Master Thesis Projects 2021

SPINTRONIQUE et TECHNOLOGIE des COMPOSANTS

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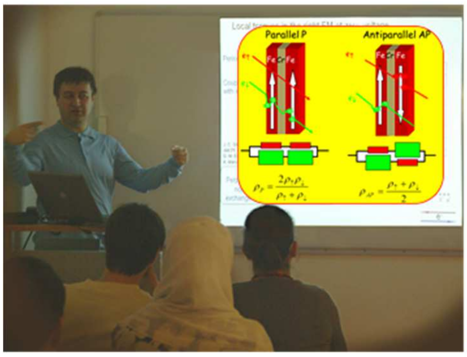
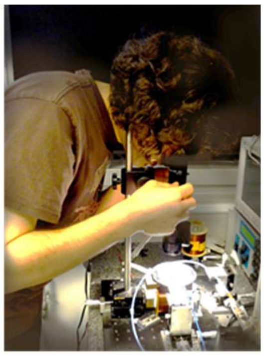
SPINTEC IN BRIEF

SPINTEC is located within the innovation research site of MINATEC in Grenoble, France. Our mission is to act as a bridge between academic research and technological applications in the field of spintronics, which is today recognized 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 with both high-rank publications and a broad portfolio of patents. Our activities are performed in collaboration with academic and industrial partners from around the world. SPINTEC has circa 100 staff, encompassing researchers, engineers, post-doc and PhD students, working cooperatively in an open structure organized around focused research topics.

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. The application-oriented topics are: magnetic random access memories, design of spin-based integrated circuits, sensors, biotechnology. Academic research concerns spinorbitronics, spintronics in 2D materials, microwave components, antiferromagnetic spintronics, and exotic spin textures.



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 will 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 academics or in the industry. Come and join us to be part of those who like to revolutionize microelectronics research and applications!

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LIST OF MASTER THESIS TOPICS by TEAM

MRAM Memories
1 - Spin-orbit torque assisted switching and field free solutions
2 - Combined spin and heat driven magnetization reversal of magnetic tunnel junction
3 - Magnetic Bit Stream Generator for Spiking Neural Networks
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5 - Designing MRAM for security applications: robustness and vulnerability analysis

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2D and Semiconductor spintronics
9 - Atomic scale analysis of 2D materials using Scanning Transmission Electron Microscopy

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11 - Spin-charge conversion in Rashba interfaces
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22 - Modeling of domain wall dynamics in core-shell nanowires: towards 3D spintronics

Proposal N° : 1

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Title

Spin-orbit torque assisted switching and field free solutions

Keywords
spin-orbit torques, MRAM

Summary

There is considerable interest in electrically controlling nano-magnets (Spintronics) in order to develop non-volatile magnetic memories (MRAM) [1, 2]. 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 [3] has emerged as a credible next-generation MRAM technology that allows for faster and more efficient magnetization writing. The proof of concept of such SOT-MRAM was recently confirmed [4], showing that it is a promising solution for SRAM replacement in cache memory, even though various challenges have to be tackled before full integration in future technology nodes can be envisaged, namely reducing the writing current and achieving field-free deterministic switching. To address these challenges, we propose in this project to study the interplay of SOT with other spin-source mechanism such as STT and voltage control of magnetic anisotropy (VCMA) in scaled integrated devices.

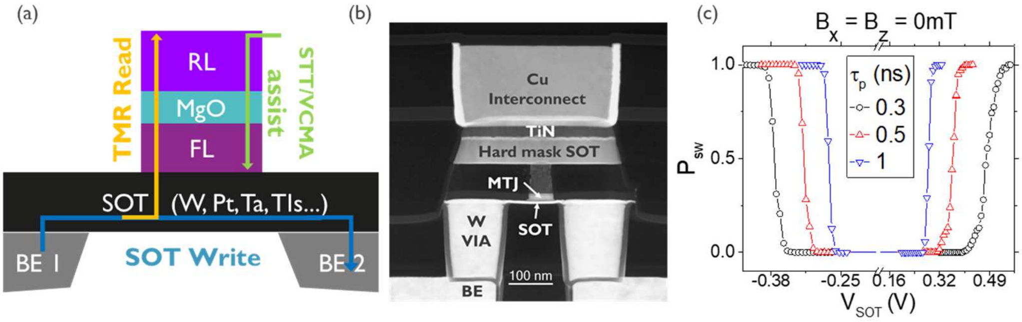

Figure 1: a) schematic of SOT-MTJ, and possibilities to assist it with STT and VCMA effects, b) TEM Cross section of a SOT-MTJ produced at IMEC [4], c) typically switching probability as a function of SOT voltage operated at 0 external field [4].

