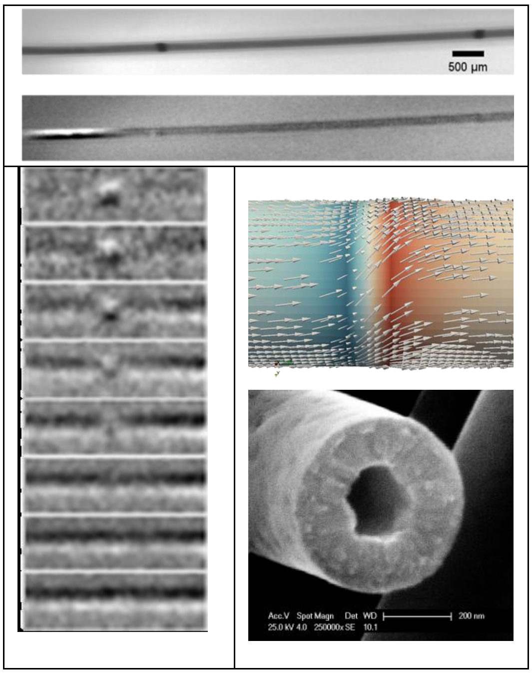
Requested background: Master 2, affinity for numerical modeling
Duration: 6 months
Start period: Feb/ March 2024, flexible
Possibility of PhD thesis : YES

Experimental search for spinwave non-reciprocity in nanowires&nanotubes

Context



(top) Chemically-modulated wires (left) Time-resolved current induced magnetization switching of the modulation, with frame every 50ps. (right) Micromagnetic simulation of the modulation, and a nanotube (yet another curvilinear system investigated)

The fields of nanomagnetism and spintronics are opening to 3D structures, giving rise to new fundamental effects and also creating opportunities for deep integration, compared with standard planar designs. New physical effects include magnetic anisotropy, magnetoresistance, spin-transfer torques, the topology of magnetization textures, magnonics etc… Concerning the latter two, specific effects are expected from the 3D spin degrees of freedom, curvature and closed boundary conditions, cylindrical nanostructures being a textbook situation. 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 with chemical modulations. These are of crucial interest to translate spintronics in a 3D geometry, as spintronic effects are provided by interfaces. In this proposal, we are interested in investigating the propagation of spin waves in such structures, using domain walls or chemical modulations as a source of excitation. The first objective of this work is to address questions such as magnetic damping and non-reciprocal effects related to curvature. More will be discussed in the interview.

Work program & Skills acquired during internship

The chemical synthesis, combining several cutting-edge techniques, is conducted by several local and international collaborators, especially at IMDEA-Madrid. The candidate will be in charge of handling core-shell nanotubes and nanowires, contact them electrically in clean rooms, characterize them under dc and ac electrical stimulus, and use a combination of several magnetic microscopies to investigate domain-walls, chemical modulations, 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 at SPINTEC and Institut Néel, 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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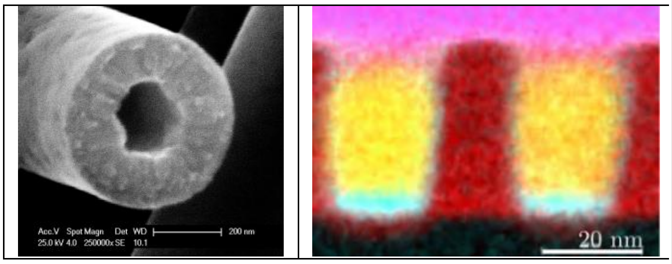
Requested background: Master 2
Duration: 6 months
Start period: Feb/March 2025
Possibility of PhD thesis : YES

Atomic Layer Deposition of Pd to seed electroless-grown high-quality ultrathin ferromagnetic layers for 3D spintronics

Context

The fields of nanomagnetism and spintronics are opening to 3D structures, giving rise to new fundamental effects and also creating opportunities for deep integration, compared with standard planar designs. New physical effects arise in magnetic anisotropy, magnetoresistance, spin-transfer torques, the topology of magnetization textures, magnonics etc… On the applied side, opportunities include the translation of logic and storage spintronic circuits to 3D designs, providing higher areal density, better thermal stability or enhanced neuromorphic capacities.



Example of 3D nanomagnetic and spintronic systems investigated at SPINTEC: (left) Core-shell Cu\CoNiB nanotube for the fundamental investigation of domain-wall motion in a tubular geometry (right) Exploratory 3D ferromagnetic storage layers embedded in a SiO2 matrix on Si wafers.

One of the challenges arising to translate spintronics from 2D to 3D is the ability to synthesis spintronic stacks on structures with variable shape and curvature, with a structural and electric quality similar to that of planar stacks. The standard physical vapor deposition technique are not suitable, as they tend to clog narrow openings and induce shading effects. Instead, one requires conformal deposition techniques, which consists of chemical approaches such as Atomic Layer Deposition and Electroless deposition. In general, the former is more suited for oxides, nitrides and some noble and refractory metals, while the latter is more suited for 3d ferromagnetic materials. Electroless deposition is often initiated on nanometer-sized Pd catalyst seeds, which is not suitable to produce ultrathin and low-roughness films. The objective of this internship is to explore the use of atomic-layer-deposited Pd as a seed to produce high-quality ultrathin electroless CoNi ferromagnetic layers.

