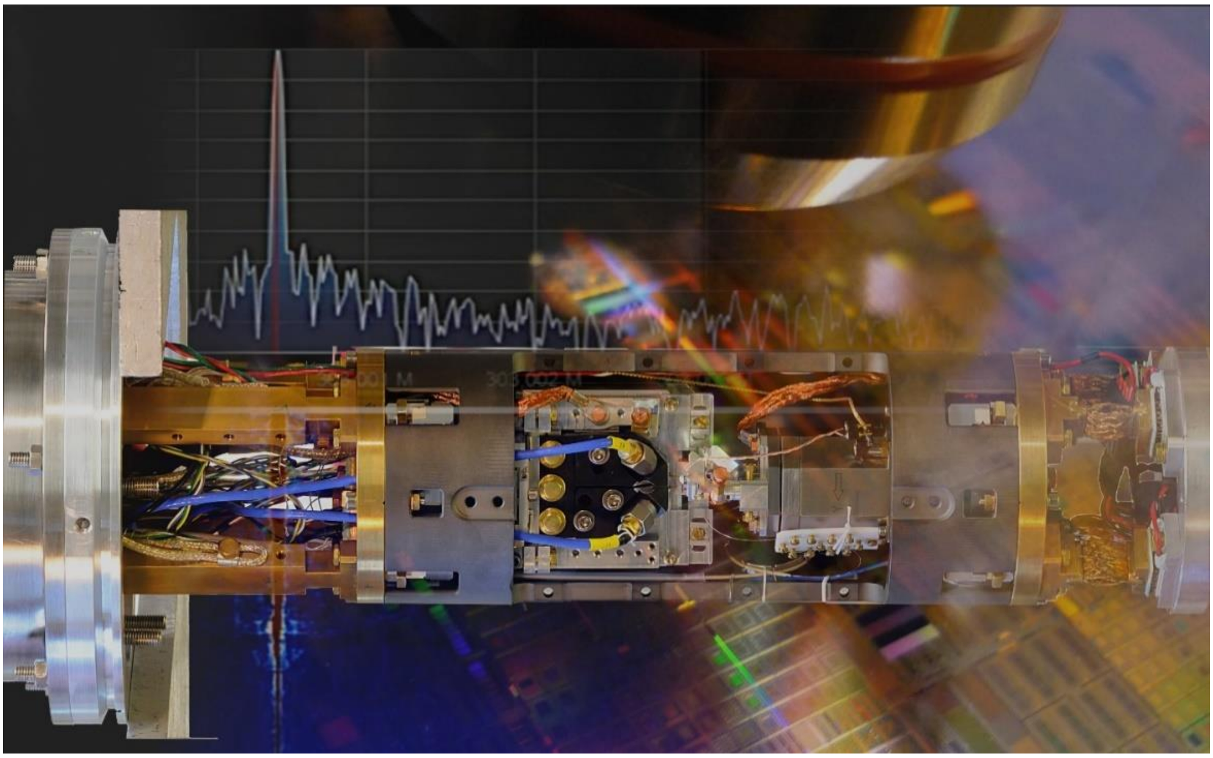
SPINTRONIQUE et TECHNOLOGIE des COMPOSANTS

Master Thesis Projects

2022



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SPINTEC IN BRIEF

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

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

SPINTEC's mission is to act as a bridge between academic research and technological applications in the field of spintronics, which is both a very rich source of new condensed-matter-magnetism physics, and recognized today as one of the major innovation routes for future microelectronics industries, sensing technology and bio-applications. As such, we are at the cross-roads of nanosciences and technology, with outputs measured by both high-rank publications and a broad portfolio of patents. SPINTEC activities are performed in collaboration with academic and industrial partners from around the world. As such, the laboratory's markers are not only scientific 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 several start-ups in the last 15 years. 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 physics concepts, 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 that provides all facilities to advance your research project and get yourself known in the academic world via participation at international conferences. Three years after defending their PhD, 90% of our students have a position in the academics or in the industry. Come and join us to be part of those who like to revolutionize condensed-matter research and unlock new microelectronics applications!

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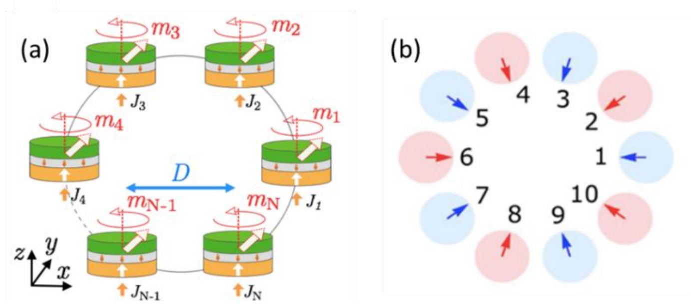
LIST OF MASTER THESIS PROJECTS

1. Development of theoretical concepts for implementing spintorque nano-oscillators in unconventional computing schemes
2. Magnetic particle dynamics in an agarose gel for biomechanics application
3. Gate voltage control of magnetic skyrmions
4. Magnetic field sensor for space exploration
5. Spintorque nano-oscillators for unconventional computing
6. MRAM for security applications: robustness and vulnerability analysis
7. Real time switching of MRAM in quantum cryo-electronics environment
8. Stable sub-20nm storage electrode with reduced supply risk materials
9. Advanced material development for spin-orbit torque MRAM applications
10. Spin-orbit torque assisted switching and field free solutions
11. Spin and heat driven magnetization reversal of magnetic tunnel junction
12. Tripartite coherent coupling between magnon-phonon-photon
13. Manipulation of magnetic skyrmions for neuromorphic computing
14. Multi-platform Image processing for Quantitative Magnetic Imaging
15. Multiphysics toolkit : from micromagnetic texture probe to predictive models
16. 3D modeling for spintronics
17. Magnetic-domain-wall motion in chemically-modulated cylindrical nanowires
18. Curvilinear magnetism and spintronics in core-shell nanotubes
19. Ferroelectric control of the spin-charge conversion

Development of theoretical concepts for implementing spintorque nano-oscillators in unconventional computing schemes

Context

Despite massive progress in computing algorithms, a huge drawback remains the hardware platform that carries those algorithms. Current computing hardware becomes more and more energy-hungry as the computing tasks become more complex. A promising alternative is to develop innovative hardware that can take inspiration from low-energy consumption computing systems such as the brain. Inspired by the collective behavior of neurons and synapses in the brain, specific implementations exploit the phase dynamics of self-sustained oscillators. **Spintronics based oscillators (called STNOs)** are promising candidates for such implementations [1]. A specific property of these STNOs is their strong coupling of amplitude and phase, which provides for frequency tuning via the injected DC current, as well as agility for locking to external signals or amongst each other. The aim of this **theoretical internship**, is to develop analytical descriptions to provide a general framework of the coupled STNO phase dynamics, considering different coupling mechanisms (electrical, dipolar interactions). These analytical descriptions will be based on common concepts developed for these STNOs [2,3] which need to be extended. In a second step, these concepts will be applied to solve a specific computational task.



Example of a coupled array of STNOs arranged on a ring structure for which different modes have been observed in numerical simulations [3].

