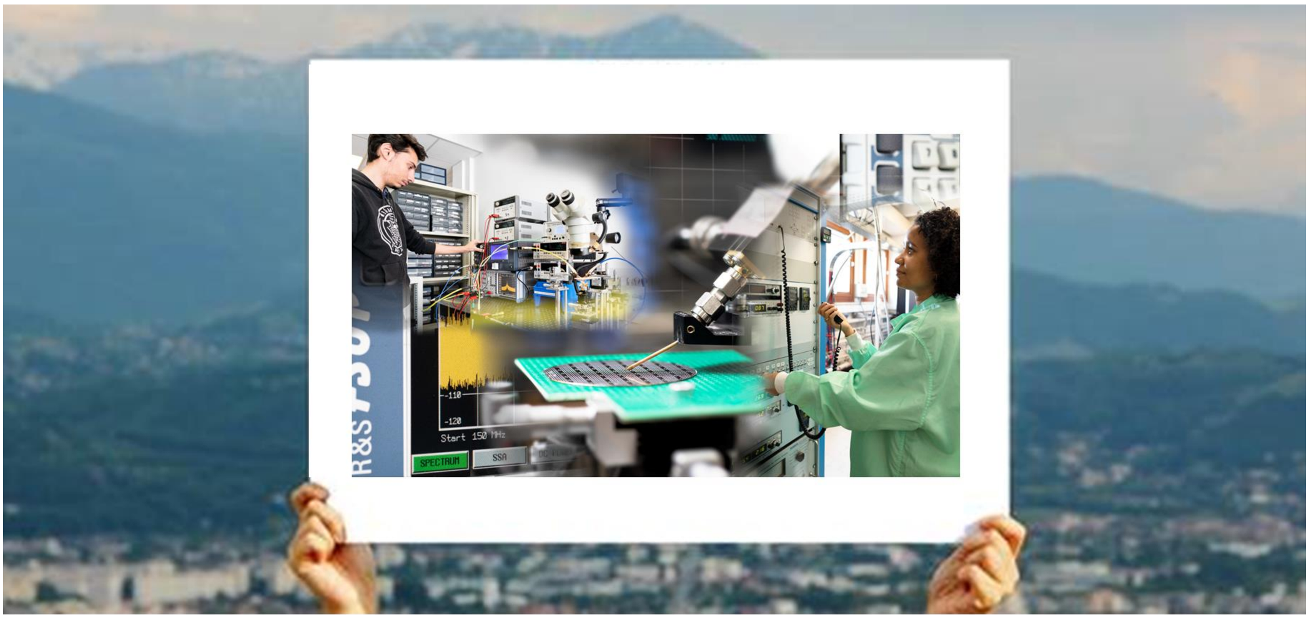
spintec

SPIN IN ELECTRONICS

SPINTRONIQUE et TECHNOLOGIE des COMPOSANTS

Master Internship Booklet

2026



Université Grenoble Alpes

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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. For more information check out our website www.spintec.fr.

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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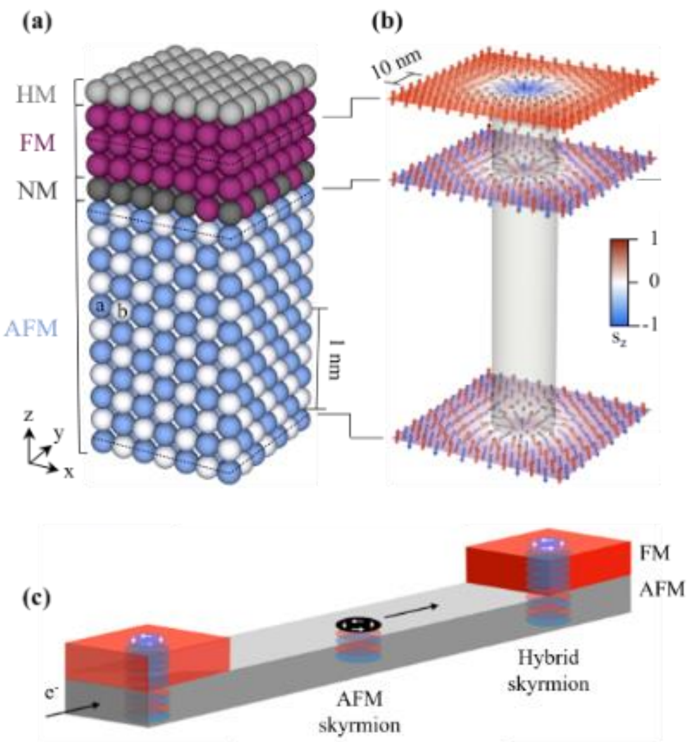
Atomistic spin dynamics modelling of novel magnetic topological objects

Context

Antiferromagnetic skyrmions, which are **novel topological objects** in magnetic materials with zero net magnetization, have attracted significant attention for their **rich spin physics** and potential as **particle-like** information carriers in **classical and quantum** spintronic technologies [1,2]. We aim to study the transfer of angular momentum between incoming electrons and antiferromagnetic skyrmions, and the resulting spin dynamics, using **atomistic models**[3]. This approach involves solving the Landau-Lifshitz-Gilbert equation. The project builds on **groundbreaking results**[4,5] from successful PhD projects, collaborating between **SPINTEC**, leaders in antiferromagnetic spintronics, and the **University of York**, pioneers in magnetic modeling and developers of a widely-used simulation code for atomistic spin dynamics.

[1]Baltz et al, Rev. Mod. Phys. 90, 015005 (2018) [2]Leiviskä et al, hal-04390931 [3]Evans et al, J. Phys.: Cond. Mat 26, 103202 (2014) [4]Thevenard et al, Phys. Rev. B 111, 224429 (2025) [5]Leiviskä et al, Phys. Rev. B 108, 184424 (2023).
All in : [*https://hal.science/*](https://hal.science/)



(a) Simulated atomic structure. (b) Overcoming the challenge of antiferromagnetic skyrmion (AFM Sk) nucleation via the imprint of predefined ferromagnetic (FM) Sks[4]. (c) Electron-current induced motion of an AFM Sk.