Work program & Skills acquired during internship

First, the literature of Pd ALD and its use to serve as seed layer (e.g., the case of Cu is well documented) will be reviewed to outline the most promising strategy in terms of precursors, deposition conditions and thickness. Second, ALD Pd films followed by electroless CoNi films will be fabricated, and characterized structurally and magnetically. We intend to first develop know-how on flat surfaces for the ease of analysis, then turn to 3D systems, such as tubular structures or embedded storage electrodes. The work is conducted jointly with colleagues from the spin textures team at SPINTEC, the functional thin films team at LMGP, and the Micro- and Nanomagnetism team at Institut Néel. Besides direct monitoring, the candidate will benefit from weekly meetings in a collaborative environment including experts in physico-chemistry, magnetic materials and electrical measurements.

The candidate will operate ALD and electroless deposition tools, and proceed to the structural and magnetic characterization of the stacks produced. The internship can be extended into a broader to fabricate and investigate novel nanomagnetic and spintronic 3D devices.

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laurent.cagnon@neel.cnrs.fr	Possibility of PhD thesis : YES

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. Important steps 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], the recent demonstration of their fast (>1km/s) manipulation using electrical currents (Fig. 1 a) [2] and their integration in magnetic tunnel junctions (Fig. 1b) [3].

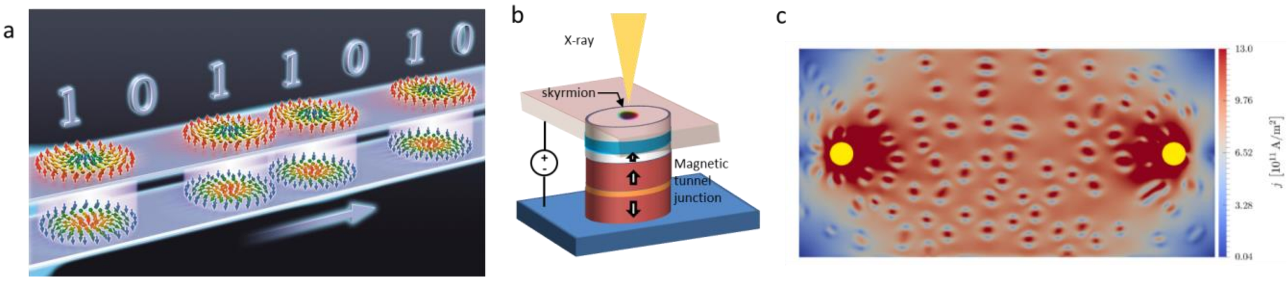

Figure 1a Antiferromagnetic skyrmions encoding the information in a racetrack [2] b skyrmion in a magnetic tunnel junction observed via scanning transmission x-ray microscopy [3]. c Proposal of skyrmion reservoir computing device [4]

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 (Fig. 1c) [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] V-T Pham, Science, 384, 693 (2024), "Le skyrmion, cette étrange structure qui pourrait bousculer l'électronique" Journal Lemonde 23 avril 2024, " Les skyrmions, des nanobulles magnétiques pour remplacer l'électronique, atteignent des vitesses records", France culture, 19 avril 2024
[3] J. Urrestarazu Larranaga et al., Nano Letters, 24, 3557 (2024)

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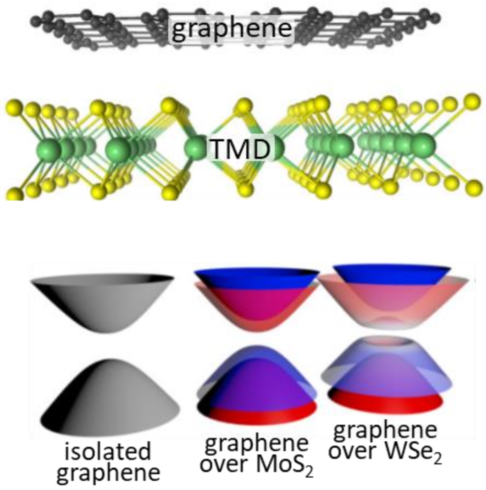
Requested background: Master 2
Duration: typically 6 months
Start period: beginning of 2025
Possibility of PhD thesis : YES

Graphene spintronics in transition metal dichalcogenides: Simulations

Context

In the context of **spintronics**, graphene is considered an ideal platform thanks to its very weak spin-orbit coupling (SOC), which allows spin scattering lengths of up to a few tens of micrometers [1]. For the same reason, however, spin manipulation is complicated. Transition metal dichalcogenides (TMDs), another class of two-dimensional materials, exhibit a considerable SOC due to the heavy metals they comprise. When graphene is over a TMD, a SOC is induced into graphene by proximity effect [2]. With a TMD such as WSe_2, which contains a very heavy metal and therefore induces a stronger SOC, thus resulting in a topological insulator and a spin quantum Hall effect.