[1] M. Romera, P. Talatchian et al., Vowel recognition with coupled spin-torque nano-oscillators, Nature, https://doi.org/10.1038/s41586-018-0632-y ; [2] J. Hem et al., Power and phase dynamics of injection-locked spin torque nano-oscillators under conservative and dissipative driving signals Phys. Rev. B 100, 054414 (2019); [3] M. A. Castro et al. Mutual Synchronization of spintorque oscillators within a ring array, arXiv:2108.04046

Work program & Skills acquired during internship

This internship (followed by a PhD) requires a very **sound background in mathematical concepts, non-linear dynamical systems**, control theory and/or neuromorphic computing. The specific task is to first determine the analytical expressions for the coupling terms considering different interaction mechanisms. In a second step different coupling topologies will be considered and then applied to a specific computing task. The student will be introduced to (i) the different concepts of spintronics (magneto-resistance, spin polarized transport, spin momentum transfer); (ii) the concepts of spin-torque driven magnetization dynamics and non-linear dynamical systems; (iii) concepts on neuromorphic computing.

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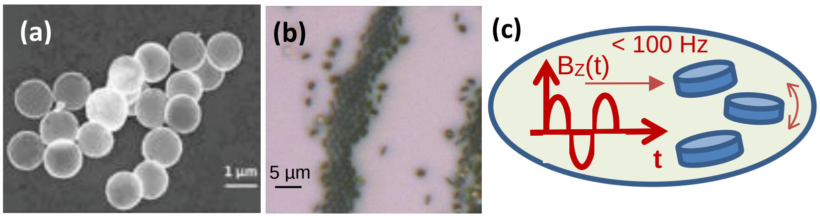
Requested background: Master 2 in applied mathematics, control theory or dynamical systems
Duration: 6 months
Start period: Feb or March 2022
Possibility of PhD thesis : YES
Proposal number : 1

Magnetic particle dynamics in an agarose gel for biomechanics application

Context

Magnetic micro- nanoparticles are widely used in biotechnology, for their ability to be remotely actuated by external magnetic field, and to interact with targeted entities of comparable sizes, such as cancer cells, bacteria, etc. In particular, a remarkable phenomenon was discovered about a decade ago, consisting in cancer cell death induction through mechanical vibrations of magnetic particles at low frequency (a few tens of Hertz), preserving neighboring healthy cells [1-2]. This purely magneto-mechanical effect - without heat production - has attracted a great deal of attention. However, this research is still at an early stage. Physical and biological aspects remain to be investigated and understood. In particular, while the dynamic behavior of magnetic particles under oscillating field has been widely investigated in a fluid (microfluidics, blood flow…) [3], it still have to be studied and quantified in media of higher viscosity mimicking organ tissue. This is important since for an effective magneto-mechanical treatment, the ability of the magnetic particles to move, rotate, or vibrate within a tumor site or in organ tissues is key.



Magnetic particles imaging.
a) SEM image of magnetic particles (Ø 1.3 µm, 60 nm-thick) from PTA, Spintec) [1]. **b)** Optical image of self-polarization of particles in a fluid (acetone) in zero magnetic field [3]. **(c)** Sketch of particles actuation [1-2], by alternating magnetic field in an agarose gel.

Work program & Skills acquired during internship

This Master 2 internship will be devoted to the study of the dynamics of magnetic particles in an agarose gel, whose density will approach that of cancerous tumors or organs such as brain.
The mechanisms of particles agglomeration, dispersion, their magnetic actuation within the agarose gel will be studied from a purely physical point of view. In the work program:

- Magnetic particles will be prepared in our clean room PTA and magnetically characterized.
- Their dynamic behavior will be studied by optical microscopy under applied field, in agarose gels of various viscosities.
- The gels will be prepared at the Biomade plateforme of SyMMES/Creab Lab.
- The study will be mainly experimental, and may include a part of magneto-mechanical modeling.

The internship will be conducted at SPINTEC, benefiting from SPINTEC's expertise in nanomagnetism and nanofabrication, in collaboration with the laboratory IRIG-SyMMES/Creab for chemistry issues, particle surface functionalization, coating, agarose gels fabrication. Contact at Creab Lab.: Yanxia Hou-Broutin.

[1] S. Leulmi et al., Triggering the apoptosis of targeted human renal cancer cells by the vibration of anisotropic magnetic particles attached to the cell membrane, Nanoscale, 2015, 7, 15904–15914
[2] C. Naud et al., Cancer treatment by magneto-mechanical effect of particles, a review, Nanoscale Adv., 2020, 2, 3632.
[3] H. Joisten et al., Self-polarization phenomenon and control of dispersion of synthetic antiferromagnetic nanoparticles for biological applications, Appl. Phys. Lett., 2010, 97, 2–4.

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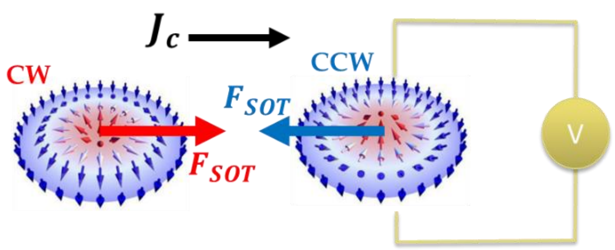
Requested background: Master 2 in nanophysics/solid state physics
Duration: 6 months
Start period: Feb/ March 2022
Possibility of PhD thesis : YES
Proposal number : 2

Gate voltage control of magnetic skyrmions

Context

Magnetic skyrmions in thin films are bubble-shaped magnetic domain with a specific spin texture : across the skyrmion, magnetization follows a cycloid with a unique sense of rotation, called chirality. This specific magnetic configuration can be stabilized in ultrathin trilayers (e.g. heavy metal/ferromagnet/oxide) with large interfacial perpendicular magnetic anisotropy (PMA). In such asymmetric systems, an antisymmetric exchange interaction called interfacial Dzyaloshinskii-Moriya (DMI) controls skyrmion chirality. Since skyrmions can be moved by electrical current, they are currently attracting considerable interest both for the underlying physics and for their applicative potential. For instance, they are envisioned as data bits for dense storage, magnetic logic operations or for neuromorphic computing. Furthermore, the possibility to tune interfacial magnetic properties by a gate voltage enables low power, versatile, local and dynamic degree of freedom that can be implemented in innovative designs.

In this context, in collaboration with Institut Néel, we have recently shown that a gate voltage allows not only switching skyrmions on and off by tuning interfacial magnetic property amplitudes (PMA and DMI), but also switching their chirality by inverting DMI sign. This breakthrough opens new possibilities for skyrmion manipulation, as a change of chirality inverts the direction of current-induced motion (see figure). It also opens new and rich physics on the dynamical and individual control of the topology of these solitons.



Spin orbit torques (SOT) induced by a current J_c create a force F_{SOT} in the direction of the current for clockwise (CW) Néel skyrmion. Application of a gate voltage may invert skyrmion chirality to counterclockwise (CCW) and lead to a motion in the opposite direction.