Work program & Skills acquired during internship

Our primary objective is to offer training and contributions in various aspects of condensed matter physics within a multidisciplinary and collaborative environment, **providing a strong start to a research career**:

(i) **atomistic modelling**
- Designing heterostructures, crystals, and tuning atomic interactions using the VAMPIRE software.
- Conducting highly parallelized simulations on calculation servers in a Unix environment.
- Post-processing and visualizing data using available software and custom Python scripts.
- Interpreting static and spin dynamic data, including their topological features.
- Presenting results to the team during weekly meetings and to the lab' during dedicated presentations.

(ii) **deep physical understanding of state-of-the-art nanomagnetism and spintronics**
Transfer of angular momentum, Topology in spin systems,
Spin-orbit physics, Antiferro- and alter-magnetism.

(iii) opportunity to follow with a PhD thesis, encompassing both modelling and experimental contributions.

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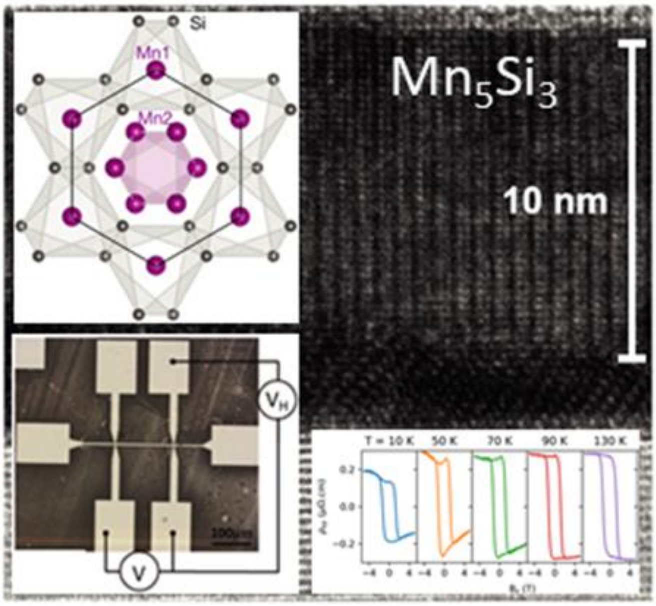
Requested background: Master 2, solid state physics, numerical simulation, good level of English
Duration: up to 6 months
Start period: Feb/ March 2026
Possibility of PhD thesis : YES

A new altermagnetic material with remarkable properties for spintronics

Context

Recent discoveries have introduced a **new class of magnetic materials called altermagnets**, which uniquely combine the advantages of both ferromagnets: spin polarization of electric currents, and antiferromagnets: robustness against magnetic fields and ultra-fast terahertz spin dynamics. Their unique properties pave the way for advancements in various fields of **quantum-based condensed matter physics**, particularly in spintronics and superconductivity. As part of an international collaboration and a result of successful PhD projects, we have experimentally **discovered one of the very first and still rare available altermagnets**: Mn_5Si_3,[1-4] opening the door to a wide field of investigation and providing us with a **strategic advantage**. To date, Mn_5Si_3 has primarily been prepared using molecular beam epitaxy, a method that produces nearly perfect films but has limitations for certain fundamental studies. We aim to establish the **growth** of Mn_5Si_3 altermagnetic layers utilizing the more versatile high-temperature sputtering co-deposition technique, and demonstrate their unrivaled **spin physics**.



Structural analysis using a transmission electron microscope, and electrical characterization performed on a Hall bar pattern fabricated in a clean room.

[1]Kounta et al., Phys. Rev. Mat. 7, 024416 (2023) [2] Reichlova et al., Nat. Commun. 15, 4961 (2024) [3] Leiviskä et al., Phys. Rev. B 109, 224430 (2024) [4] Rial et al., Phys. Rev. B 110, L220411 (2024). *All in : https://hal.science/*

Work program & Skills acquired during internship

Our primary objective is to offer training and contributions in various aspects of condensed matter physics within a multidisciplinary and collaborative environment, **providing a strong start to a research career:**

(i) **broad spectrum of experimental contributions**:

- Carry out the growth of Mn_5Si_3 thin films by high-temperature co-sputtering & post-anneal the films.
- Characterize the structural properties of the films by X-ray diffraction: crystallography, interfaces.
- Fabricate mesoscopic devices in clean room & measure spin-dependent transport properties.
- Analyze, interpret & present the results at weekly team meetings and monthly consortium meetings.

(ii) **deep physical understanding of state-of-the-art nanomagnetism and spintronics**:

Altermagnetism, Berry-curvature physics, Anomalous Hall physics

(iii) **strong collaborative environment:**

- 'Antiferromagnetic spintronics' team, in close collaboration with the 'Materials' team.
- International consortium, with partners from France, Germany, and the Czech Republic[1-4].

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Requested background: Master 2, solid state physics,
good level of English
Duration: up to 6 months
Start period: Feb/ March 2026
Possibility of PhD thesis : YES

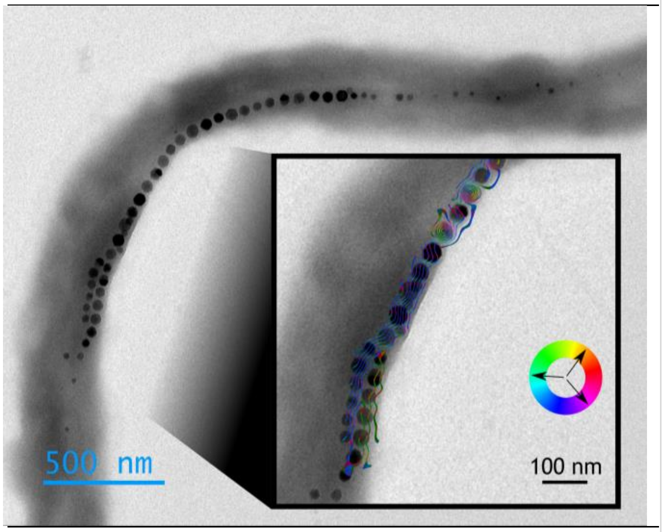
Spin textures of magnetotactic bacterias with Electron Microscopy

Context

Magnetotactic bacteria are specific microorganisms sharing the ability to intracellularly form nanoparticles called magnetosomes. These are magnetic crystals typically made of magnetite (Fe_3O_4) embedded in a phospholidic membrane. The magnetosomes are aligned in chains along the long axis of the bacteria, functioning as a compass to passively orient the cells along the magnetic field lines of the Earth.