[1] "Graphene spintronics: the European Flagship perspective", S. Roche et al, *2D Mater.* 2, 030202 (2015)
[2] "Trivial and inverted Dirac bands and the emergence of quantum spin Hall states in graphene on transition-metal dichalcogenides", M. Gmitra et al, *Phys. Rev. B* 93, 155104 (2016)

Work program & Skills acquired during internship

The internship is jointly proposed by CROMA (Centre for Radiofrequencies, Optic and Micro-nanoelectronics in the Alps) and SPINTEC (SPINtronique et TEchnologie des Composants) Research Laboratories affiliated with Univ. Grenoble Alpes, Grenoble INP-UGA, CEA and CNRS.
The objective of this internship is to study, through simulations based on the density functional theory, the effect of a **polycrystalline TMD on the band structure of graphene** above it. This is a common disorder in non-exfoliated TMDs, the consequences of which on graphene-induced SOCs merit further study. The different crystal orientations could lead to the formation of spin-polarized states in graphene in correspondence to the grain boundary, with important theoretical and application consequences. With the balance between **theory** and **numerical computation** existing between our two laboratories, the intern student will develop important skills in the use of *ab initio* and tight-binding codes. It would also be an opportunity to start a new collaboration between CROMA and Spintec and will allow the intern to continue working in our laboratories with activities focused on magnetic or ferroelectric memories for low-power electronics and artificial intelligence.

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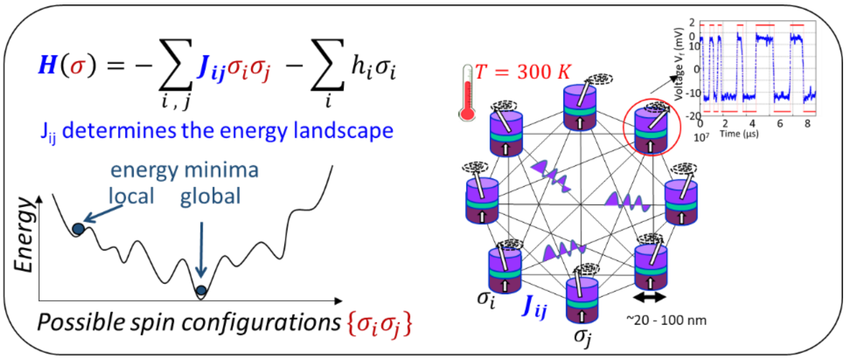
Requested background: Master 2
Duration: 6 months
Start period: Feb/ March 2025
Possibility of PhD thesis : YES

Development of an Ising-spin based analog computing platform using a network of coupled spin-torque nano-oscillators

Context

Digital computers based on conventional CMOS hardware reach their limits in terms of energy consumption. Novel approaches are under investigation, such as analog computers that exploit physics concepts and reduce overall energy consumption due to their inherent parallel computing capabilities. A powerful example is based on the Ising model, where binary-valued Ising spins σ_i, σ_j are coupled through coupling constants J_{ij}. Depending on the coupling matrix and operational conditions, such an Ising-based analog computing platform can be used for memory, logic, or optimization-problem-solving tasks [1]. This versatility is enhanced when exploiting the intrinsic thermal noise, thus making use of naturally available energy resources to explore the energy landscape.



The aim of the internship is to validate such an Ising-based analog computing platform using the binarized phase states (Ising spins) of spintronics oscillators. In a recent work [2], we demonstrated that thermal noise induces stochastic transitions between these phase states and that both states are equiprobable. Via an external signal one can control the phase state probability and generate a probabilistic bit. Their interaction will then allow for performing optimization, logic, or memory tasks [1]. In collaboration with CEA/LETI our team is about to develop a CMOS-integrated coupling circuit to efficiently and controllably couple these phase-state probabilistic bits.

Work program & Skills acquired during internship

The internship is experimental. It will combine fundamental studies of the phase dynamics of coupled spintronics oscillators with electrical characterization of the spintronic/CMOS network. The final goal is to demonstrate and investigate the computing performances of such a spintronic-oscillator-based Ising-spin network. The student will acquire expertise in (i) concepts of spintronics (spin-polarized transport, spin momentum transfer, spin-torque driven magnetization dynamics); (ii) concepts of unconventional computing and (iii) high-frequency measurement techniques. The work is carried out in interaction with the different members of Spintec's RF devices and Artificial intelligence teams.

Interested students, please send a CV and a motivation letter.

[1] Knoll et al. NPJ Unconv. Computing 1, 5 (2024) https://doi.org/10.1038/s44335-024-00005-1; Cai et al. Applied Phys. A 129, 236 (2023) https://doi.org/10.1007/s00339-022-06365-4

[2] N.-T. Phan et al. Phys. Rev. Appl. 21, 034063(2024) DOI: 10.1103/PhysRevApplied.21.034063

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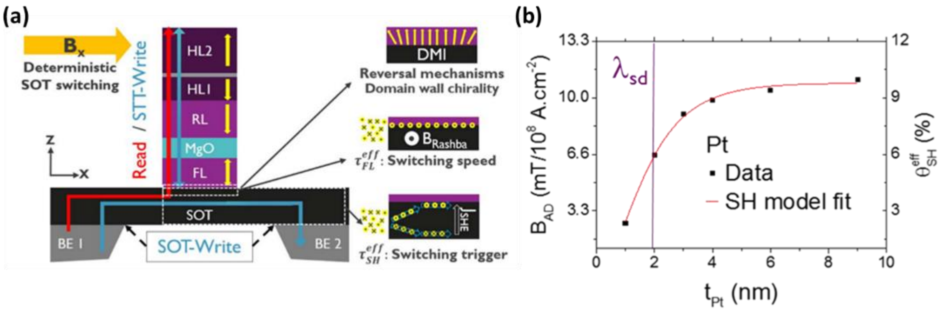
Requested background: Master 2 in condensed matter physics and/or in nanosciences; good taste for experiments; knowledge of electronic circuits or microwave signal processing will be of advantage.
Duration: 4-6 months
Start period: February/March 2025
Possibility of PhD thesis : YES