Work program & Skills acquired during internship

Within this experimental internship, we propose to study the motion of skyrmions under current in micrometric tracks with the goal to control their velocity and direction with a gate voltage using:

- magnetic characterization (vibrating sample magnetometer), magnetic imaging (magneto-optical Kerr effect microscopy) to characterize interfacial magnetic properties and skyrmion characteristics as a function of material type and thicknesses (typically in Ta/FeCoB/TaOx trilayers)
- microfabrication of samples using micro- and nanopatterning techniques (UV or laser lithography, atomic layer deposition, lift-off, ion beam etching) for gate voltage application and current injection
- characterization of gate voltage effect on magnetic properties and on skyrmion behaviour

The M2 student will be integrated in a team of 4-5 people with daily support and weekly meetings. This project is part of a collaboration with Néel Institute where some experiments will be conducted.

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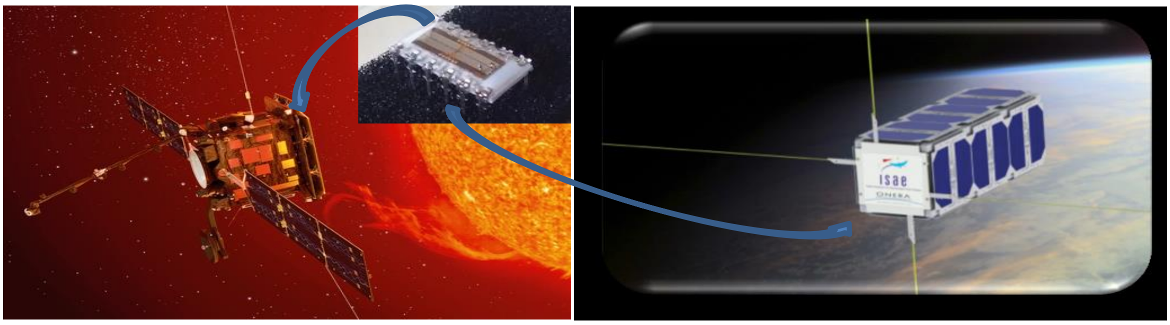
Requested background: Master 2 physics of condensed matter, nanophysics
Duration: 6 months
Start period: Feb/ March 2022
Possibility of PhD thesis : YES
Proposal number : 3

Magnetic field sensor for space exploration

Context

Magnetic field is a key quantity in the universe and measuring it in space is essential to explore and understand our solar system. State-of-the-art magnetic sensors have an excellent resolution but are large and heavy; they are not adapted to the new tiny satellites (cubesat) that are set to revolutionize space exploration. Therefore, we are developing a miniaturized magnetic field sensor by combining a magnetic tunnel junction with an on-chip modulation system. The challenge is to obtain the same performances as the present sensors with a weight reduction of a factor 100, with the objective of launching our prototype on board a satellite in 2026.

Our project combines the expertise of two laboratories on spin-electronics (SPINTEC) and on space instrumentation (LPC2E) and is supported by the national space agency (CNES). The work program is based on our previous patented achievements and recent technological developments. In this context, the objective of the internship is to optimize the signal-to-noise ratio of magnetic tunnel junctions by a proper choice of materials and geometry. This M2-internship can be continued as PhD thesis to optimize the sensor architecture and fabricate the prototype for the 2026 space mission.



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

Work program & Skills acquired during internship

The work program includes :

- Patterning magnetic tunnel junctions in clean room using microfabrication techniques, such as photolithography, etching and deposition.
- Measuring the junction electric response with an automatic prober. The M2 student will analyze the data to extract characteristics such as sensitivity, field range and optimum working point.
- Performing noise measurements on a dedicated set-up. Using this data, the M2 student will estimate the final sensor detectivity by assuming a perfectly efficient modulation.
- Performing micromagnetic simulations on the free software Mumax3 to predict the behavior of the junction under applied magnetic field for various new geometries of the junction.

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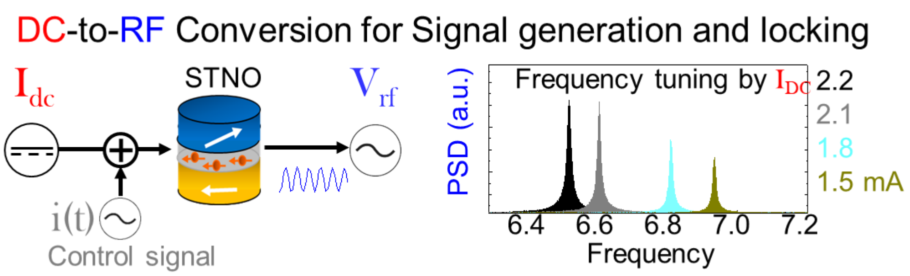
Spintorque nano-oscillators for unconventional computing

Context

Despite massive progress in computing algorithms, a huge drawback remains the hardware platform that carries those algorithms. Existing computing hardware becomes more and more energy-hungry as the computing tasks become more complex. A promising alternative is to develop innovative hardware that can take inspiration from low-energy consumption computing systems such as the brain. Inspired by the collective behavior of neurons and synapses in the brain, specific implementations exploit the phase dynamics of self-sustained oscillators. **Spintronics based oscillators** (called STNOs) are promising candidates for such implementations [1] due to their nanoscale size, frequency agility and room temperature operation. STNOs are made from the basic **spintronics building block**, a magnetic tunnel junction, that is capable of converting an incoming DC signal into a microwave output signal (see fig). Its phase dynamics can be controlled via additional rf signals [2, 3]. The aim of this **experimental internship**, is to validate novel concepts that **exploit the phase dynamics of synchronized STNOs**. Spintec is a leading laboratory for the development and characterization of such spin torque oscillators and provides all experimental facilities.



Schematics of the operation of a spintorque oscillator, where the DC current excites steady state oscillations and the control signal acts on the amplitude, frequency or phase of the microwave output signal.

[1] M. Romera, P. Talatchian et al., Vowel recognition with coupled spin-torque nano-oscillators, Nature, https://doi.org/10.1038/s41586-018-0632-y ; [2] A. Litvinenko et al., Analog and digital phase modulation of spin torque nano-oscillators, arXiv:1905.02443; [3] A. Litvinenko et al., Ultrafast Sweep-Tuned Spectrum Analyzer with Temporal Resolution Based on a Spin-Torque Nano-Oscillator, NanoLetters https://dx.doi.org/10.1021/acs.nanolett.0c02195

Work program & Skills acquired during internship

The **specific task of this experimental internship** (followed by a PhD) will be to characterize the signal generation and injection locking properties of different magnetic tunnel junction configurations, and to evaluate from the corresponding phase dynamics their potential for implementation in different computing schemes. This will be done by first studying the free running dynamics in the frequency and time domain, followed by studies under additional time varying control signals. The student will be introduced to (i) the different concepts of spintronics (magneto-resistance, spin polarized transport, spin momentum transfer); (ii) the concepts of magnetization dynamics in general and spin-torque driven dynamics and non-linear dynamical systems more specifically; (iii) concepts on neuromorphic computing. Furthermore, the student will obtain a sound training on using high frequency measurement techniques (spectrum analyzers, fast oscilloscopes, vector network analyzers) and on documenting and presenting research results. Depending on the student's interest, there is also the possibility to complement the experimental studies via numerical simulations and learn about numerical approaches.

