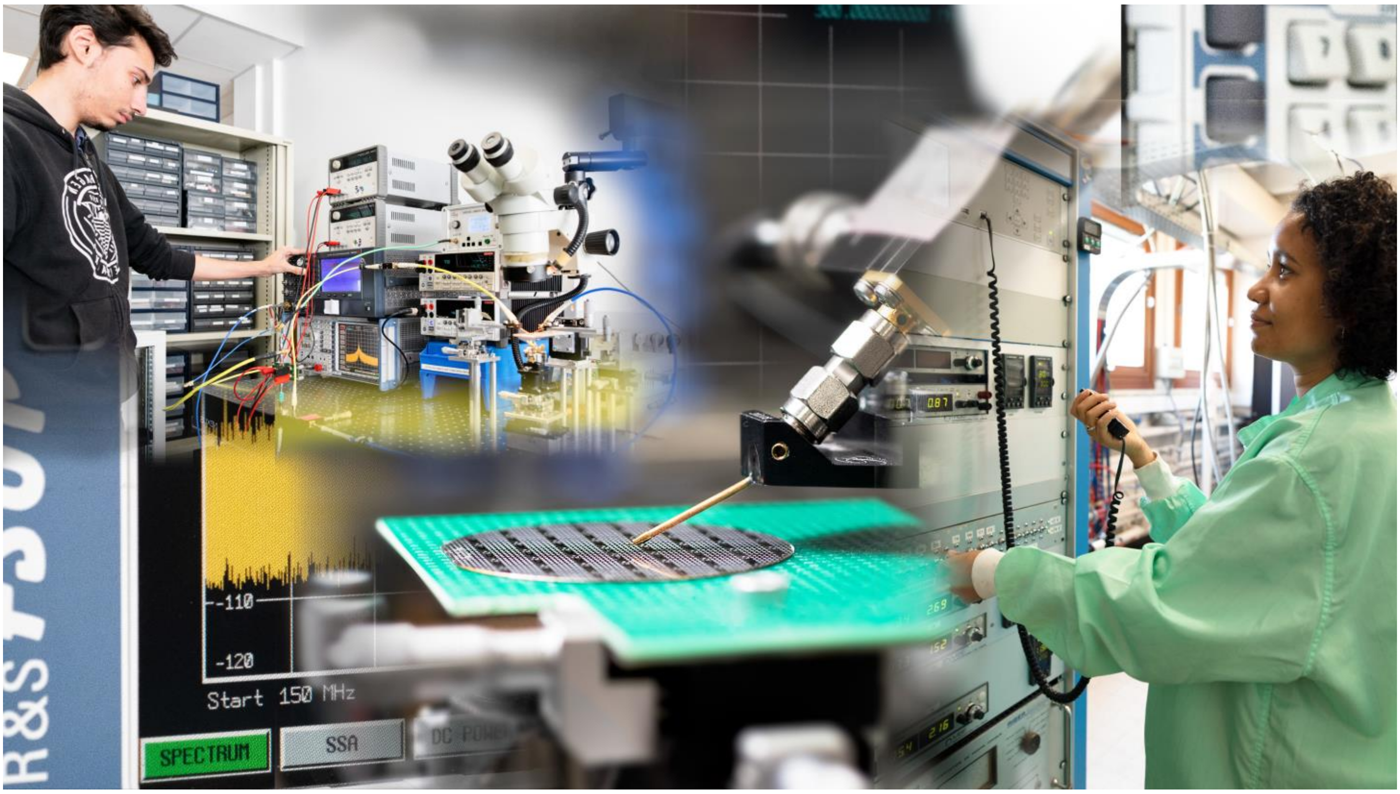
SPINTRONIQUE et TECHNOLOGIE des COMPOSANTS

Master Internships Booklet

2024



www.spintec.fr

SPINTEC IN BRIEF

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

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

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

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

SPINTEC FOR YOUR MASTER OR PHD PROJECT

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

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

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

Lucian PREJBEANU, Director / lucian.prejbeanu@cea.fr / +33(0)4 38 78 91 43
Olivier FRUCHART, Deputy Director / olivier.fruchart@cea.fr / +33(0)4 38 78 31 62