Characterization of orbital and spin-orbital torques for MRAM applications

Context

Spintronic devices exploit the spin, as well as the charge, of electrons and could bring new capabilities to the microelectronics industry, that is facing major challenges related to the volatility of CMOS cache memory elements (usually SRAM and eDRAM) [1]. Magnetic random access memories (MRAM) devices are among the most credible non-volatile candidates that are low power and fast enough to compete with SRAM. Advanced MRAM devices are magnetic tunnel junctions (MTJ) that are operated by spin transfer torque (STT) effect. Spin-orbit torque (SOT) MRAM has emerged as a credible next-generation MRAM technology that allows for faster and more efficient magnetization writing [2].
In SOT-MRAM devices the ferromagnetic storage layer (FL) is in contact with a non-magnetic heavy metal (HM) channel such as Ta, W, or Pt [3]. When a current flows through the channel, a perpendicular spin current is generated and transferred to the magnetization of the FL, inducing magnetization reversal. To enable SOT-MRAM as viable technology, several challenges need to be overcome. In terms of material innovation, improving the write efficiency (SOT material, interface) is key.

We propose in this project to engineer and study materials combinations (thickness, compound) , in order to improve SOT efficiency and address SOT-MRAM write challenges.



(a) Typical SOT-MTJ structure and spin-transport effect involved (spin Hall effect, Rashba interation). (b) Characteristic variation of SOT fields as a function of SOT material thickness.

Work program & Skills acquired during internship

The internship thesis will consist in:

i. Characterize magnetic properties (magnetization saturation, anisotropy) by the mean of VSM and MOKE.
ii. Characterize spin torques amplitudes as a function of thicknesses and material compounds
iii. Synthetize and report results.

[1] B. Dieny et al., "Opportunities and challenges for spintronics in the microelectronics industry", *Nat. Electron*. 3, pp. 446-459 (2020)
[2] K. Garello et al.,"Manufacturable 300mm platform solution for Field-Free Switching SOT-MRAM", IEEE Symp. VLSI Tech.,T194-T195 (2019)
[3]A. Manchon et. al, ""Current-induced spin-orbit torques in ferromagnetic and antiferromagnetic systems," *Rev. Mod. Phys.*, 035004, (2019

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Requested background: Master 1 / Master 2
Duration: 3-6 months
Start period: From January to March 2025
Possibility of PhD thesis : Yes

Characterization of SOT-MTJ Devices at Cryogenic Temperatures

Context

Spintronic devices leverage both the spin and charge of electrons, offering potential solutions to challenges in the microelectronics industry, particularly the volatility of CMOS cache memory (SRAM and eDRAM) [1]. Magnetic random access memory (MRAM) is a promising non-volatile candidate due to its low power and speed, making it a competitor to SRAM. Advanced MRAM devices, based on magnetic tunnel junctions (MTJs), use spin transfer torque (STT) for operation. Spin-orbit torque (SOT) MRAM, a next-generation technology, and enables faster and more efficient magnetization writing [2]. In SOT-MTJ, a non-magnetic heavy metal (HM) layer, such as Ta, W, or Pt, generates a spin current that reverses the magnetization of the ferromagnetic storage layer (FL) [3]. The understanding of SOT-MTJ at low temperatures is under-explored which could broaden its potential as cryogenic memory especially in high-performance and quantum computing [4].

We propose in this project to characterize and understand the temperature dependence of various SOT-MTJ device parameters namely TMR, coercivity, anisotropy field, thermal stability and SOT switching efficiency.

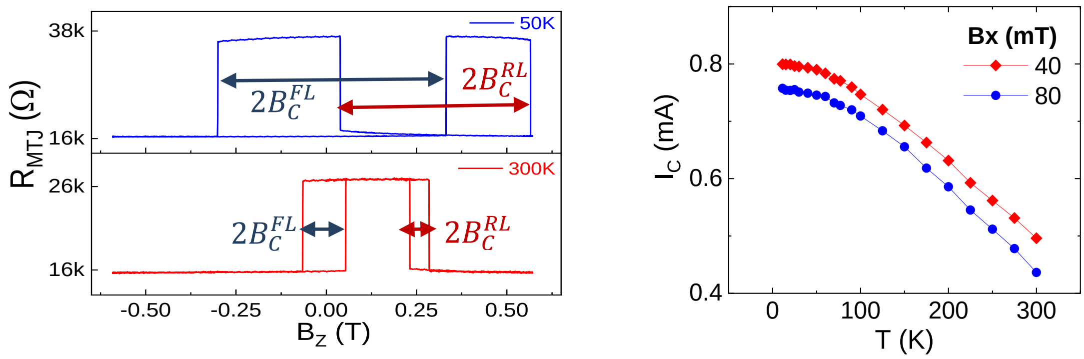

Figure: RH loop depicting hysteresis loops for FL and RL is shown on left and critical switching current dependence with temperature on right for a typical SOT-MTJ device.

Work program & Skills acquired during internship

The internship thesis will consist of:

iv. Characterization of magnetic properties through electrical measurements in cryostats.
v. Analysis and understanding of SOT switching with field and temperature.
vi. Document and report results.