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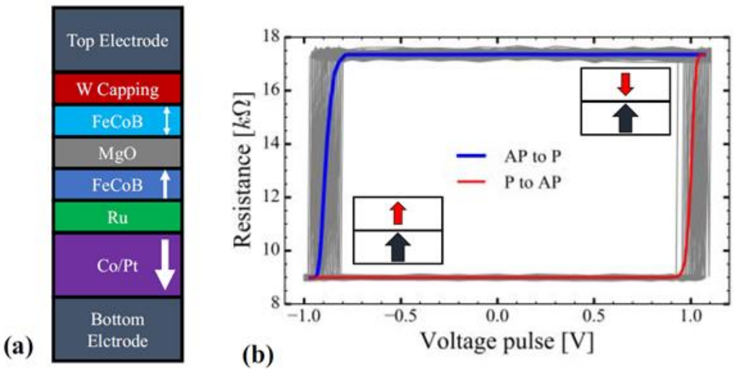
Requested background: Master 2 in nanoscience, nanophysics, nanotechnologies
Duration: 6 months
Start period: Feb or March 2022
Possibility of PhD thesis : YES
Proposal number : 5

MRAM for security applications: robustness and vulnerability analysis

Context

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



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

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

Work program & Skills acquired during internship

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

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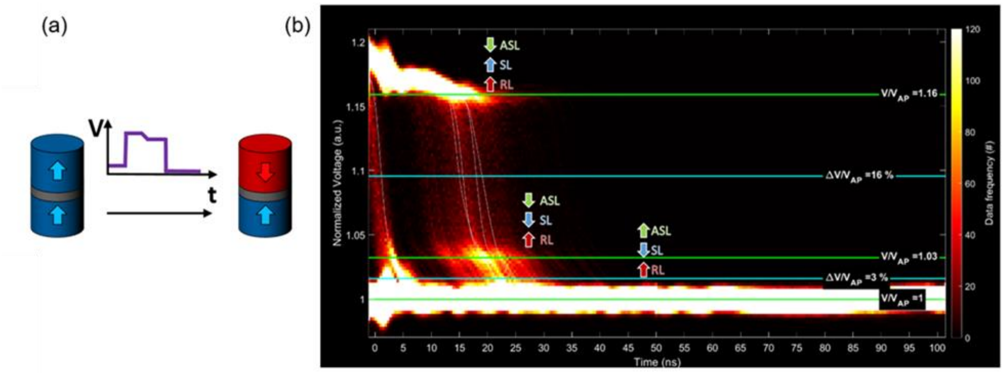
Requested background: Master 2
Duration: 6 months
Start period: Feb/ March 2022
Possibility of PhD thesis : YES
Proposal number : 6

Real time switching of MRAM in quantum cryo-electronics environment

Context

The microelectronics industry is increasingly seeking to develop components specifically optimized for low temperature operation to reduce the power consumption of electronic circuits. In this context, magnetic MRAM memories, currently under research and development, can play a significant role in cryoelectronic circuits. They combine the advantages of non-volatility, nanosecond writing speed, and endurance. Memory allows for a trade-off between retention and the energy required to change its state. At low temperature (e.g. 3K), the thermal activation is reduced by 2 orders of magnitude compared to room temperature (300K), considerably increasing the thermal stability of the storage layer magnetization. The same memory retention time should be possible with lower write currents, which requires a complete re-optimization of the memory stack composition [1].
The thesis goal is to do real time characterization of the MRAM reversal process at sub-100K temperatures to confirm expected low power operation. A second step will be to model the reversal mechanism itself.



a) Magnetization reversal in magnetic tunnel junction MRAM cell.
b) Oscilloscope real time traces of the reversal process.

[1] A. A. Timopheev et al., 'Inhomogeneous free layer in perpendicular magnetic tunnel junctions and its impact on the effective anisotropies and spin transfer torque switching efficiency', Phys. Rev. B, vol. 96, no. 1, p. 014412, Jul. 2017, doi: 10.1103/PhysRevB.96.014412.

Work program & Skills acquired during internship

Typical electrical characterization of MRAM bitcells consists in measurements of tunnel magnetic resistance (TMR) under voltage pulses resulting in spin transfer torque (STT) switching. Magnetic and electrical characterizations will be performed on nanostructured pillars. Measurements of switching currents as a function of pulse duration, statistical studies to determine the improvement in write error rates associated with the reduced stochasticity of magnetization reversal, real-time measurements to characterize the dynamics of magnetization reversal at the nanosecond scale. Magnetic simulation codes developed at Spintec will allow understand the influence of materials, magnetic anisotropy, and thermal fluctuations on magnetic stability and magnetization reversal speed and stochasticity.

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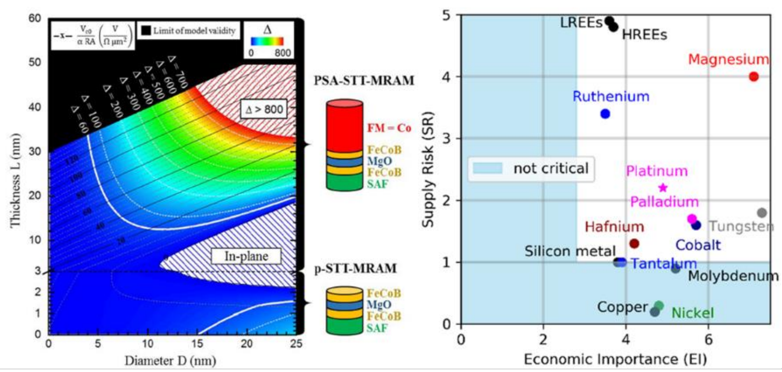
Requested background: Master 2
Duration: 6 months
Start period: Feb/ March 2022
Possibility of PhD thesis : YES
Proposal number : 7

Stable sub-20nm storage electrode with reduced supply risk materials

Context

Magnetic Random-Access Memory (MRAM) is a nonvolatile class of solid-state storage device where the information is stored in the magnetic state of a ferromagnetic layer. Microelectronic industry has recently shown a strong interest for MRAM as they are very promising for embedded RAM applications and particularly embedded FLASH replacement. The storage layer building bloc is a perpendicular anisotropy electrode of an MRAM typically a ferromagnetic layer of 1.2 nm thickness on thin insulating tunnel barrier. This interface provides perpendicular anisotropy, enough to stabilize electrodes down 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 ferrimagnet-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 thesis goal develop a magnetic multilayer stack with multiple ferromagnetic / insulator interfaces with high perpendicular anisotropy targeting sub-20 nm diameter non-volatile cells. The goal is to confirm expected high efficiency operation and explore high stability configurations without supply risk materials.



a) Stability diagram of a cylindrical storage layer based on interfacial and shape perpendicular anisotropy. b) Material criticality assessment for typical metal contained in spintronic MRAM stack.