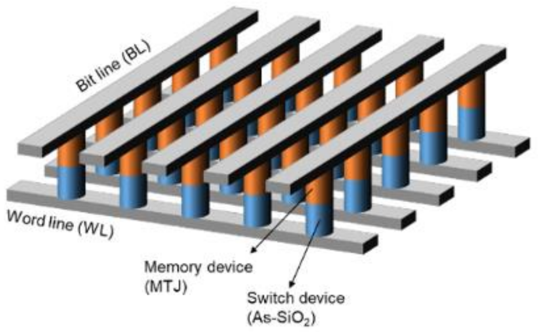
List of proposals

1. Study of emerging materials for Threshold Switching Selector for MRAM technology
2. Spin-orbit phenomena in heterostructures with two-dimensional materials
3. Design for ultralow-power memory/logic devices
4. Coupling between Spin and Orbital Angular Momentum of magnons
5. 3D modeling for spintronics
6. Spintronics-based non-volatile FPGA development for space applications
7. Spin-torque nano-oscillators for unconventional computing
8. True random number generation using spin-torque nano-oscillators
9. Arrays of coupled spintronic nano-oscillators
10. Spin waves in nanowires and nanotubes
11. Manipulation of magnetic skyrmions for neuromorphic computing
12. Spin transfer torque based magnetic field sensors
13. High efficiency STT-MRAM and stable sub-20nm storage electrode

Study of emerging materials for Threshold Switching Selector for MRAM technology

Context

The objective of this internship is to explore novel Threshold Switching Selector (TSS) materials [1] for emerging MRAM (Magnetic Random-Access Memory) technologies [2]. A selector serves as a simple two-terminal device, behaving like a switch or a diode that turns on above a certain voltage and stays off otherwise. When combined to a memory element, it prevents sneak current in non-selected memory cells, enabling denser memories. In addition, TSS aims at replacing the selection transistor and at reducing the number of vias to connect with the CMOS, thus saving power and surface area.



MRAM-based 1S1MTJ cross point array. Such architecture requires a threshold switching selector (TSS) combined to a magnetic tunnel junction (MTJ) [3].

To achieve TSS compatible with MRAM, it is critical to develop new selectors materials that match the characteristics of magnetic tunnel junction (MTJ). For example, Ovonic threshold switch (OTS) used with phase change PC-RAM (in production) has a threshold voltage larger than 2V. This voltage is too high for MTJs that must be operated below 1V to avoid degrading the MgO tunnel barrier.

In this context, the internship will study a very new attractive material that has the potential to behave like a voltage-dependent resistor at low voltage. The material is a 2D insulator where electrons can only move along the surface. It will be deposited by Atomic Layer Deposition (ALD) on 200 mm silicon wafers using the CMOS-LETI platform. Then, it will be integrated at the Upstream Technology Platform (*PTA*) in close connection with the team that is currently in charge of the MRAM nanofabrication.

Work program & Skills acquired during internship

The trainee will be in charge of the nanofabrication of the very first devices and their electrical testing. The goal is to evaluate the electrical material performances depending on the deposition conditions and process integration. This work is part of a transverse collaborative effort to evaluate MRAM as a new non-volatile memory technology between CEA/LETI and CEA-IRIG/SPINTEC. The candidate will work within the LETI memory devices laboratory in collaboration with material engineers on the 200/300mm CMOS Platform. They will also closely collaborate with recognized physicists of MRAM at SPINTEC who will provide insight in the nanofabrication and the fundamental operating principles.

Skills and training: We are looking for a highly motivated M2 candidate, proficient with materials, nanofabrication and microelectronics, with a strong interest for emerging memory technologies. Prior clean room and nanofabrication experience is an advantage. A knowledge of spintronics and magnetic devices will be appreciated, though not mandatory.

[1] *G. Molas, E. Nowak, Advances in emerging memory technologies: From data storage to artificial intelligence, Appl. Sci. 11 (23) 11254 (2021)*, [2] *B. Dieny, K. Garello et. al, Opportunities and challenges for spintronics in the microelectronics industry, Nat. Electron. 3,(8) 446–459 (2020),* [3] *S. M. Seo et al., First demonstration of full integration and characterization of $4F^2$ 1S1M cells with 45 nm of pitch and 20 nm of MTJ size, 2022 International Electron Devices Meeting (IEDM), pp. 10.1.1-10.1.4 (2022)*

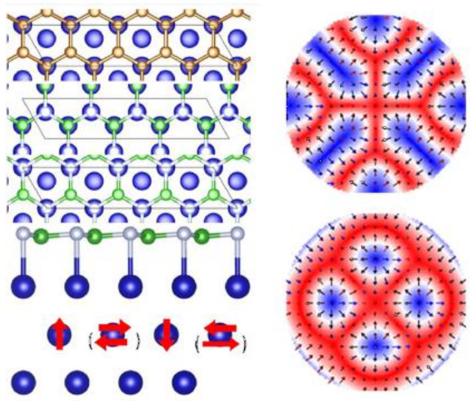
http://www.spintec.fr/
17 avenue des martyrs
38054 GRENOBLE cedex 9
Contacts : bernard.viala@cea.fr
kevin.garello@cea.fr