Off-axis electron holography in the transmission electron microscope (TEM) is a powerful technique to quantitatively assess the magnetic properties of nanocrystals at the single particle level. It was used about 30 years ago to demonstrate that magnetite crystals were all single magnetic domains, and that the magnetization directions of small superparamagnetic crystals were constrained by magnetic interactions with larger crystals in the chains[1]. However, this study was performed on a very reduced amount of samples that in addition were not fully representative of the variability encountered in biological samples in general. Over the years, genetic as well as chemical techniques have been developed to experimentally modify the dimension and the organization of magnetosomes *in vivo*. There is thus now a demand of characterization of nanocrystals structure, organization and alignment to the light of their magnetic properties.

Here, we thus propose to profit from recent developments to construct a magnetic state phase diagram depicting the magnetic state (superparamagnetic vs stable single domain) depending on the particle size as well as the interparticle spacing within the chains. In addition, we aim at correlating the magnetic structure of the particles as determined with electron holography with the structure of the crystals as determined by High Resolution Transmission Electron Microscopy. In the best-case scenario, the experimental data will be compared with analytical models of superparamagnetism, which will account for size, spacing, crystal shape and crystal structure.



Example of a TEM analysis of the magnetosomes (dark dots) inside a bacteria (grey). Each magnetosome may be scrutinized thanks to TEM with its structural (here gray level only) and magnetic textures (inset : electron holography) to relate its micromagnetic behavior (vortex or mono-monodomain) to its position vs other elements.

[1] - Science **282** (1998), *1868-1870,* Magnetic microstructure of magnetotactic bacteria by electron holography
(Free version : https://www.rafaldb.com/papers/J-1998-Science-magnetotactic-bacteria.pdf)

Work program & Skills acquired during internship

The candidate will learn basic microbiological techniques and sample preparation for electron microscopy. She/He will then learn high resolution and magnetic imaging (electron holography) in a TEM as well as data treatment. She/He will develop a deep physical understanding of nanobiomagnetism providing a solid and broad basis to start a scientific research career, which we aim to be extended with a PhD project that is already funded.

The biological samples will be prepared at the University of Latvia (Riga, Latvia) in the Living Materials group (D. Faivre). Electron microscopy studies and data treatment are performed @ Grenoble PFNC – Minatec in the Spin-Textures team of Spintec (A. Masseboeuf).

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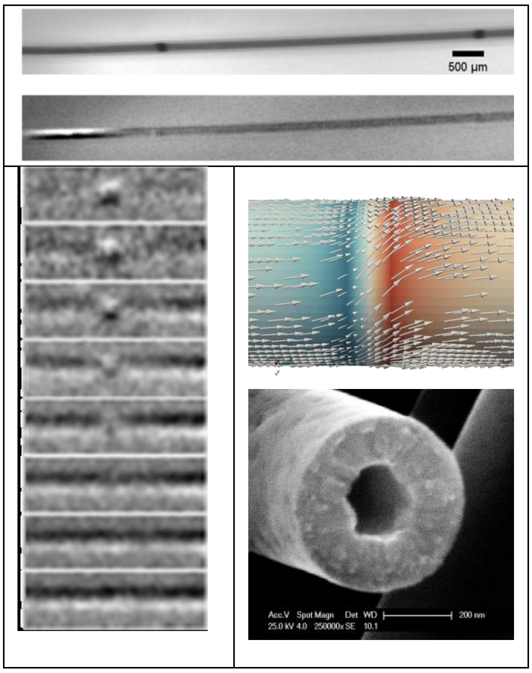
Requested background:
Biophysics / Soft Matter,
Solid-State Physics
Data (Image) Treatment
Experimentalist flavor

Experimental search for spinwave non-reciprocity in nanowires & nanotubes

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 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 are a textbook situation. This is 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**.



(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)

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 2026
Possibility of PhD thesis : YES

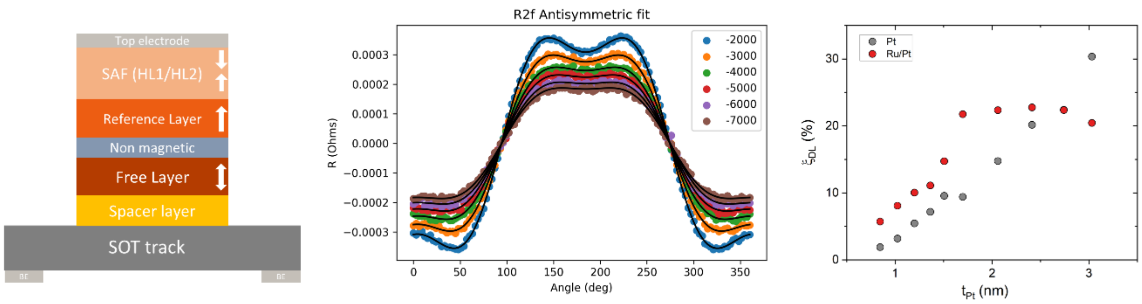
Characterization of orbital and spin-orbital torques for MRAM applications

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 via spin Hall effect (SHE)and Rashba-Edelstein effect (REE), 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. Recently, the SHE and REE have been predicted to arise from more fundamental effects [4], namely Orbital Hall effect (OHE) and Orbital Rashba-Edelstein effect (OREE). These effects feature greater magnitudes and diffusion lengths compared to the spin counterpart and they are present in a much wider class of materials, including light metals with low resistivity. Hence, they offer the possibility to integrate more efficient, and more conductive material, possibly reducing the devices power consumption.