[1] B. Dieny et al., “Opportunities and challenges for spintronics in the microelectronics industry”, *Nat. Electron*. 3, pp. 446-459 (2020)
[2] K. Garello et al.,”Manufacturable 300mm platform solution for Field-Free Switching SOT-MRAM”, IEEE Symp. VLSI Tech.,T194-T195 (2019)
[3] A. Manchon et. al, ““Current-induced spin-orbit torques in ferromagnetic and antiferromagnetic systems,” *Rev. Mod. Phys.*, 035004, (2019)
[4] Alam, S., Hossain, M.S., Srinivasa, S.R. et al. Cryogenic memory technologies. Nat Electron 6, 185–198 (2023)

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Possibility of PhD thesis : yes

High efficiency STT-MRAM and stable sub-20nm storage electrode

Context

Magnetic Random Access Memory (MRAM) is a nonvolatile class of solid-state storage devices where the information is stored in the magnetic state of a ferromagnetic layer. The microelectronic industry has recently shown a strong interest for MRAM as they are very promising for embedded RAM applications and particularly embedded FLASH replacement. The storage layer building-bloc is a perpendicular anisotropy electrode of an MRAM typically a ferromagnetic layer of 1.2 nm thickness on a thin insulating tunnel barrier. This interface provides perpendicular anisotropy, enough to stabilize electrodes up to 20nm diameter. At sub-12 nm dimensions, stability can be provided by shape anisotropy of thicker 20-30nm electrodes. For intermediate diameters, the use of multiple ferromagnet-tunnel barrier interfaces can provide higher stability and high write power efficiency [1]. This solution might also prove beneficial in reducing the use of supply risk materials, such as Pt or Co, from the magnetic tunnel junction stack.
A first goal is to develop a magnetic multilayer stack with multiple ferromagnetic / insulator interfaces with high perpendicular anisotropy targeting sub-20 nm diameter nonvolatile cells. Second, confirm expected high-efficiency operation and explore high-stability configurations without supply risk materials.

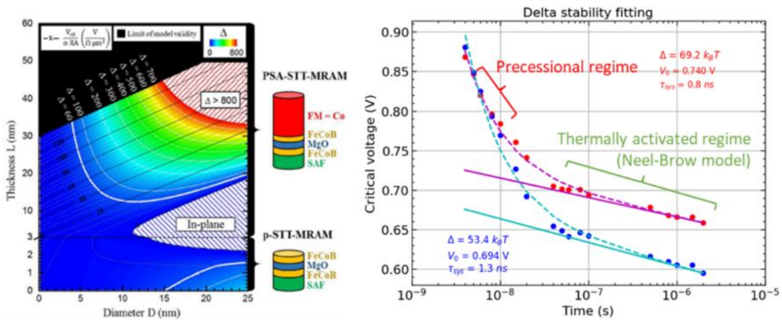

Figure 2 a) Stability diagram of a cylindrical storage layer based on interfacial and shape perpendicular anisotropy. b) Precessional and thermally activated switching.

[1] D. Sanchez Hazen et al., 'Double magnetic tunnel junctions with a switchable assistance layer for improved spin transfer torque magnetic memory performance', Nanoscale, vol. 13, no. 33, pp. 14096–14109, 2021, doi: 10.1039/D1NR01656C.

Work program & Skills acquired during internship

Typical magnetic characterization of MRAM cell stacks consists in measurements of VSM and MOKE hysteresis curves under perpendicular and in-plane field to determine the stability of each stack. These investigations rely on wedge thickness samples to establish the perpendicular and in-plane anisotropy thickness regions and their evolution with thermal annealing targeting stable solutions up to 400°C. Magnetic and electrical characterizations will be performed on nanostructured pillars to measure tunnel magnetic resistance (TMR) spin transfer torque (STT) switching voltages. Magnetic simulation codes developed at Spintec will allow understand the influence of materials, magnetic anisotropy on the magnetic stability, and their suitability for low diameter cells.

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Possibility of PhD thesis : YES

Spin transfer torque based magnetic field sensors

Context

Magnetic nonvolatile memory (MRAM) is a technology that is being developed at Spintec. MRAM cell resistance change that can be greater than 100%, and the 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 first validate the operating principle and, second, 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 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.

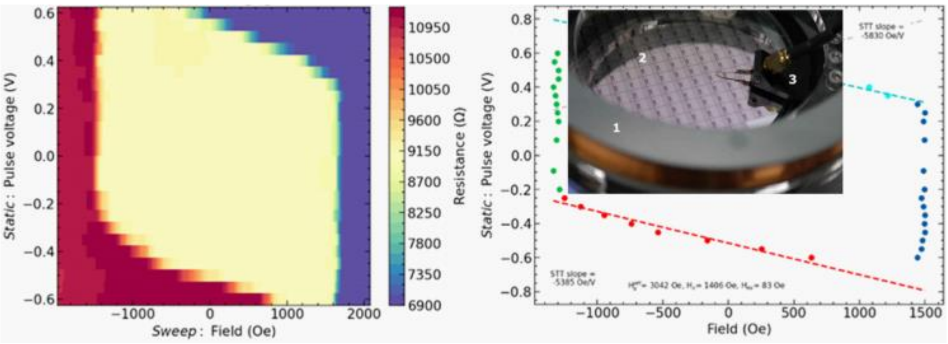

Figure 3 *Perpendicular anisotropy tunnel junction showing the variation of the resistance in state-phase diagram when applying current pulses. The boundaries of the yellow bi-stable region change linearly with applied field.*

Work program & Skills acquired during internship

Different material stacks and the size of the memory element are arranged so that the magnetization of the storage layer remains stable against thermal fluctuations while allowing for accurate sensing of the magnetic field. The physics involved is well understood, so modeling of these structures by simulation will be possible. Experiments will consist of magnetic multilayer characterization as well as fabricated device electrical properties.