Requested background: Master 2
Duration: 6 months
Start period: Feb/ March 2024
Possibility of PhD thesis : YES

Spin-orbit phenomena in heterostructures with two-dimensional materials

Context

Spin electronics, or spintronics, is a rapidly expanding field of high interest for both scientists and engineers since its breakthrough research discoveries give rise to novel development of industrial applications in the fields of magnetic recording, sensors and memory devices. Spin-orbit phenomena such as perpendicular magnetic anisotropy (PMA) or Dzyaloshinskii-Moriya interaction (DMI) have become of tremendous interest since they play a major role in particular for magnetic random access memories based on spin transfer (STT-MRAM) and spin-orbit torques (SOT-MRAM) as well as emergence of spin-orbitronics [1,2]. At the same time, 2D materials such as graphene, transition metal dichalcogenides and associated van der Waals heterostructures including 2D magnets have become of major interest in recent years since they may serve as an efficient alternatives for these and next generation of spintronic devices, thus giving rise to emergence of graphene and 2D spintronics[3,4,5].



Gr/Co, h-BN(AB)/Co and h-BN(AC)/Co structures and relaxed magnetization distributions of h-BN(AC)/Co(3ML) with domains transformed into skyrmion states (From Ref. [6]).

This internship project aims on unveiling microscopic mechanisms of spin-orbit phenomena including DMI, PMA as well as spin-charge interconversion (Rashba and Rashba-Edelstein effects) in heterostructures comprising traditional materials (transition metals, oxides) and van der Waals 2D (transition metal dichalcogenides, 2D magnets, graphene…) in order to help optimizing spintronic devices. In particular, the mechanisms of their control via external stimuli (strain, external electric and magnetic fields) and possibility of inducing chiral magnetic structures such as skyrmions will be investigated [6].

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, Nanjing Univ. China…) is previewed.

[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] S. Roche et al., ***2D Mater.*** 2, 030202 (2015) [url]
[4] Q. H. Wang et al, ***ACS Nano*** 16, 6960 (2022) [url]
[5] H. Yang et al, ***Nature*** 606, 663 (2022) [url]
[6] A. Hallal et al, ***Nano Lett.*** 21, 7138 (2021) [url]

http://www.spintec.fr/
17 avenue des martyrs
38054 GRENOBLE cedex 9
Contact mair.chshiev@cea.fr

Requested background: Master 2
Duration: 6 months
Start period: Feb/ March 2024
Possibility of PhD thesis : YES

Design for ultralow-power memory/logic devices

Context

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

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

Exemple of ultralow-power device developed in our team.

Work program & Skills acquired during internship

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

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

[1] Manipatruni et al., Nature 565.7737 (2019): 35.
[2] Noël, Attané, Vila et al., Nature 580.7804 (2020): 483 ; cf. also our more recent papers on this topics : Varotto et al., Nature Elec., 4, 740 (2021). Trier et al., Nature Rev. Mat., 7, 258 (2022)

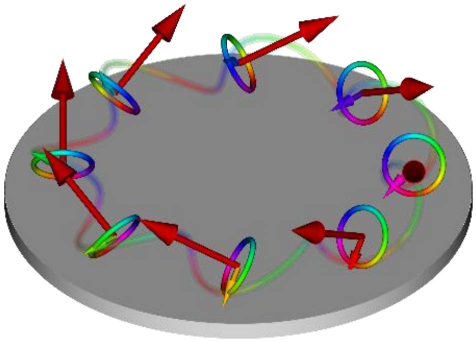
http://www.spintec.fr/ 17 avenue des martyrs 38054 GRENOBLE cedex 9 Contacts jean-philippe.attane@cea.fr laurent.vila@cea.fr	Requested background: Master 2 Duration: 6 months Start period: Feb/ March 2023 Possibility of PhD thesis : YES

Coupling between Spin and Orbital Angular Momentum of magnons

Context

The laws of conservation of angular momentum are fundamental to spintronics. They apply not only to the spin of the electron, but also to spin waves, which can carry angular momentum. Recently, we have developed a general framework for determining the spin and orbital angular momentum of spin waves. We are now interested in studying the coupling between these two components and how they might hybridize with other waveforms, such as acoustic or electromagnetic waves.