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 exploiting novel orbital effects.



Example of spin-orbit and orbital torque characterization in SOT-based devices that will be studies in this project.

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. Fabrication of Hall bars via DUV lithography
iii. Characterize spin torques amplitudes as a function of thicknesses and material compounds
iv. 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)
[4] D. GO, et al., "Intrinsic Spin and Orbital Hall Effects from Orbital Texture", Phys. Rev. Lett. 121, 086602 (2018)

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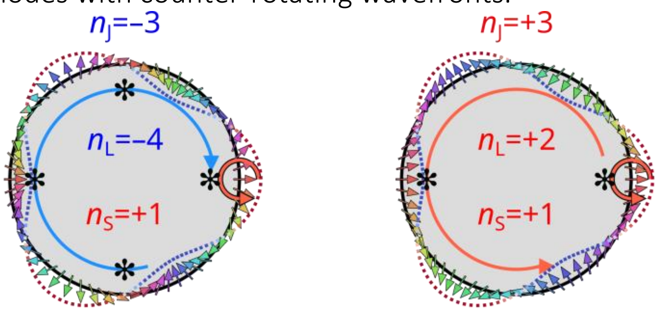
Requested background: Master 1 / Master 2
Duration: 6 months
Start period: From January 2026 to July 2026
Possibility of PhD thesis: Yes

Orbital Angular Momentum of Magnons

Context

There has been an increasing realization in recent decades of the fundamental importance of the angular momentum (AM) carried by wave fields, which can be separated into spin (SAM) and orbital (OAM) components in certain cases. The latter is a universal feature of waves in uniform continuum media represented by helical or rotational wavefronts, and can potentially encode a large amount of information for mode multiplexed communication channels or multi-level registers of quantum states. Theoretical and experimental investigations of wave AM are already well developed for electromagnetic waves, plasma waves, fluid waves or elastic waves. In recent years, experiments have found AM transfer between spin-waves (SWs) and optical vortices, or elastic waves. Most of these works, however, focused on SAM of SWs, leaving their OAM experimentally unresolved. During this internship, we propose to study the experimental evidence for non-zero magnon orbital angular momentum inside magnetic disk, by resolving the frequency splitting between magnon modes with counter-rotating wavefronts.



Caption : *Spatial snapshot patterns formed by azimuthal SW modes of index $n_J=\pm3$ propagating in a magnetic disk normally magnetized. Amplitude wise, the index $|n_J|$ counts the number of oscillations of the wavefront (see dotted line) , while $|n_L|$ counts the number of revolutions of the dynamical vector (see the repetition of the orientation at 0°). Polarity wise, each pattern uniquely links the sense of gyration of its wavefront to the direction of the local precession. By convention, a positive index indicates the Larmor direction: right-handed with respect to the magnetization so $n_J=n_L+n_S$.*

Bibliography : *T. Valet, K. Yamamoto, B. Pigeau, G. de Loubens, and O Klein*
« The Orbital Angular Momentum of Azimuthal Spin-Waves » arXiv:2503.06556
« Field Theory of Linear Spin-Waves in Finite Textured Ferromagnets » arXiv:2503.06557

Work program & Skills acquired during internship

The work program will consist of i) performing magnetic resonance experiments using a home-built spectrometer on nanolithographically prepared magnetic microdisks and ii) comparing the spectra with finite element simulations. The skills required are a basic knowledge of solid state physics and an interest in experimental developments. 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.

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Requested background: Master 2
Duration: 4-6 months
Start period: Feb/ March 2026
Possibility of PhD thesis : YES

Memristor arrays based on ferroelectric devices

Context

Memristor arrays have emerged as a promising hardware platform for neuromorphic computing [1]. By emulating the adaptive and parallel processing capabilities of synapses, memristors enable energy-efficient, in-memory computation and can support complex learning algorithms directly in hardware. This approach contrasts with traditional von Neumann architectures, which are limited by the energy and latency costs of shuttling data between memory and processing units.

In this context, ferroelectric memristors offer distinct advantages. Ferroelectric materials, which exhibit switchable polarization states, provide non-volatile memory, low power operation, and high scalability. Their ability to achieve analog resistance modulation—mimicking synaptic plasticity—makes them particularly well-suited for implementing artificial neural networks with high density, fast operation, and low energy consumption [2,3]. Additionally, ferroelectric devices can enable multi-level data storage and robust retention, further enhancing the efficiency and performance of neuromorphic systems.

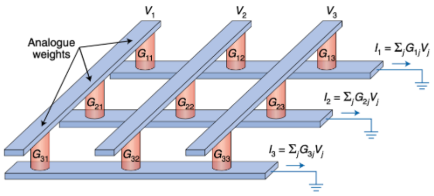

Figure 1: Schematic illustration of our ferroelectric-based memristor arrays.

At the cross-road between ferroelectricity and quantum physics and materials engineering, such devices allow to modulate very simply their resistance in a non-volatile way using electric fields, thus without resorting to energy-costly mechanisms of other currently studied memristor implementations such as magnetization switching or phase-change. This makes ferroelectric memristors very good candidates for ultralow-power neuromorphic Artificial Intelligence architectures.

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 FE-based memristor arrays. The student will characterize the basic materials properties and the memristive character of ferroelectric devices and ultimately integrate such devices into memristor arrays. The intern will be involved in the full process from the nanofabrication and electrical measurement of single devices and small memristor arrays to the writing of papers and patents. The intern will also interact regularly with other members of the team working on the design of electrical circuits and AI systems based on such devices. The project 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.

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Ferroelectric control of spin-charge interconversion

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), similar to the magneto-electric spin-orbit logic devices recently proposed by Intel [3].