Student profile: Master 2 in nanophysics/solid state physics, knowledge of instrumentation programming (Python), interest in microelectronics. It will be possible to follow a Ph.D. thesis on this subject after the internship.

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Possibility of PhD thesis : YES

Spintronic devices for efficient out-of-plane magnetic field sensing

Context

Detection and quantification of magnetic field remains highly competitive research topic both for academy and industry as well as for our everyday life. Numerous physical principles are employed to cover wide range of detectivity starting from 1 femtoTesla and reaching tens or even hundreds of Tesla. Over the last decade, spintronics became a serious contributor to this field as well. Magnetic sensors based on Tunnel Magnetoresistance (TMR), commercially available devices as for today, are considered to replace traditional Hall sensors in many applications. More yet to come with spin-transfer and spin-orbit torque devices, topological insulators and new magnetic multilayers. The purpose of the internship project is to explore various possibilities of efficient out-of-plane magnetic field sensing, build magnetic sensor model, assess the feasibility and make a prototype of device. The project will involve literature documentation, micromagnetic simulations, experimental work on thin films and nanofabricated devices. The work will be done jointly with other TMR sensor projects involving an industrial partner.

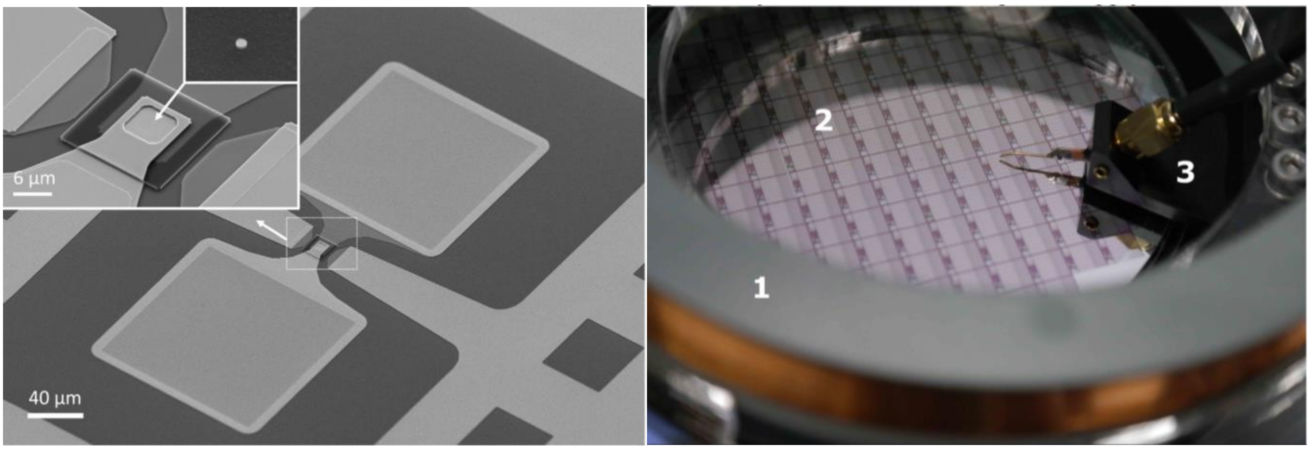

Figure 4. *(left) SEM image of TMR device on the wafer. The two large pads are connected to the top and bottom electrode of the MTJ. (right) Experimental setup for OOP sensing test (1. Helmholtz coil, 2. Wafer, 3. Probe). More information could be found elsewhere: http://dx.doi.org/10.1109/JSEN.2023.3241967 .*

Work program & Skills acquired during internship

Different material stacks and the size of the sensor elements arranged so that the magnetization of the sense layer is sensitive to the required magnetic field direction while maximizing sensing accuracy. The physics involved is well understood, so modeling of these structures by simulation will be possible. Experiments will consist of magnetic multilayer characterization as well as fabricated device electrical tests. Student profile: Master 2 in nanophysics/solid state physics, knowledge of instrumentation programming (Python), interest in microelectronics. It will be possible to follow a Ph.D. thesis on this subject after the internship.

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Possibility of PhD thesis : YES

Ferroelectric control of the spin-charge conversion

Context

The conversion of a conventional charge current into a spin current, carrying not charges but angular momentum, can be done in quantum materials using the spin-orbit coupling. We recently demonstrated in two articles (Nature & Nature Electronics [1,2]) that combined with high spin-orbit coupling elements, ferroelectrics have a natural potential to generate an electrically-switchable, highly efficient spin-charge interconversion, that can be used to develop new ferroelectric devices (cf. fig. 1).
At the cross-road between spintronics, ferroelectricity and quantum materials physics, these devices generate, manipulate and convert spin currents using electric fields, in a non-volatile way, thus without resorting to the energy-costly magnetization switching. This makes ferroelectrics good candidates for ultralow-power neuromorphic Artificial Intelligence architectures, and for post-CMOS logic devices.