To this end, a joint European research program coordinated by the Université Grenoble-Alpes seeks to appoint a creative and motivated M2 student to participate in this effort. The position will be funded by the Horizon Europe program, which brings together leading European research groups working on the magnetization dynamics in magnetic garnet disks. The goal of the M.Sc. project will be to evaluate the spin-orbit coupling of azimuthal spin-wave modes, by visualization of the spatio-temporal profile with a NV-center microscope. The appointed candidate will be responsible for performing magnetic resonance imaging at microwave frequencies. S/he will perform the experiment, document the process, and implement the necessary steps to study and optimize the observed effect. S/he will also collaborate with other members of the consortium working on related topics in ferromagnetic resonance, simulation and Brillouin light scattering.



Work program & Skills acquired during internship

The work program will consist i) of performing magnetic resonance imaging experiments using a home-made NV-center microscope on magnetic microdisks prepared by nanolithography and ii) of comparing the spatio-temporal image with finite element simulations. The skills required are basic knowledge in 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 imaging and finite element simulations. The project will lead to a Ph.D. thesis, for which funding is already available.

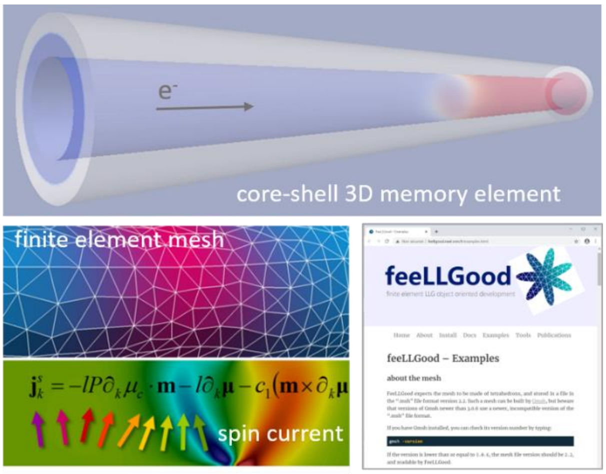
http://www.spintec.fr/
17 avenue des martyrs
38054 GRENOBLE cedex 9
Contact olivier.klein@cea.fr

Requested background: Master 2
Duration: 4-6 months
Start period: Feb/ March 2024
Possibility of PhD thesis : YES

3D modeling for spintronics

Context

Three-dimensional spintronics exploits the interaction of magnetic moments with electron spins in cylindrical objects. These 3D building blocks of nanoscale devices are fascinating objects for fundamental research as well as for data storage advanced technologies. In particular, the information stored in a single material wire or tube, should be encoded by magnetic domains separated by magnetic domain walls. In order to write information, the domain wall motion in wires may be achieved by applying spin-polarized current. Recent progress in domain wall nucleation and its control in cylindrical nanowires in our laboratory offer new challenges for theory and modeling. To simulate non-trivial 3D magnetic textures and the impact of current on its dynamics we have developed the multi-physics finite element C++ software *feeLLGood* jointly in Spintec and Néel Institute. Our open source software is permanently enlarged with new physics to accompany experimental development and is available on a dedicated website 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 frame of this internship.



feeLLGood – Examples

about the mesh

FeeLLGood expects the mesh to be made of tetrahedrons, and stored in a file in the ".msh" file format version 2.2. Such a mesh can be built by Gmsh, but beware that versions of Gmsh newer than 3.0.6 use a newer, incompatible version of the ".msh" file format.

If you have Gmsh installed, you can check its version number by typing:

```
gmsh -version
```

If the version is lower than or equal to 3.0.6, the mesh file version should be 2.2, and readable by FeeLLGood.

Key aspects of 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 explore and learn with our help different aspects of finite element modeling for spintronics starting from the numerical experiments design to the contribution to the dedicated website and interaction with experimentalists. We are looking for a motivated candidate who will help us to:

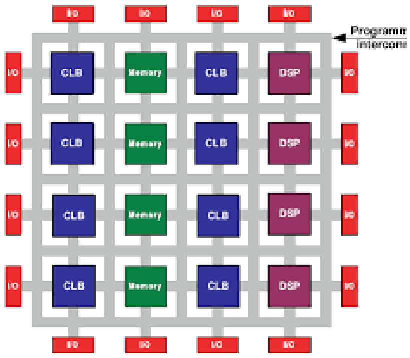
- Carry out the pre-study of typical physical structure using COMSOL software;
- Prepare non-regular finite element meshes using GMSH software;
- Drive massive simulations on the calculation server in the UNIX environment;
- Post-treat and visualize obtained data with Paraview software and home-made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

http://www.spintec.fr/ 17 avenue des martyrs 38054 GRENOBLE Cedex 9 Contacts daria.gusakova@cea.fr olivier.fruchart@cea.fr	Requested background: Master 2, affinity for numerical modeling Duration: 6 months Start period: Feb/ March 2024 Possibility of PhD thesis : YES

Spintronics-based non-volatile FPGA development for space applications

Context

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



FPGA schematic

On the other hand, **Magnetic RAM (MRAM)** memories are widely studied and developed worldwide in the electronics domain. They are intrinsically non-volatile and low sensitive to radiations. They also have the advantage to be very dense, to have a high endurance and a low power consumption compared to other non-volatile emerging memories.