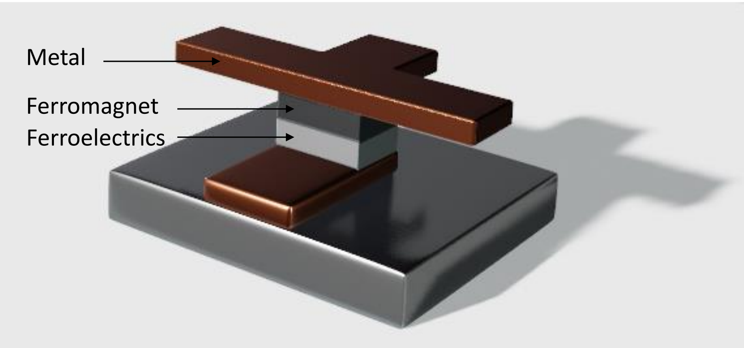

Figure 2: Schematic of our new ferroelectric spinorbitronics (FESO) device

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.

[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.

Work program & Skills acquired during internship

This experimental Internship (and possible PhD) project aims at exploring the possibilities offered by these features, in particular for the development of FESO devices and this, with various candidate material families and combinations. The material characterization and gate dependence of the conversion will be done in order to optimize the interconversion signal and the power consumption. The intern will be fully involved from the device nanofabrication (lithography and deposition tools) until the electrical measurement of spin-charge interconversion in our magneto-transport setups going from room temperature down to cryogenic temperatures (few kelvin). They will also participate to the writing of papers and filing of patents. The intern will also interact regularly with other members of the team working on the design of electrical circuits and AI systems based on such devices. The project 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. As such, the intern will thus work in a highly collaborative environment within the team and with external partners.

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Requested background: Master 2
Duration: 4-6 months
Start period: Feb/ March 2026
Possibility of PhD thesis : YES

Digital circuit design based on ferroelectric spin-orbit devices

Context

With the quick rise in energy consumption of the information and communication technology (ICT) sector expected to reach up to 15% of the total global electricity demand by 2030, giants of the microelectronics industry are actively searching for alternatives to existing technologies. New paradigms of computation beyond von Neumann and technologies beyond-CMOS such as in-memory computing and spintronic-based components seem very promising solutions to answer these challenges. We recently demonstrated in two articles (Nature & Nature Electronics [1,2] the concept and physical foundations for a new type of non-volatile device coined FESO as it is based on ferroelectrics (FE) and spin-orbitronic (SO) phenomena, that have a natural potential to generate an electrically-switchable, highly efficient signal transduction with ultra-low power switching but without resorting to energy-costly mechanisms such as magnetization switching.

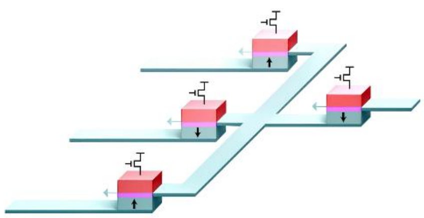

Figure 3. Schematic illustration of a majority gate based on ferroelectric spin-orbit (FESO) devices.

Such devices can be used advantageously to perform logic operations when combined (cf. fig. 1), similar to the magneto-electric spin-orbit (MESO) logic devices recently proposed by Intel [3] but in a simplified version. This makes ferroelectrics good candidates for ultralow-power post-CMOS logic devices or even for neuromorphic Artificial Intelligence architectures.

[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.

Work program & Skills acquired during internship

The Internship (and possible PhD) project aims at exploring the possibilities offered by FESO devices in particular for the development of non-volatile logic functionalities. Building on previous work in our laboratory, the student will contribute to building a library of various individual logic functions exploiting the advantages of FESO, and study how such gates can be efficiently and reliably interconnected. The intern will be involved in the full process from the low-level digital design to larger demonstrator circuit simulations and benchmarking and then to the writing of papers and patents. The intern will also interact regularly with other members of the laboratory working either on the design of electrical circuits and AI systems based on such devices, or on their experimental realization. The project will benefit from the existence of a large collective momentum in our teams towards the development and integration of ferroelectric-based devices, with ongoing ANR and EU projects, and more importantly with a valorization project with the start-up Nellow, based on this technology. The student will be working within the IC design team of SPINTEC and in strong interaction with the Topological Spintronics team and the startup.

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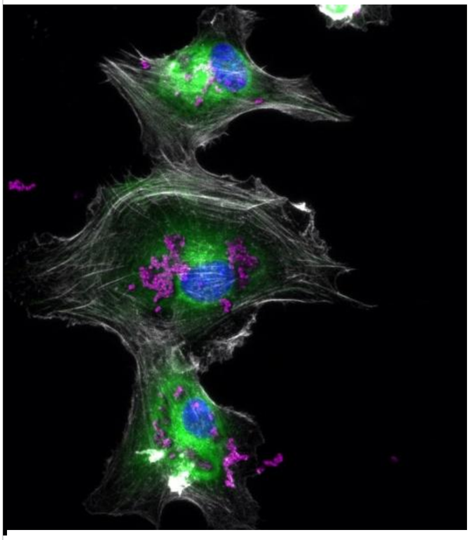
Requested background: Master 2
Duration: 4-6 months
Start period: Feb/ March 2026
Possibility of PhD thesis : YES

Selective destruction of pancreatic cancer cells by magneto-mechanical stimulation of the cells

Context

A novel approach to destroy cancer cells is under investigation in the frame of a collaboration between a biology laboratory (BIOMICS) and a magnetism laboratory (SPINTEC), both within the IRIG Institute. It makes use of magnetic particles dispersed among cancer cells. The particles are set into low frequency vibration (1-20Hz) by an applied rotating magnetic field. These vibrations induce a mechanical stress on the cells which results in various physiological reactions. The intensity of the stress can be tuned by the amplitude and frequency of the applied field and adjusted so as to trigger the cancer cells death (apoptosis). The effect has already been qualitatively demonstrated in vitro on a variety of cancer cells (glioma, pancreatic, renal) cultured in 2D in Petri dishes. Experiments were also conducted in 3D spheroids of pancreatic cancer cells (tumoroids) and for comparison on 3D spheroids of pancreatic healthy cells (organoids). The advantage of these 3D assemblies of cells is that they much better mimic the texture and organization of real biological tissues than cells cultured at 2D in a liquid. This greatly eases the transition towards in-vivo studies and minimizes the reliance on animal models. The first observations have revealed that pancreatic cancer cells have a higher affinity for the magnetic particles and are more sensitive to the mechanical stress than the pancreatic healthy cells. This actually enables to destroy the cancer cells without affecting the healthy cells. These very encouraging results need to be confirmed and statistically quantified. One of the key goal of the internship will be to determine whether or not we can demonstrate a specificity between cancer cells and healthy cells when mixed in a 3D scaffold to confirm the biomedical promise of this approach.