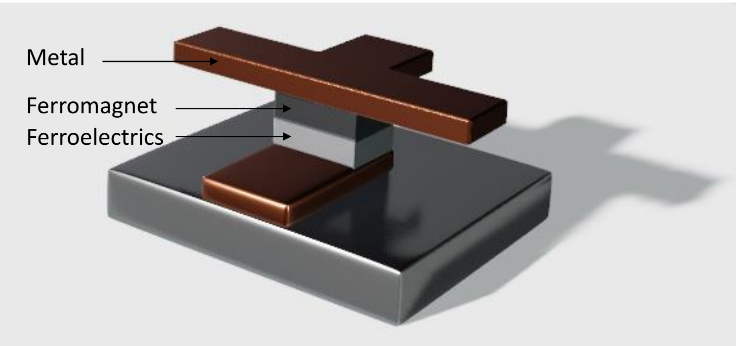

Fig. 1 : Scheme of our new ferroelectric spintronics device. The dimensions are nanometric.

Work program & Skills acquired during internship

The Internship (and possible PhD) project aims at exploring the possibilities offered by these features, in particular for the development of devices similar to the magneto-electric spin-orbit logic devices recently proposed by Intel [3]. The gate dependence of the conversion and the material characterization will be done in order to optimize the interconversion signal and the power consumption. The intern will realize the device nanofabrication in order to measure the spin-charge interconversion electrically, participate to paper writing and patent deposit. The intern will also interact with the team dealing with the electrical design and AI aspects of such devices. This 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 with the start-up Nellow, based on this technology.

[1] Noël, Attané, Vila et al., Nature 580.7804 (2020): 483-486.
[2] Varotto, Attané, Vila et al., Nature Electronics 4, 740–747 (2021)
[3] Manipatruni et al., Nature 565.7737 (2019): 35.

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Possibility of PhD thesis : YES

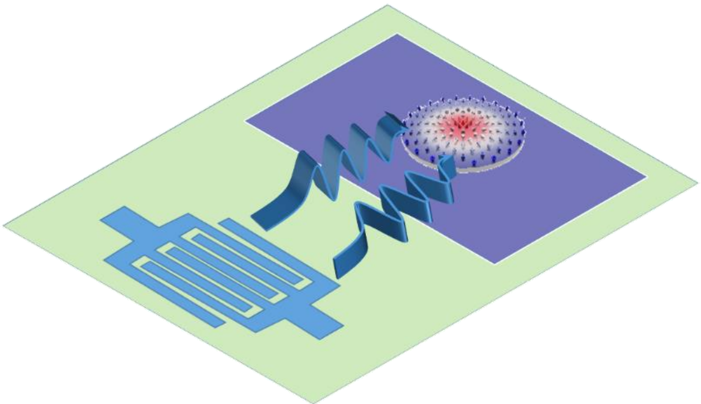
Surface acoustic waves for the manipulation of magnetic skyrmions

Context

Magnetic skyrmions in thin films are spin textures across which magnetization follows a cycloid with a unique sense of rotation, called chirality. This specific magnetic configuration can be stabilized in ferromagnetic thin films, sandwiched between films of a heavy metal and an oxide, and which presents large interfacial perpendicular magnetic anisotropy. Additionally, the lack of inversion symmetry allows an antisymmetric exchange interaction called interfacial Dzyaloshinskii-Moriya (DMI). Since skyrmions are topological solitons that can be moved by electrical current, they are currently attracting considerable interest both for the underlying physics and for their applicative potential.

Interfacial magnetic properties are essential for skyrmion stabilization and vary with the nature of the materials, but also with the presence of electric charges or ions at the interfaces with the surrounding nonmagnetic materials. Deformation of the crystal lattice and changes in interatomic distances are expected to strongly affect these magnetic parameters via magneto-elastic effects.

In the present project, we propose to take advantage of the surface acoustic waves to manipulate skyrmions, more particularly nucleate / erase them or move them. These waves propagate at sound velocity in a given direction at the surface of a piezoelectric material, when an AC electric field is applied. Such new method for skyrmion manipulation would allow taking advantage of radio-frequency remote addressing of devices based on surface acoustic waves.



Caption: Creation of a skyrmion in the magnetic stack (purple) using surface acoustic waves (blue arrows) generated by biased interdigitated tranducers (blue) on a piezoelectric substrate (green).

Work program & Skills acquired during internship

Within this experimental internship, we propose to develop the control of skyrmions by using surface acoustic waves:

- Optimization of material stacks (eg Ta/FeCoB/TaOx trilayers) on piezoelectric substrates: magnetic imaging (magneto-optical Kerr effect microscopy) to observe skyrmions, characterization of skyrmion stability variation under static strain (DC bias on the piezoelectric substrate)
- Fabrication of the transducers using micro- and nanopatterning techniques (UV or laser lithography, lift-off, ion beam etching) for injection of surface acoustic waves
- Characterization of the effect of surface acoustic waves on skyrmions

The M2 student will be integrated in a team of 6 people with daily support and weekly meetings. This project is part of a collaboration with 5 other labs in France where some experiments will be conducted.