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

Work program & Skills acquired during internship

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

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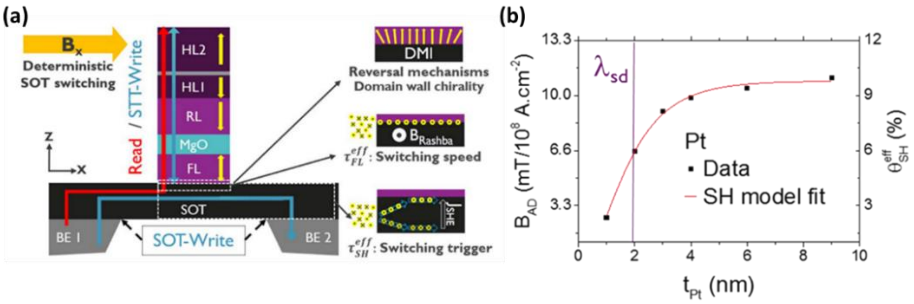
Requested background: Master 2
Duration: 6 months
Start period: Feb/ March 2022
Possibility of PhD thesis : YES
Proposal number : 8

Advanced material development for spin-orbit torque MRAM applications

Context

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



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

Work program & Skills acquired during internship

The internship thesis will consist of:

i. Growth by sputtering method of simplified SOT devices aiming at optimizing SOT efficiency and free layer properties for identifying best materials to fabricate *SOT-MTJ devices.*
ii. Nanofabrication of simplified devices (Hall bars) to characterize SOT amplitudes as a function of thicknesses and material compounds
iii. Systematic study as a function of annealing temperature in order to analyze the impact of thermal budget on SOT amplitude, free layer retention and critical switching current density.

For the characterization of deposited stack, an extensive toolset for structural, magnetic and electrical characterization is available including: XRR, XRD, VSM, MOKE, current-in-plane tunneling and SOT set-up.

The end goal of the internship is to realize 400°C-compatible SOT-MTJ stacks with perpendicular magnetic anisotropy and improved SOT write efficiency.

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

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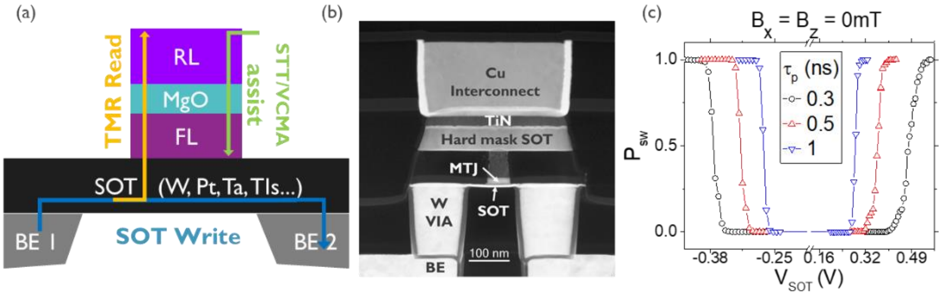
Duration: 6 months
Start period: Feb/ March 2022
Possibility of PhD thesis : conditioned to funding grants
Proposal number : 9

Spin-orbit torque assisted switching and field free solutions

Context

There is considerable interest in electrically controlling nano-magnets (Spintronics) in order to develop non-volatile magnetic memories (MRAM) [1]. Indeed, the microelectronics industry is facing major challenges related to the volatility of CMOS cache memory elements (usually SRAM and eDRAM), and MRAMs are among the most credible candidates with low power and fast enough to compete with SRAM and replace them at cache level. Most advanced MRAM devices are magnetic tunnel junctions (MTJ) that are operated by spin transfer torque (STT) effect, and nowadays commercial products using this technology for microcontroller and eFlash replacement start appearing on market. Spin-orbit torque (SOT) MRAM has emerged as a credible next-generation MRAM technology that allows for faster and more efficient magnetization writing. Manufacturability of SOT-MRAM was recently confirmed [2], showing that it is a promising solution for SRAM replacement in cache memory. However, various challenges remain to be tackled to improve its performances, such as reducing the writing current and achieving field-free deterministic switching.

We propose in this project to address these challenges by studying the interplay of SOT with other spin mechanisms such as STT and voltage control of magnetic anisotropy (VCMA) in scaled integrated devices.



a) schematic of SOT-MTJ, and possibilities to assist it with STT and VCMA effects, b) TEM Cross section of a SOT-MTJ [2], c) typically switching probability as a function of SOT voltage operated at 0 external field [2].

Work program & Skills acquired during internship

Using STT and VCMA effect are very promising approach toward low power field-free switching SOT-MRAM [3]. However, the speed and reliability limits of these approaches was poorly explored, as well as the generality of these mechanisms to any type of SOT materials and MTJ structures.

To this end, the internship thesis will consist in characterizing integrated SOT-MTJs devices on an advanced MRAM tester. We will investigate the possibility of performing low energy field-free SOT switching using STT and VCMA assistance as a function of i. device size (from 100nm to 50nm), ii. pulse width (from 0.3ns to 20ns), iii. SOT/STT voltage ratio, and MTJ magnetic configuration and composition. Building phase diagrams, we will provide a complete picture of dominant reversal mechanism and we will establish technological operation boundaries of such approach.

[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] M. Wang et al.," Field-free switching of perpendicular magnetic tunnel junction by the interplay of spin orbit and spin transfer torques", *Nat. Electron*. 1, 11, pp. 582-588 (2018)

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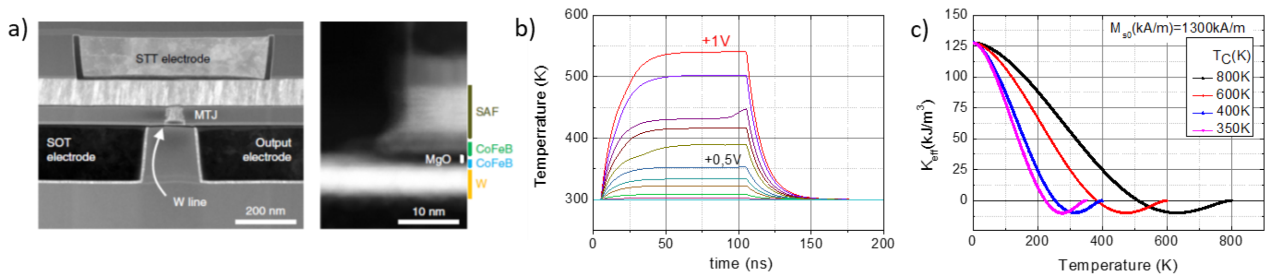
Requested background: Master 2
Duration: 6 months
Start period: Feb/ March 2022
Possibility of PhD thesis : YES
Proposal number : 10

Spin and heat driven magnetization reversal of magnetic tunnel junction

Context

The magnetic tunnel junctions (MTJ) constitute the core element of many spintronic devices *(e.g.* memories, sensors, oscillators,...)[1]. Their structure relies on an ingenious stacking of very thin ferromagnetic layers separated by non-magnetic insulator and/or conductors. Since the magnetization dynamics is mainly current driven (*e.g.* STT-spin transfer torque, SOT-spin orbit torque,...), there is an inherent heating induced by the currents flowing in the sample. This is affecting most of the sample parameters (magnetization, exchange, anisotropy) during the write, which has severe consequences such as creating switching failures (write error rate) or accelerating aging of the device.