Glioma cells (brain cancer) loaded with magnetic particles (colored in pink). The fibers constituting the cell cytoskeleton are visible, the nucleus appear in blue, the cytoplasm in green.

Work program & Skills acquired during internship

This work is highly interdisciplinary. The intern is expected to have a transverse background in cell biology and physics in order to perform biology experiments at BIOMICS and use magnetic materials from SPINTEC, the two labs being both located within the CEA campus. The intern will use 3D cell culture systems, expose those spheroids to magnetic fields and subsequently characterize their biological responses. Biological characterization will be performed using quantitative microscopy acquisition and a methodological pipeline will have to be developed. SPINTEC will provide the magnetic particles and the sources of magnetic field required to stimulate the cells. If time allows, the intern will interact with SPINTEC for evaluation of the mechanical forces and torques exerted on the cells.

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Requested background: Master 2
Duration: 4-6 months
Start period: Feb/ March 2026
Possibility of PhD thesis : YES

Physics and functionalities of nanopillars for 3D spintronic devices

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 in microelectronics, compared with standard planar designs. New physical effects include combined surface and volume spin-transfer torques, the topology of magnetization textures, non-reciprocal magnetization dynamics etc. Prospects for applications include Perpendicular-Shape-Anisotropy magnetic random-access memories, taking the form of short vertical nanocylinders for storing information, which promise denser and more temperature-resilient memory cells. On the longer run, non-volatile and highly-dense on-chip memories based on the concept of race-track memories using domain wall moving along vertical magnetic lines has been proposed, whose development may sharply cut the on- and off-power consumption of chips.

We are addressing fundamental and technological challenges to unlock the translation of these concepts into real devices, hand-in-hand with the MRAM and Theory teams at SPINTEC. In this internship we propose to investigate experimentally individual vertical magnetic 3D nanopillars, from their synthesis to nanomagnetic and spintronic characterizations. **More will be discussed in the interview**.

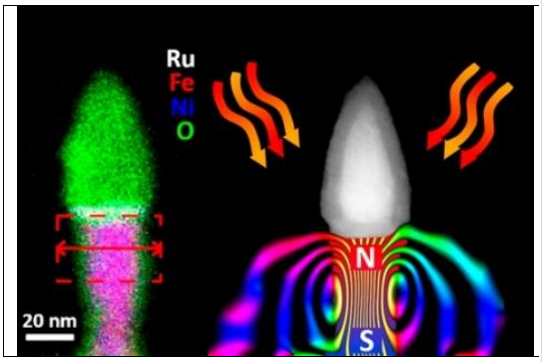

Illustration of a 3D nanopillar magnetic test element fabricated at SPINTEC, in the framework of the Perpendicular-Shape Anisotropy magnetic random access memory project. The magnetic part appears as pink on the left-hand side, while magnetic induction lines on the right-hand side allow to track the magnetic state of a single pillar. While such elements are fabricated with a top-down approach as isolated elements, the present project relies on magnetic elements mass-fabricated directly from large-scale molds, bringing both fabrication challenges and opportunities for high-quality and fully-integrated physical devices.

Work program & Skills acquired during internship

The candidate will be in charge of contributing to the synthesis of magnetic nanopillars, alongside several experts, involving clean-room nanofabrication and electroplating. A challenging step, part of the objectives, is to implement a tunneling magnetic junction atop of the nanopillar, required for the readout of its state. Characterization of the physical devices will be both magnetic (magnetometry, magnetic microscopies) and electrical (characterizing magnetic states through magneto-resistive effects, and conversely, with final goal to write individual pillars with the so-called spin-transfer effect). The work is conducted jointly with colleagues from the MRAM group at SPINTEC, CEA/LETI, and Micro/Nano-Magnetism group at 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 2026
Possibility of PhD thesis : YES

High efficiency STT-MRAM for femtosecond pulse laser writing

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-block 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.
The combination of ultra-fast demagnetization at femtosecond timescales opens the possibility of expected high-efficiency operation adding selectivity that is non-existing in present all-optical switching solutions [2].

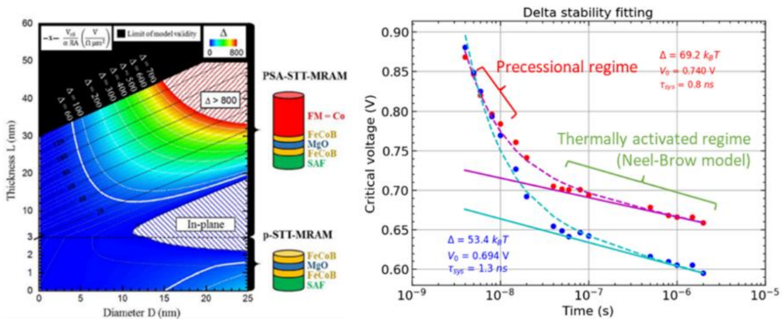

Figure 4 a) Stability diagram of a cylindrical storage layer based on interfacial and shape perpendicular anisotropy. b) Precessional and thermally activated switching.

[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.
[2] D. Salomoni et. al., Phys. Rev. Applied 2023, 20 (3), 034070, doi.org/10.1103/PhysRevApplied.20.034070.