The purpose of this internship is to evaluate the use of MRAM as a configuration memory for FPGAs and in particular as a way to improve/simplify the implementation of standard hardening techniques for space applications.

Work program & Skills acquired during internship

This master thesis proposes to **combine the use of MTJ into FPGA architecture** trying to improve the performance and radiation robustness and validate through electrical simulations.

During the internship, a **first bibliography phase** is necessary in order to have a clear overview of the current state of the art. Then, an **architectural design phase** will enable to propose innovative structures that will be evaluated / validated by **electrical simulations**. **Particle perturbation** will be injected to evaluate the global robustness.

This internship has **clearly the ambition to pursue in a Ph. D.** in which all these aspects will be studied exhaustively in depth, in parallel to electrical simulation model development and integration into radiation specific simulations tools for space application.

The candidate should have a **master degree or equivalent, from university or engineer school**. Skills should cover microelectronics **full-custom/circuit level design** preferably using Cadence. **Digital design notions** would be an asset. The level of **English** should allow the candidate to read and write **scientific articles**, as well as attending **technical discussions** that could be in English.

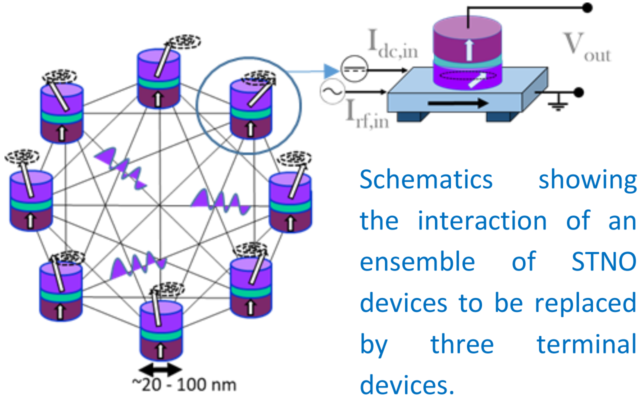
http://www.spintec.fr/
17 avenue des martyrs
38054 GRENOBLE cedex 9
Contact gregory.dipendina@cea.fr

Requested background: Master 2 – Eng. School PFE
Duration: 6 months
Start period: Feb/ March 2024
Possibility of PhD thesis : **YES** (to be confirmed)

Spin-torque nano-oscillators for unconventional computing

Context

Despite massive progress in computing algorithms, a huge drawback remains the hardware platform that carries those algorithms. Promising alternatives take inspiration from low-energy consumption computing systems such as the brain. In particular, due to the collective behavior of neurons and synapses in the brain, specific implementations exploit the phase dynamics of self-sustained oscillators.
Spintronics oscillators (or spin-torque nano-oscillators STNOs) are good candidates for such brain-inspired implementations [1]. They are based on magnetic tunnel junctions and exploit different spintronics concepts to convert an incoming DC current into a microwave signal. A defining property of these STNOs is their strong coupling of amplitude and phase, which provides a convenient and easy control mechanism to tune the frequency or to injection-lock the microwave oscillations to external signals. The aim of this internship is to develop three terminal spintronics oscillators that allow for a more convenient electrical coupling of different STNO devices, upon separating the input and output signal of the STNO (see figure). The internship is a first step in this direction and aims at optimizing the magnetic multilayer materials, leading to good signal generation properties.



Schematics showing the interaction of an ensemble of STNO devices to be replaced by three terminal devices.

[1] M. Romera, P. Talatchian et al., Vowel recognition with coupled spin-torque nano-oscillators, Nature **563**, 230-234 (2018). https://doi.org/10.1038/s41586-018-0632-y

Work program & Skills acquired during internship

This internship requires a sound background in condensed matter physics and/or in nanosciences with an emphasis on material science. In collaboration with material science engineers, the student will design and deposit the magnetic multilayers and characterize their magnetic properties by magnetometer techniques. The parameters to optimize are the interlayer exchange coupling, the perpendicular magnetic anisotropy and the charge-to-spin current conversion at the interface of the free layer. The experimental work will be accompanied by numerical simulations to guide the material choice and layer thicknesses. The student will get familiar with spintronics concepts, phenomena of non-linear magnetization dynamics, magnetometer techniques, numerical simulation tools, as well as the concepts of unconventional computing. The student will interact with the teams of RF spintronics, AI, theory/simulation, as well as the materials and nanofabrication team.
Although M2 students are targeted, M1 students are welcome to apply.