The objective of the internship will be to evaluate the impact of the heating on the magnetization dynamics of the MTJ in the frame of micromagnetic equations coupled with the heating equation. As expected outcome, we are intending to get a complete comparison between the SOT-MRAM and STT-MRAM and confrontation with experimental field-voltage measurements.



a) TEM Cross section of a SOT-MTJ [3]. b) Typical time evolution of the temperature of the MTJ sample for different bias voltage pulses. c) Temperature-induced variation of the effective anisotropy of a CoFeB free layer depending on its Curie temperature Tc.

Work program & Skills acquired during internship

During this project, micromagnetic simulation software will be used to study the time evolution of the magnetization of thin ferromagnetic layer variable diameters, typically < 100nm [see Fig.a]. The action of an external magnetic field and spin driven torque will be investigated to identify the suitable conditions to reverse the magnetization orientation. The resulting induced Joule effect will also be simulated [Fig.b] in order to evaluate its impact on the material parameters and switching properties [Fig.c].

The project aims to perform a comparison between the STT-based and SOT-based writing schemes for the same MTJ nanopillar. Field-voltage writing diagrams will be simulated for various pulse duration. The nucleation of the magnetic domain wall will be carefully analyzed to establish the most suitable conditions that can reduce the stochasticity, detrimental to memory device performances. The parameters of the simulations will be set using input from our experimental characterization. The results of this project will guide experimental data interpretation and will be used as benchmark of our self-consistent heating-LLG model.

[1] B. Dieny et al., "Opportunities and challenges for spintronics in the microelectronics industry", *Nat. Electron*. 3, pp. 446-459 (2020)
[2] E. Grimaldi et al., *Nat. Nanotech*. **15**, 111 (2020).
[3] N. Strelkov et al. Phys. Rev. B **98**, 214410 (2018).

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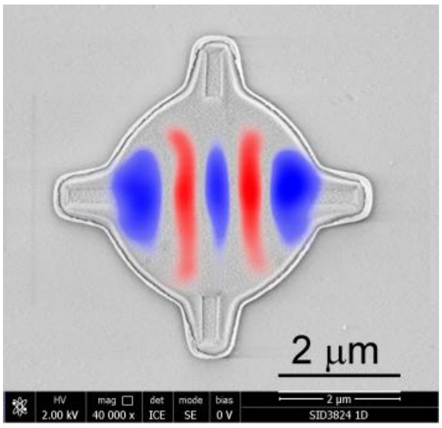
Requested background: Master 2
Duration: 6 months
Start period: Feb/ March 2022
Possibility of PhD thesis : YES
Proposal number : 11

Tripartite coherent coupling between magnon-phonon-photon

Context

The coherent transfer of information [1,2] between different waveforms is an important ingredient of quantum information processing as it allows interfacing, storage or transport of quantum states. However, an efficient hybridization process requires to reach the strong coupling regime, where the interaction rate between two collective states becomes larger than their relaxation rate. In this respect, yttrium iron garnet (YIG) holds a unique position in nature for combining the lowest possible magnetic damping, excellent acoustic attenuation (10× better than quartz, and optical transparency. YIG is thus probably the best possible coherent interlink between magnons, phonons, and both microwave and optical photons. One main difficulty that has so far hampered the development of garnet thin films for integrated solutions is that their epitaxial growth could only be achieved on gadolinium gallium garnet (GGG) substrates. However, for both photons and phonons, GGG substrates must be considered for all practical purposes a matched medium preventing in consequence the confinement of their oscillating energy within the YIG layer. To overcome this problem, recently, a new process developed by the group of G. Schmidt in Halle has allowed fabricating freestanding micron-size YIG beams with high magnon life time. These new garnet objects, which benefit from greatly reduced phononic and photonic energy leakage through the substrate, have the potential to become game-changing coherent microwave transducers exploiting their ultra-high finesse in integrated components.



SEM image of a suspended drum-like YIG resonator with an overlay of a spin wave pattern measured on the same structure by magneto-optics.

The objective of this master project will be to evaluate how these suspended structures perform as magnon-phonon-photon transducers. This will be achieved by coupling these slabs to microwave antenna or interdigited piezoelectric transducer. The project will not only try to achieve strong coupling within a microstructure. The project is designed as a collaboration between the group of Spintec and the University of Halle in Germany.

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[1] «Coherent long-range transfer of angular momentum between magnon Kittel modes by phonons» Kyongmo An, et al. Phys. Rev B 101, 060407(R) (2020)
[2] «Bright and dark states of two distant macrospins strongly coupled by phonons» Kyongmo An, et al. arXiv:2108.13272

Work program & Skills acquired during internship

The work program will consist essentially of performing magnetic resonance spectroscopy on micro-mechanical device prepared by nano-lithography. The skills learnt are microwave technology, magnetization dynamics and data acquisition on homemade setups. The project will give rise to a thesis proposal for which a funding is already available.

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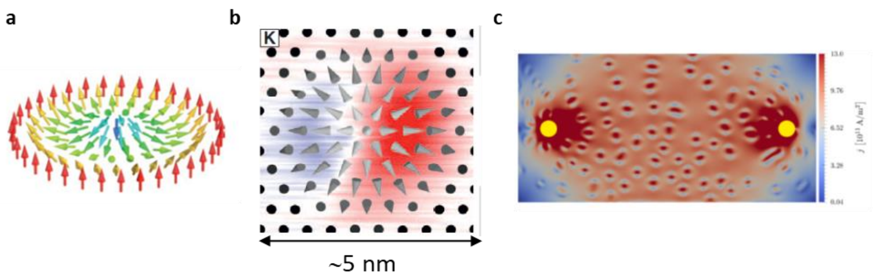
Duration: 3-6 months
Start period: Feb/ March 2022
Possibility of PhD thesis : YES
Proposal number : 12

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.(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 based on standard CMOS architectures.

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.

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).

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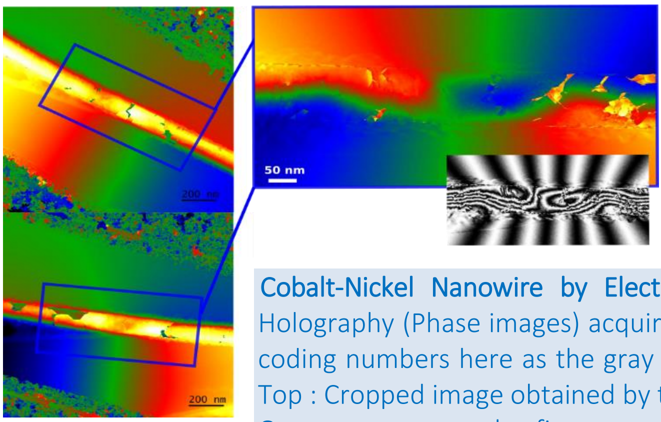
Possibility of PhD thesis : YES
Proposal number : 13

Multi-platform Image processing for Quantitative Magnetic Imaging

Context

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



Cobalt-Nickel Nanowire by Electron Holography. Left : two acquisitions with Electron Holography (Phase images) acquired before and after a reversal of the sample. The color are coding numbers here as the gray level but using a temperature level (from Yellow to Blue). Top : Cropped image obtained by the exact subtraction of the two blue area in original image. One can now see the fine structure of the magnetic domain wall that can be highlighted showing only iso-phase variations (B&W image in the inset)

Work program & Skills acquired during internship

This Master 2 internship will be devoted to experimental image processing using a Python ecosystem developed in the electron microscopy platform.