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

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].

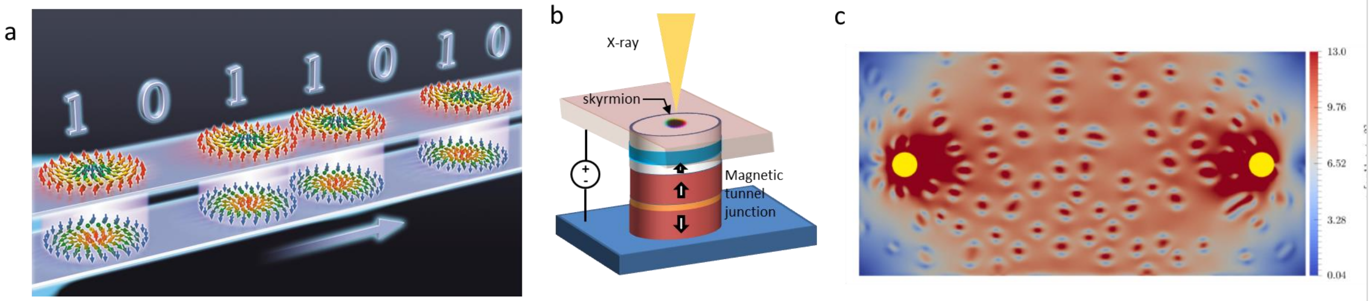

Figure 5a Antiferromagnetic skyrmions encoding the information in a racetrack [2] b skyrmion in a magnetic tunnel junction observed via scanning transmission x-ray microscopy [3]. c Proposal of skyrmion reservoir computing device [4]

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.

[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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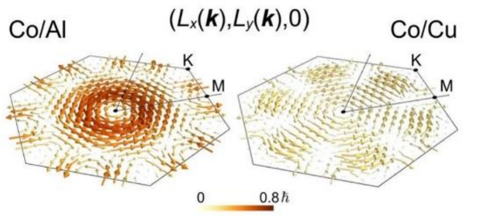
Possibility of PhD thesis : To be discussed

Orbitronic effects in heterostructures with two-dimensional materials

Context

Spin-orbitronic phenomena such as perpendicular magnetic anisotropy (PMA), Dzyaloshinskii-Moriya interaction (DMI) and spin-orbit torques (SOT) play a major role for development of industrial applications such as sensors and memory devices.[1,2,3]. Over the last decade, 2D materials such as graphene, transition metal dichalcogenides (TMDC) and associated van der Waals heterostructures including 2D magnets have become of major interest since they may serve as an efficient alternative to conventional ones (e.g., transition metals or oxides) used for development of aforementioned applications, giving rise to emergence of 2D spintronics[4,5,6]. Very recently, a new field of orbitronics has emerged that focuses on the control and use of the orbital angular momentum of electrons, in addition to or instead of their spin (as in spintronics) or charge (as in conventional electronics)[7,8].



In-plane orbital textures at the interfacial Co layer in the Brillouin zone calculated for CoAl and Co(0001 heterostructures. Arrows for the Co/Cu interface are magnified by a factor of 2 for clarity [Ref. 8].

This internship project aims at theoretical studies of orbitronic effects including Orbital Edelstein Effect (OEE) in nanostructures comprising both conventional and 2D materials, using *ab initio* calculations combined with tight-binding approach and linear response theory. In particular, by combining the OEE with its spin counterpart, i.e. Rashba-Edelstein effect (REE) that allows generating SOT to control the magnetization, the results of this work will help optimizing spintronic devices making thereby a significant contribution to the development of sustainable microelectronics.

Work program & Skills acquired during internship

The selected candidate will set up supercells combining various van der Waals 2D materials with oxides and/or metals and will primarily perform *ab initio* calculations in order to find optimal material combinations ensuring optimal values of aforementioned phenomena. The calculations will be performed on Spintec computational cluster nodes using first-principles packages based on density functional theory (DFT) combined with other simulation techniques. Results obtained will be carefully analyzed with possibility of publication in international scientific journals. Strong collaboration with labs in France (CEA/LETI, Univ. of Montpellier, Aix-Marseille Univ…) and abroad (ICN2/Spain, Zhejiang Univ. China…) is previewed.

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[1] B. Dieny and M. Chshiev, ***Rev. Mod. Phys.*** 89, 025008 (2017) [url]
[2] A. Fert, M. Chshiev, A. Thiaville and H.-X. Yang, ***J. Phys. Soc. Jpn.*** 92, 081001 (2023) [url]
[3] A. Manchon et al, ***Rev. Mod. Phys.*** 91, 035004 (2019) [url]
[4] S. Roche et al., ***2D Mater.*** 2, 030202 (2015) [url]
[5] Q. H. Wang et al, ***ACS Nano*** 16, 6960 (2022) [url]
[6] H. Yang et al, ***Nature*** 606, 663 (2022) [url]
[7] D. Jo et al, ***npj Spintronics*** 2, 19 (2024) [url]
[8] S. A. Nikolaev, M. Chshiev, F. Ibrahim et al, ***Nano Lett.*** 24, 13465 (2024) [url]

Out-of-equilibrium thermally activated magnetization reversals in magnetic tunnel junctions

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.