http://www.spintec.fr/
17 avenue des martyrs
38054 GRENOBLE cedex 9
Contacts ursula.ebels@cea.fr
philippe.talatchian@cea.fr

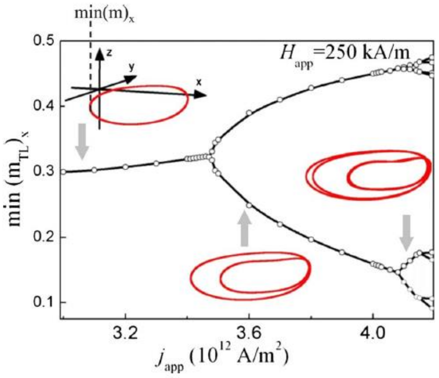
Requested background: Master 2
Duration: 4-6 months
Start period: Feb/ March 2024
Possibility of PhD thesis : YES

True random number generation using spin-torque nano-oscillators

Context

Secure communication of data within wireless sensor and wireless communication networks is an important issue. Secure communication relies on encryption of data that makes use of random number generation to define an encryption key. However, most random number generators are only pseudo-random, corresponding to numbers generated by deterministic algorithms on traditional computers that are predictable. Hence, they are prone to be decrypted by third parties. To achieve true random number generation, it is preferable to make use of physical mechanisms, such as noise and chaos that are much harder to reproduce by third parties.

This internship will investigate concepts to generate true random numbers using spin torque nano-oscillators (STNO). These are spintronic devices, based on magnetic tunnel junctions that generate microwave voltage signals upon injecting a DC current (so-called DC-to-RF converters). Here, the spin transfer torque compensates for intrinsic losses of the magnetization precession, leading to auto-oscillations of the magnetization. Upon exploiting the non-linear dynamical as well as noise properties of single and coupled auto-oscillations, stochastic and chaotic signals can be generated (see Fig. 1). This internship will explore different concepts and will use statistical test suites for randomness to check whether the STNO output signal fulfills criteria for a high-quality random number generation.



Period doubling route to chaos of a coupled magnetic layer system upon increasing the current density j_{app} through the spin-torque nano-oscillator device (D. Gusakova et al., Phys. Rev. B **79**, 104406 (2009))

Work program & Skills acquired during internship

The student will characterize the dynamic output signals of the DC-to-RF conversion of different magnetic tunnel junctions by varying external control signals. Maps will be established for the different dynamic states vs. the control parameters. The results will be compared to numerical simulations. The student will get familiar with spintronics concepts, phenomena of non-linear magnetization dynamics, high frequency measurement techniques, numerical simulation tools, as well as the concepts of true random number generation. The student will interact with the teams of RF spintronics, AI and theory/simulation.

Successful candidates should have a sound background in physics and/or nanosciences and should master programming languages (Python, C or Matlab), needed for data analysis and for interfacing experimental tools. The M2 project will lead to a PhD thesis for which funding has already been obtained by the French national research agency. Although M2 students are targeted, M1 students are welcome to apply.

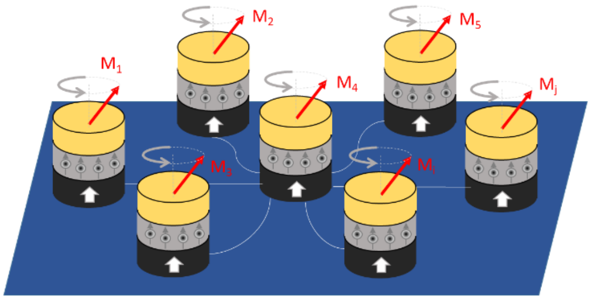
http://www.spintec.fr/
17 avenue des martyrs
38054 GRENOBLE cedex 9
Contacts ursula.ebels@cea.fr
philippe.talatchian@cea.fr

Requested background: Master 2
Duration: 4-6 months
Start period: Feb/ March 2024
Possibility of PhD thesis : YES