Description

SOT-MTJ with perpendicular magnetization presents technological challenges. Firstly, it requires the presence of an in-plane magnetic field (B_x) to ensure deterministic switching. Various credible solutions have been proposed and demonstrated in the literature, such as embedding a magnet as a field generator during integration process[4]. Recently by assisting reversal with STT effect [5]. In addition, the writing current density is relatively large (>100 MA/cm^2) and must be reduced as it strongly impacts the cell area. To this end, it has been proposed in the literature to reduce writing energy through VCMA during writing [6], and recent experiment have shed more light on the intrinsic reversal mechanisms and the interplay of SOT, STT and VCMA [7]. Using STT and VCMA effect seems therefore an elegant and very promising approach toward low power field-free switching SOT-MRAM. 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] A. Kent& D.C. Worledge,”A new spin on magnetic memories”, *Nat. Nanotech.* 10, 187–191 (2015)

[3] Manchon et. al, “Current-induced spin-orbit torques in ferromagnetic and antiferromagnetic systems” Rev. Mod. Phys. 91, 035004 (2019)

[4] K. Garello et al.,” Manufacturable 300mm platform solution for Field-Free Switching SOT-MRAM”, IEEE Symp. VLSI Tech., T194-T195 (2019)

[5] 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)

[6] H. Yoda et. al, “Voltage-Control Spintronics Memory (VoCSM) Having Potentials of Ultra-Low Energy-Consumption and High-Density”, *IEEE IEDM*, pp. 27.6.1-27.6.4 (2016)

[7] E. Grimaldi et al.,”Single-shot dynamics of spin-orbit torque and spin transfer torque switching in 3-terminal magnetic tunnel junctions” *Nat. Nanotech*. 15, pp. 111-117 (2020)

Requested skills

Master 2 in nanophysics/solid state physics

Possibility to follow with a PhD : Yes (to be confirmed!)

Proposal N° : 2

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Title

Combined spin and heat driven magnetization reversal of magnetic tunnel junction

Keywords

magnetic tunnel junctions, spin transfer torque, heating effect, magnetization dynamics, MRAMs

Summary

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. The interfaces between various materials are playing a major role in generating peculiar interactions (*e.g*. perpendicular interfacial magneto-crystalline anisotropy, Dzyaloshinskii-Moriya exchange interaction, RKKY coupling,...) which together with the materials themselves are controlling the magnetic proprieties of the different layers. The systems called "perpendicular" having the magnetization pointing perpendicularly to the plane of the layers appear to be the most promising choice to satisfy standard requirements of stability, energy consumption and operation speed. However the magnetization dynamics is mainly spin driven (*e.g*. STT-spin transfer torque, SOT-spin orbit torque,...) and thus the heating inherent with the currents flowing in the sample is affecting most of the sample parameters. Especially the interface related parameters as the anisotropy are known to be very sensitive with the local temperature. The objective of the internship is 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.

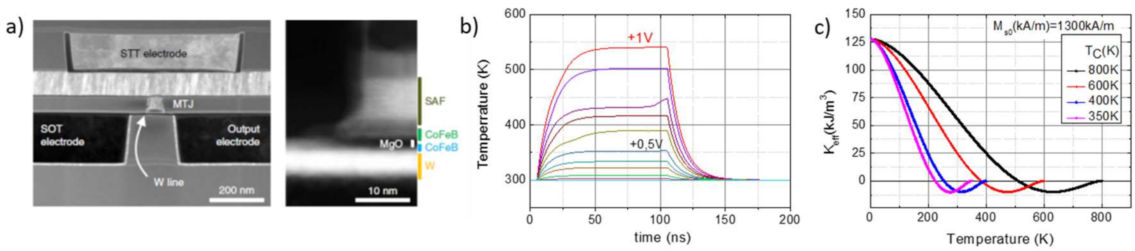

Figure 1: a) TEM Cross section of a SOT-MTJ [3]. b) Typical time evolution of the temperature of the MTJ sample for different bias voltage pulses. c) Temperature-induced variation of the effective anisotropy of a CoFeB free layer depending on its Curie temperature Tc.

Description

The time evolution of the magnetization distribution of a ferromagnetic sample is commonly described by the phenomenological Landau-Lifshitz-Gilbert equation. This equation accounts for various internal interactions (*e.g*. exchange, magnetostatic, anisotropy) but also for the Zeeman coupling with an external applied field and optionally one might add supplemental terms dues to the spin polarized current (STT, SOT). During this project a LLG based formalism will be used to study the time evolution of the magnetization of thin ferromagnetic layer of thickness around 1nm and variable lateral size below 100nm subject [see Fig1.a]. Simultaneously the action of an external magnetic field and spin driven torque will be investigated to identify the suitable conditions to reach the magnetization equilibrium state or to reverse the magnetization orientation. Once the bias current is injected the associated Joule effect should be monitored since the resistance of the sample might change and thus the temperature of the sample evolves [Fig.1b]. Therefore the material parameters of the sample are instantaneously affected with a direct impact on the internal fields of the LLG equation [Fig.1c]. This joint effect of heating and spin current has been poorly investigated by the past and often limited to the macrospin approximation [3]. For MTJ with tens of nm lateral size we are expecting to have a strong impact on the magnetization dynamics and particularly on the magnetic domain wall nucleation occurring during the magnetization reversal mechanism.