Various tasks will be devoted at first to the student :

- **hdf5** handling (automatic generation, reading & sorting) for various magnetic images sources
- **image registration** procedures in multiple steps (automatic & manual steps)
- open-access data with **Jupyter notebook** data treatment : from raw image to physical data
- Implementation (translation or adaptation) of magnetic imaging libraries

The main activity will then be dedicated to physical studies using **correlative microsopies** (association of various techniques on same single object) by taking part to experimental acquisition of data (either in front of or remotely) of TEM (Electron holography) and STXM+Ptychography at synchrotrons, and moreover to handle a cross-talking in-between experimental images & micromagnetic models.

Candidate will gain various research skills such as: **image processing**, **electron** microscopy, transmission **x-ray** microscopy, team work, **micromagnetism**, advanced python programming.

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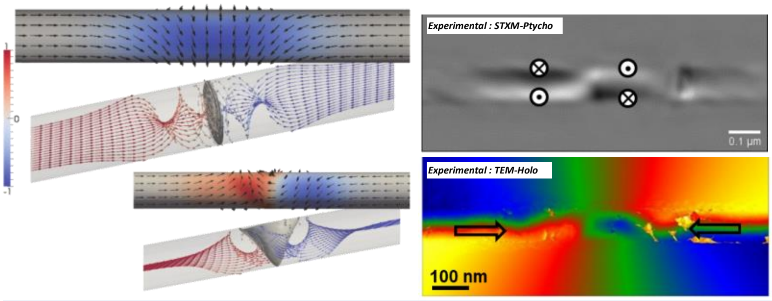
Requested background: **Python skills** - Master 2 in nanophysics/solid state physics
Duration: 6 months
Start period: Feb/ March 2022
Possibility of PhD thesis : YES
Proposal number : 14

Multiphysics toolkit : from micromagnetic texture probe to predictive models

Context

The field of Spintronics exploits the interaction between the spin of itinerant electrons and magnetic textures, for data storage applications and nanoscale logical devices. Recently, this development benefited from advances in theoretical modeling as well as from magnetic textures imaging techniques. Nowadays the minimum requirement for the spintronics modeling tools is to be versatile, predictive and to deal with any complex shape geometry. From the other hand, the progress in the advanced instrumentation for the imagining techniques allowed the scientific community to reach high resolution (nanometric) and high sensitivity (see Fig.). Unfortunately, both developments, sophisticated theoretical tools and costly experimental instruments, do not benefit efficiently from each other. Up to day, there is no accurate and direct comparison between magnetization textures obtained experimentally and numerically. Indirect comparison between averaged quantities, using for example domain wall dynamics as a probe, is largely not satisfying to make a quantitative breakthrough in fundamental aspects as well as in low consuming device development. In this context, our ambition is to create a dedicated multi-physics virtual platform, which will unify purely theoretical modeling tools (such as micromagnetics, spin dependent transport) and post-treatment as well as in-line tools for experimental imaging (electron, x-ray or near field probes). In simple words, we aim at developing a **numerical twin** that could discuss with its experimental brothers, merging initial theoretical concept with relevant physical ingredients and experimental observation.



3D micromagnetic modelling (left) of a domain wall in a nanowire is a key tool for understanding the physic as well as experimental parameters that drive micromagnetic object that we want to address. Reciprocally, STXM & TEM magnetic images (right) are

Work program & Skills acquired during internship

This Master 2 training is dedicated to a student who want to deepen its understanding of nanomagnetism by modeling the physic that is driving the dynamic of magnetic structures, aiming at modifying the concept of magnetic storage and logic in a strong relationship with up-to-date experiments in magnetic imaging. Achieving this will requires the student to work closely with two teams of Spintec, namely the **Theory** group and the **Spin-textures** groups.

- Translation of numerical models in magnetic images
- Human-machine interface for direct observation of models in front of experiment
- Advanced experimental data processing and methodology for sensitivity enhancement

Candidate will gain various research skills such as : numerical modeling, advanced magnetic imaging (**electron holography** & **x-ray microscopy**), team work and multi-scale analysis.

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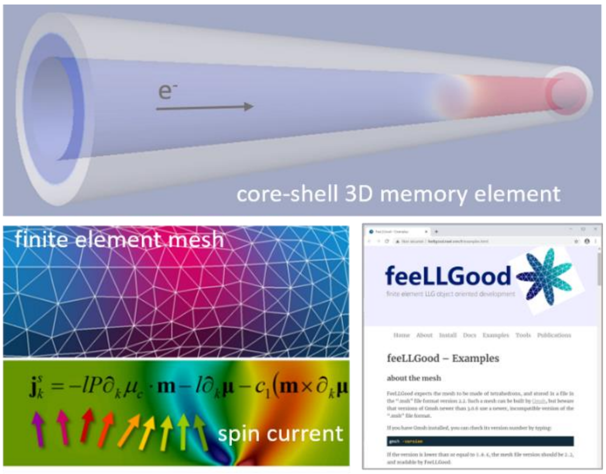
Requested background: Master 2 in nanophysics/solid state physics
Duration: 6 months
Start period: Feb/ March 2022
Possibility of PhD thesis : YES
Proposal number : 15

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, could 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.



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 would contribute to:

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

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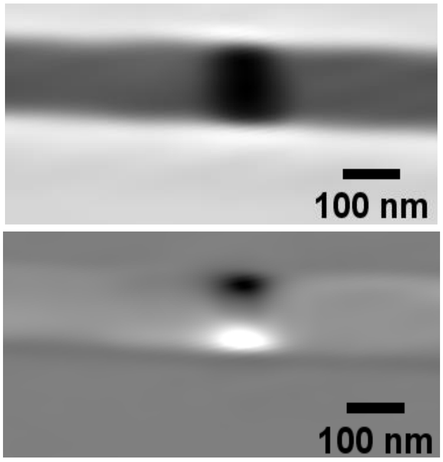
Requested background: Master 2, affinity for numerical modeling
Duration: 6 months
Start period: Feb/ March 2022
Possibility of PhD thesis : YES
Proposal number : 16

Magnetic-domain-wall motion in chemically-modulated cylindrical nanowires

Context

The ability to excite magnetization with a spin-polarized current was predicted, and soon confirmed, twenty years after the discovery of magnetoresistance. This signed the birth of the second generation of spintronics, rich with new condensed-matter physics, and enhancing its technological relevance. Among all resulting new phenomena, **current-driven magnetic-domain-wall motion brings particularly challenging physics**, owing to the large number of degrees of freedom involved. While most experiments so far have been conducted on planar strips fabricated by thin-film and clean-room technology, **cylindrical magnetic nanowires have been outline by theory as presenting specific features**, owing to their three-dimensional and rotational invariant nature. Due to this, cylindrical nanowires should host a unique type of domain wall, coined Bloch-point domain wall owing to the occurrence of a ferromagnetic singularity at its very center. Such walls have been predicted to reach stable velocities over 1 km/s, avoiding instabilities found in planar structures, known as Walker breakdown. Besides their interest for **multiscale condensed-matter physics** ranging from tens of nanometers for domain walls, down to the atom for the Bloch point, such objects have been proposed as the key building block in a **disruptive concept of memory**, implementing three-dimensional domain-wall based data storage.