Arrays of coupled spintronic nano-oscillators

Context

The race for energy-efficient technologies is ongoing, and spintronics phenomena can play a decisive role in the development of suitable solutions. This master project explores the complex non-linear dynamics of spin-torque nano-oscillators (STNOs). These are nanoscale magnetic tunnel junction devices (MTJ) capable to convert a DC input signal into a microwave output-voltage signal by using the spin momentum transfer. The non-linear magnetization dynamics of an STNO is driven by spin polarized currents and its frequency is tunable by the input DC signal level. The response of a single STNO to external stimuli (dc/rf applied magnetic field and/or currents) has been intensively studied in the past [1, 2]. However, to design innovative secure communication protocols, wireless communication systems or unconventional computing paradigms, the collective dynamical states of a coupled STNO array will provide novel concepts to address the different issues [3]. This project aims to explore, through modelling, the properties of coupled STNOs as a function of their geometric layout (1D lines, 2D arrays, see the schematics from the left-side figure), taking into account various coupling mechanisms (dipolar, electrical). The outcomes of this study will guide ongoing experimental work and will impact various applications.



[1] A. Litvinenko et al. (2022) https://doi.org/10.1021/acs.nanolett.1c04031
[2] Hem et al. (2019) DOI: 10.1103/PhysRevB.100.054414
[3] Finocchio at al. (2021) https://doi.org/10.1016/j.jmmm.2020.167506

Work program & Skills acquired during internship

During the project, simulations will be carried out to study magnetization dynamics in coupled MTJ pillars. Two levels of approximation will be used, depending on the number of STNOs. Smaller arrays will be studied within the framework of micromagnetism, which will enable a finer, more precise description of the local magnetization vector distribution. On the other hand, for the sake of the computation time, large-scale networks will be treated using a macrospin model. Strong interaction with experimentalists from RF and MRAM teams are planned to feed the models with appropriate parameters and to describe adequately electrical coupling. The candidate will become familiar with state of the art concepts in spintronics and will be autonomous in performing simulations.

Applicants should have a background in nanophysics and be eager to discover the physics by modeling. The project will result in a PhD thesis project for which funding is already obtained and that will be carried out jointly with C2N (CNRS/Université Paris-Saclay).

http://www.spintec.fr/
17 avenue des martyrs
38054 GRENOBLE cedex 9
Contacts liliana.buda@cea.fr
ursula.ebels@cea.fr

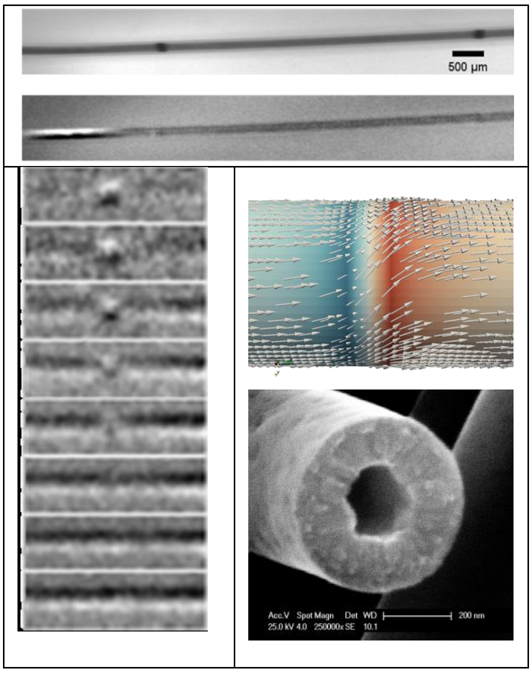
Requested background: Master 2
Duration: 6 months
Start period: Feb/ March 2024
Possibility of PhD thesis : YES (confirmed)

Spin waves in nanowires and nanotubes

Context

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

This field is the background of the Spin Textures research team of SPINTEC. We have recently developed several key systems, consisting of core-shell magnetic nanotubes and nanowires 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. The candidate will be in charge of handling core-shell nanotubes and nanowires, contact them electrically, characterize them in dc and ac electrical measurements, and use a combination of several magnetic microscopies to investigate domain-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, 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.

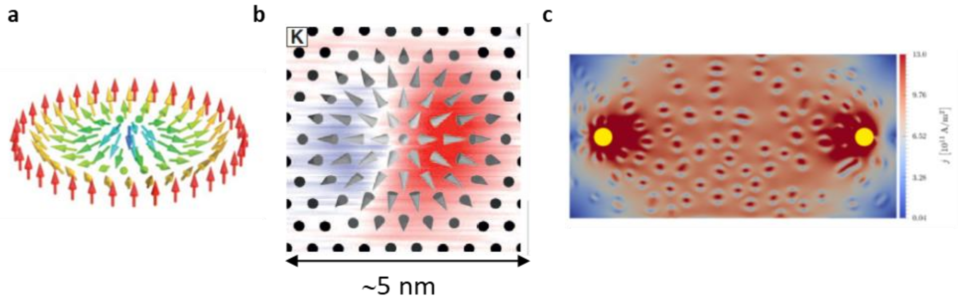
The candidate will learn nanofabrication techniques, electrical measurements and magnetic imaging, as well as a deep physical understanding of nanomagnetism and spintronics, providing a solid and broad basis to start a scientific research career, which we aim to be extended with a PhD project