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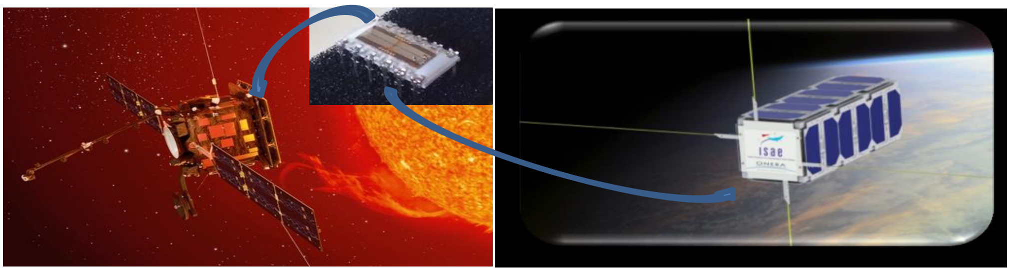
Start period: Feb/ March 2025
Possibility of PhD thesis : YES

Magnetic field sensor for space exploration

Context

Magnetic field is a key quantity in the universe and measuring it in space is essential to explore and understand our solar system. State-of-the-art magnetic sensors have an excellent resolution but are large and heavy; they are not adapted to the new tiny satellites (cubesat) that are set to revolutionize space exploration. Therefore, we are developing a miniaturized magnetic field sensor by combining a magnetic tunnel junction with a flux concentrator and we are planning to develop an on-chip modulation system. The challenge is to obtain the same performances as the present sensors with a weight reduction of a factor 100, with the objective of launching our prototype on board a satellite.

Our project combines the expertise of two laboratories on spin-electronics (SPINTEC) and on space instrumentation (LPC2E) and is supported by the national space agency (CNES). The work program is based on our previous patented achievements and recent technological developments. In this context, the objective of the internship is to optimize the performances of our flux concentrator and explore the possibility of modulating its gain. This M2-internship can be continued as PhD thesis to optimize the sensor architecture and fabricate a prototype for a space mission.



Caption: our miniaturized sensor (inset) can be launched on board a usual satellite (left) or a cubesat (right). The cubesat here is made of 3 cubes of 10 cm side length.

Work program & Skills acquired during internship

The work program includes :

- Patterning magnetic tunnel junctions in clean room using microfabrication techniques, such as photolithography, etching and deposition.
- Fabricating flux concentrator by using electrodeposition technique ; test the implementation of a piezoelectric material to modulate the flux concentrator gain
- Measuring the junction electric response with an automatic prober. The M2 student will analyze the data to extract characteristics such as sensitivity, field range and optimum working point as well as the flux concentrator gain
- Performing simulations on Comsol software to predict the gain of the flux concentrator and the efficiency of the gain modulation.

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Requested background: Master 2 solid state physics, nanophysics
Duration: 6 months
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Possibility of PhD thesis : YES

Out-of-equilibrium thermally activated magnetization reversals in magnetic tunnel junctions (theory/simulations)

Context

In recent years, magnetic tunnel junctions (MTJs) have been commercialized as part of nonvolatile memory elements, and are now envisioned as stochastic neurons for unconventional and biosinspired computing schemes.

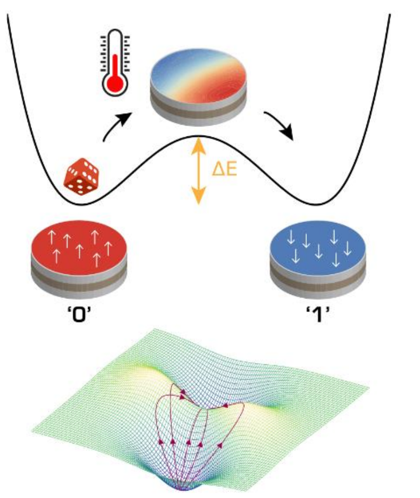

Figure 5: Top: Energy profile for magnetization reversal in an MTJ ; bottom: sketch of the multidimensional energy landscape with multiple pathways to the transition state;

MTJs exhibit two metastable states separated by an energy barrier, depending on the relative orientations of the free and fixed layers. At room temperature, thermal fluctuations can randomly flip the magnetization of the free layer, with mean dwell times which can generally be described by the Arrhenius law: $\tau = \tau_0 \, e^{\Delta E/kT}$, where ΔE is an energy barrier, kT is the thermal energy, and τ_0 is a prefactor. While it is common practice in the magnetic community to consider τ_0 a characteristic timescale of the dynamics of few nanoseconds, in reality, this prefactor also contains a large entropic contribution related to the number of pathways to the transition state [Desplat & Kim, *Phys. Rev. Lett.* **125**, 107201 (2020)].

These considerations apply at thermal equilibrium. However, to control the magnetization, non-negligible electric currents must typically be applied to these systems.

Work program & Skills acquired during internship

The aim of this internship is to go beyond the current state of the art, and compute mean dwell times in MTJs under applied currents. To achieve this, developments and simulations will be carried out in the magnum.np micromagnetics framework based on the PyTorch library [Bruckner et al., Sci. Rep. 13, 12054 (2023)]. This will be done in collaboration with the magnum.np developers in the group of Dieter Suess at the University of Vienna. During the internship, the student will:

- Familiarize themselves with key micromagnetics concepts, the Hamiltonian, the dynamics including with temperature, and basic concepts of MTJs;
- Learn the basics of computing transition rates: energy barrier computations, equilibrium prefactors, dwell time computation;
- Learn to develop python scripts to run magnum.np;
- Implement a path sampling scheme in magnum.np to compute dwell times under constant electric currents;
- If time allows: explore mean dwell times under time-dependent currents.

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Notes