We are actively working on this topic with a mostly academic focus, in a **tight experimental and theoretical effort**. We have been pioneering experimental results, thanks to the combination of advanced expertise in nanofabrication, electric measurements and magnetic microscopy. Among others, we have been first to confirm the existence of the Bloch-point domain wall, and its motion under spin-polarized current, reaching several hundreds of meters per second. To move forward beyond our initial demonstrations, we are now designing, fabricating and investigating cylindrical nanowires, whose **chemical composition can be adjusted along the wire axis**. The purpose is to provide control over the domain-wall position and pinning. This shall be useful for **setting up new experiments such as pump-probe magnetic imaging** to scrutinize in real time domain-wall motion, as well as move **one step further towards the applicability** of such systems, for which the control of the domain-wall position is obviously a requirement.



Chemical (top) and magnetic (bottom) images of a chemically-modulated cylindrical nanowire, revealing a curling of magnetization at the modulation, due to the mismatch of magnetization between the two materials.

Work program & Skills acquired during internship

During the internship, the candidate will be made familiar with clean-room technology for patterning electrical contacts, electric measurements involving nanosecond pulses of electric current, and various types of magnetic microscopy, both in the lab and at synchrotrons. The objective is to robustly control the domain-wall motion from one modulation to the next. The working framework includes weekly group meetings bringing together experimentalists and theoreticians, and interaction with colleagues expert in chemical synthesis of the nanowires through international partners.

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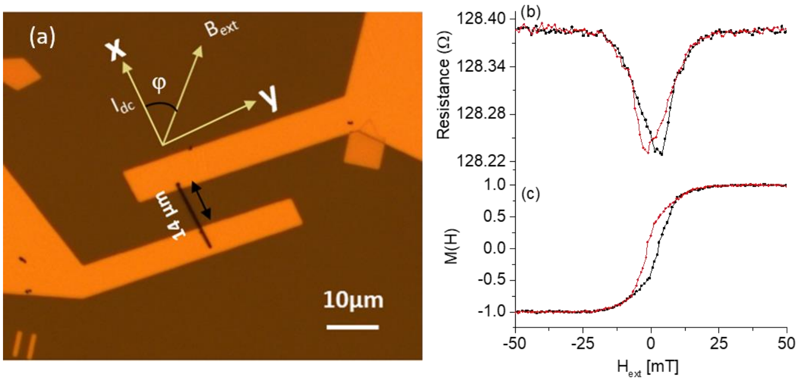
Requested background: Master 2
Duration: 6 months
Start period: Feb/ March 2022
Possibility of PhD thesis : YES
Proposal number : 17

Curvilinear magnetism and spintronics in core-shell nanotubes

Context

The physics of nanomagnetism and spintronics has been mainly developed based on planar structures, making use of thin-film deposition and clean-room patterning technology. This concerns interfacial magnetic anisotropy, magnetoresistance effects, spin-transfer torques, magnonics etc. 3D nanomagnetism and spintronics emerged recently as a new research direction. While some concepts are simply translated from the planar to the 3D geometry, fundamentally new physics arise, 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 fast-developing field is the main background of the Spin Textures research team of SPINTEC. We have recently developed a key system, consisting of core-shell magnetic nanotubes. It is of crucial interest to translate spintronics in a 3D geometry, as spintronic effects are provided by interfaces. Besides, cores and shells with different functions can be brought together. Here, we propose to make use of a unique system dedicated to both domain-wall motion and magnonics, *i.e.*, spin wave propagation. In both cases, we will seek to evidence signatures of the impact of curvature on magnetism.



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

Work program & Skills acquired during internship

The chemical synthesis, combining several cutting-edge techniques, is performed by an international expert collaborator. The candidate to the internship will be in charge of handling the core-shell nanotubes to contact them electrically, and use a combination of several magnetic microscopies to investigate domain-wall motion under nanosecond pulses of electric current, and the controlled excitation of spin waves. This may involve both in-lab measurements, as well as stays at synchrotron-radiation facilities. The work is conducted jointly with our colleagues from the theory group, providing a quick and effective support. Besides the direct monitoring, the candidate will benefit 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 and magnetic imaging as a **strong experimental background** as well as a deep physical understanding of nanomagnetism and spintronics, bringing him a **broad theoretical basis** to start a scientific research career that we aim to be pursued with a PhD.

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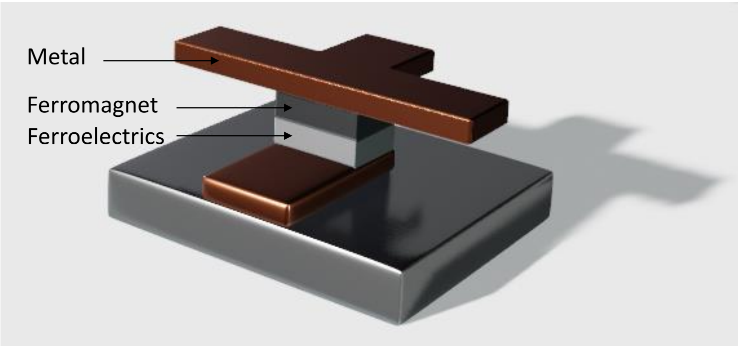
Ferroelectric control of the spin-charge conversion

Context

The conversion of a conventional charge current into a spin current, carrying not charges but angular momentum, can be done in quantum materials using the spin-orbit coupling. We recently demonstrated in two articles (Nature & Nature Electronics[1,2]) that combined with high spin-orbit coupling elements, ferroelectrics have a natural potential to generate an electrically-switchable, highly efficient spin-charge interconversion, that can be used to develop new ferroelectric devices (see figure).
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.



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

Work program & Skills acquired during internship

The Internship (and possible PhD) project aims at exploring the possibilities offered by these features, in particular for the development of devices similar to the magneto-electric spin-orbit logic devices recently proposed by Intel[3]. The gate dependence of the conversion and the material characterization and optimization will be done by spin pumping. The intern will realize the device nanofabrication in order to measure the spin-charge interconversion electrically, participate to paper writing and patent deposit. 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.

[1] Noël, Attané, Vila et al., Nature 580.7804 (2020): 483-486.
[2] Varotto, Attané, Vila et al., arXiv preprint arXiv:2103.07646., accepted in Nature Electronics (2021)
[3] Manipatruni et al., Nature 565.7737 (2019): 35.

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Requested background: Master 2
Duration: 4-6 months
Start period: Feb/ March 2022
Possibility of PhD thesis : YES
Proposal number : 19