https://www.spintec.fr/ 17 avenue des martyrs 38054 GRENOBLE cedex 9 Contacts olivier.fruchart@cea.fr aurelien.masseboeuf @cea.fr	Requested background: Master 2 Duration: 6 months Start period: Feb/ March 2024 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. A first step toward application was made in Spintec with the first direct observation of magnetic skyrmions at room temperature in ultra-thin Pt/Co(1nm)/MgO multilayer nanostructures [1] and the demonstration of their fast (>100 m/s) manipulation using electrical currents [2].



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

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

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

Work program & Skills acquired during internship

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

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

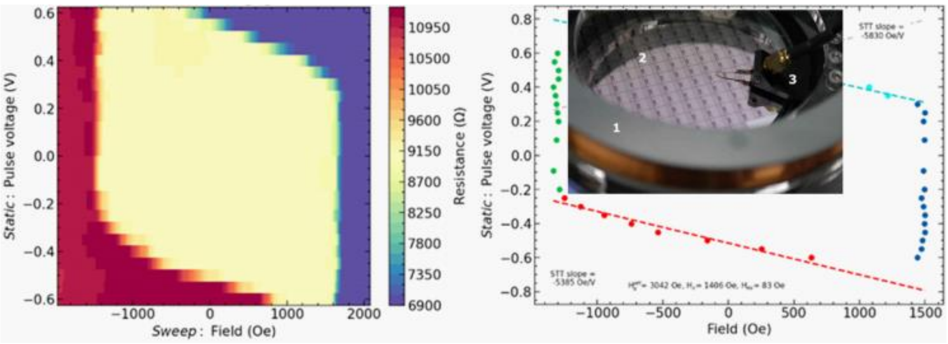
http://www.spintec.fr/
17 avenue des martyrs
38054 GRENOBLE cedex 9
Contact olivier.boulle@cea.f r

Requested background: Master 2
Duration: 6 months
Start period: beginning of 2024

Spin transfer torque based magnetic field sensors

Context

Magnetic nonvolatile memory (MRAM) is a technology being developed at Spintec. MRAM cell resistance changes 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 validate the operating principle and determine the material space parameters and how they affect the resolution of the memory in field sensor mode. We will optimize the measurement procedure to optimize it in terms of speed and sensitivity. The temperature dependence of 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.



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.

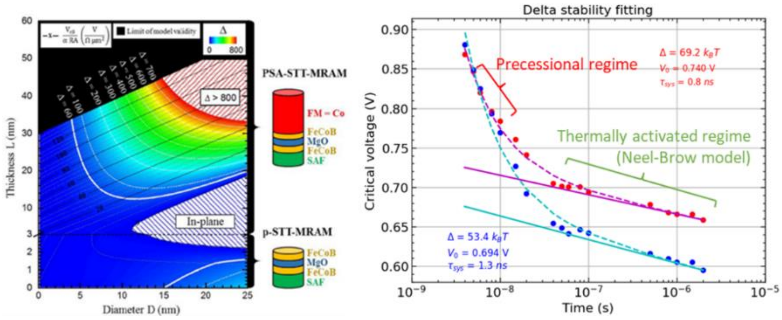
Student profile: Master 2 in nanophysics/solid state physics, knowledge of instrumentation programming (Python), interest in microelectronics. It will be possible to follow a Ph.D. thesis on this subject after the internship.

http://www.spintec.fr/ 17 avenue des martyrs 38054 GRENOBLE cedex 9 Contact : ricardo.sousa@cea.fr	Requested background: Master 2 Duration: 6 months Start period: March 2024 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-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 to reduce the use of supply risk materials, such as Pt or Co, from the magnetic tunnel junction stack.
The goal is to develop a magnetic multilayer stack with multiple ferromagnetic / insulator interfaces with high perpendicular anisotropy targeting sub-20 nm diameter non-volatile cells, and to confirm expected high-efficiency operation and explore high-stability configurations without supply risk materials.



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

[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.

http://www.spintec.fr/
17 avenue des martyrs
38054 GRENOBLE cedex 9
Contact : ricardo.sousa@cea.fr

Requested background: Master 2
Duration: 6 months
Start period: March 2024
Possibility of PhD thesis : YES