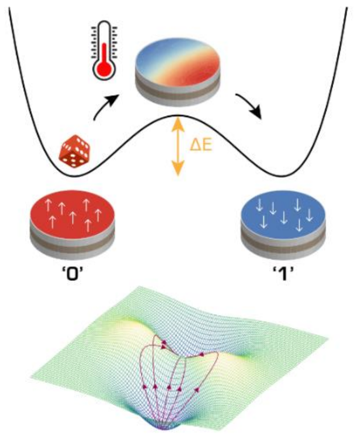

Figure 6: Top: Energy profile for magnetization reversal in an MTJ ; bottom: sketch of the multidimensional energy landscape with multiple pathways to the transition state;

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. Under negligible currents, we have successfully explained femtosecond mean dwell times measured in 50 nm perpendicularly magnetized MTJs [Soumah, Desplat, et al. *Phys. Rev. Appl.* **14,** L011002 (2025)]. However, to control the magnetization or enable interjunction coupling for computing applications, 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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Requested background: Master 2
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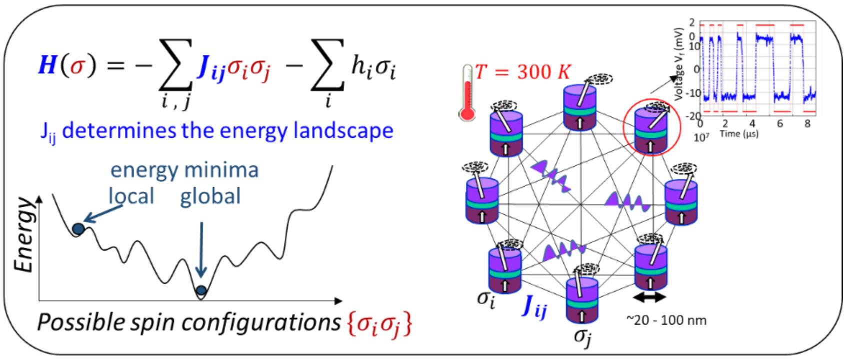
Possibility of PhD thesis : Yes

Characterization of a network of coupled spin-torque nano-oscillators for Ising-spin based analog computing

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 [2].



At SPNTEC, we recently have built such an analog computing platform based on spintorque nano-oscillators, which are magnetic tunnel junctions that use spintronics concepts to convert a DC voltage into an oscillating output signal oscillating at RF frequencies. The aim of the internship is to use this Ising-model analog computing platform to demonstrate the potential for different computing tasks: optimization, logic, or memory tasks [1]. Such implementation requires as a first step a full understanding of the coupled dynamics of spintorque oscillators that will be the focus of this internship.

Work program & Skills acquired during internship

The internship has two options to address the scientific questions: either experimental or by simulation. It will combine fundamental studies of the phase dynamics of coupled spintronics oscillators with electrical characterization of the spintronic network, needed to control the coupling strength and phase. The student will acquire expertise in (i) concepts of spintronics (spin-polarized transport, spin momentum transfer, spin-torque driven magnetization dynamics); (ii) concepts of coupled dynamical systems; (iii) concepts of unconventional computing and (iv) high-frequency measurement techniques. The work is carried out in interaction with the different members of Spintec's RF Spintronics 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 or programming;
Duration: 4-6 months
Start period: February/March 2025
Possibility of PhD thesis : YES

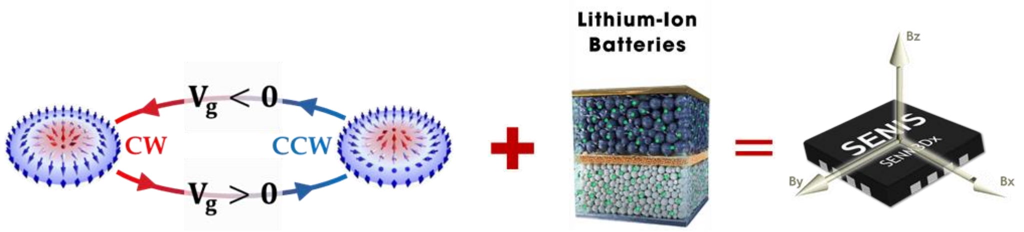
Li-ion battery technology for efficient manipulation of magnetic skyrmions

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 (PMA). 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.

In this project, we investigate β-phase tungsten (β-W) as a replacement for Ta in Ta/FeCoB/TaOx stacks popular for skyrmion based devices. With its large spin Hall angle, β-W is expected to enhance spin-orbit torque (SOT) efficiency, enabling more reliable nucleation, manipulation, and detection of skyrmions. To establish a detailed understanding of skyrmion - SOT interactions in β-W heterostructures, we will perform quantitative studies of SOT effective fields using harmonic Hall measurements.

Building on this platform, we will combine high-efficiency SOT from β-W with voltage control enabled by lithium phosphorous oxynitride (LiPON). In collaboration with CEA-LETI, which provides the required LiPON deposition and testing facilities, we will integrate a solid-state magneto-ionic layer directly into skyrmion-hosting heterostructures. Li-ion intercalation through LiPON allows reversible tuning of interfacial spin-orbit coupling and PMA, offering deterministic control over skyrmion chirality, size, and stability. This dual control approach with β-W for strong SOT actuation and LiPON for low-power ionic gating creates a versatile materials platform to engineer programmable skyrmion dynamics. This will be exploited to probe noise signatures, benchmark energy-efficient skyrmion manipulation, and ultimately develop voltage-programmable skyrmion sensors and computing devices.



Caption: Voltage-controlled reversal of skyrmion chirality (CW ↔ CCW) combined with Li-ion battery-based gating enables the development of tunable magnetic sensors.

Work program & Skills acquired during internship

Within this project, the M2 student will develop material platforms for skyrmion control by combining high-efficiency spin-orbit torques (SOT) with voltage driven magneto-ionics.

- **Optimize β-W/FeCoB/TaOx stacks** as skyrmion platforms, using Kerr microscopy to map stability and harmonic Hall/current switching to quantify SOT.
- **Integrate LiPON gating layers** in collaboration with CEA-LETI to reversibly tune anisotropy and interfacial spin–orbit coupling via Li-ion intercalation.
- **Characterize dual-control dynamics**, combining β-W SOT and LiPON gating to tune skyrmion chirality, size, and stability, with noise measurements to assess device performance.

The M2 student will be integrated into a collaborative team, benefiting from daily supervision and regular meetings, with complementary expertise provided through the partnership with CEA-LETI.

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Requested background: Master 2 physics of condensed matter, nanophysics
Duration: 6 months
Start period: Feb/ March 2026
Possibility of PhD thesis: YES

Notes