The project aims to perform a comparison between the two writing schemes STT-based and SOT-based 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 to reduce the stochasticity detrimental for a memory device. The parameters of the simulations will be set according to the input from our experimental characterization. The results of this project will not be only helpful for the data interpretation but also for benchmarking the self-consistent heating-LLG model.

[1] B. Dieny et al., *Nat. Electron*. 3, 446 (2020).
[2] E. Grimaldi et al., *Nat. Nanotech*. 15, 111 (2020).
[3] N. Strelkov et al. Phys. Rev. B 98, 214410 (2018).

Requested skills
Master 2 in nanophysics/solid state physics

Possibility to follow with a PhD : Yes

Proposal N° : 3

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Title

Magnetic Bit Stream Generator for Spiking Neural Networks

Keywords

spintronics, magnetic memory, MRAM, neuromorphic cell, multilevel states

Summary

Applications in artificial intelligence architectures require devices that are able to take multiple states based on different cell inputs. Hardware realizations of such elements can rely on magnetic non-volatile memory (MRAM) technology. In this project, we are proposing a concept based on an all-perpendicular magnetic tunnel junction with two weakly coupled magnetic free layers (M_1 and M_2 on the figure). When both magnetic layers are free to move, the spin transfer torques [1] acting on each other generate a perpetual switching of their magnetizations, called "windmill motion" [2]. The two magnetizations M_1 and M_2 alternate between parallel (low resistance) and antiparallel alignment (high resistance). The goal of the internship is to determine possible operation windows of the described cell. This will be done by both simulation and electrical measurements on nanofabricated cells. The sensitivity the windmill regime depending on control parameters will be investigated, focusing on the amplitude and duration of the pulse voltage, applied magnetic field, temperature,... Time-resolved experiments will be used to reveal the bit stream properties and the generation of spikes of various shapes, with expected time features in the tens of ns.

Description

MRAM magnetic memories combine non-volatility with writing speeds of tens of nanoseconds. These memories are emerging as a commercial product from major foundry companies (Samsung, TSMC, GlobalFoundries). The most advanced MRAM concepts use cells having perpendicular magnetic anisotropy layers, and current pulses to switch between two states of resistance. Applications in artificial intelligence architectures need devices abled to have multiple states of resistance depending on different cell inputs. Thus the magnetic non-volatile memory (MRAM) are very promising candidates for such hardware realizations. One of the most interesting implementation concerns the control of the switching rate of the magnetic memory cells. This replaces multi-resistance state approach by a stream of bits, defined by the time the cells spends in each state (high or low resistance). The cell can be made for low retention, providing the possibility to control the rate between the two states with a very small amount of energy.

Our project illustrated in the figure, is focused on an all-perpendicular magnetic tunnel junction (MTJ) with two weakly coupled magnetic free layers (M_1 and M_2). The magnetic layers are coupled through the MgO spacer, the spin transfer torques acting on each other might generate a regular switching of their magnetizations ("windmill motion"). The two magnetizations M_1 and M_2 alternate between parallel (low resistance, P) an antiparallel alignment (high resistance, AP) once a voltage pulse is injected in the nano-pillar. This configuration is well suited to tailor the spike shapes by engineering the coupled switching of the two magnetizations, as demonstrated recently, to generate neuron-like spikes in response to voltage pulses [2].

Preliminary experimental and simulation results of our group show the feasibility of this approach. Upon application of voltage pulses of sufficient amplitude, the voltage–field switching diagram shows a region around zero field where switching of both layers merge and where neither the P or AP state are stable. The experimental finding are confirmed by modelling. Analysis of the time traces of the signal show a perpetual switching ("windmill motion") of the two layers where the magnetizations M_1 and M_2 are going back and forth between the parallel an antiparallel alignment. This results in a well-defined sequence of spikes in the device resistance.

During the internship, a systematic study is proposed in order to identify the suitable "windmill" operation conditions. The challenge is to control the stochasticity of the magnetization switching, which can become chaotic [2]. Electrical measurements on nanofabricated MTJ cells will be carried on depending on the cell parameters (composition, shape, size,..). Time-resolved experiments will be used to reveal the bit stream properties and the generation of spikes of various shapes, with time features in the tens of ns. Multiple control parameters such as the amplitude and duration of voltage pulse or the external magnetic field will be monitored in order to qualify their impact on the windmill response of the MTJ nano-pillar. Jointly numerical simulation will be performed having as input parameters from the experiments in order to get a deeper understanding of the magnetization dynamics of the coupled layers and select the suitable manner to control the sequence of generated spikes.

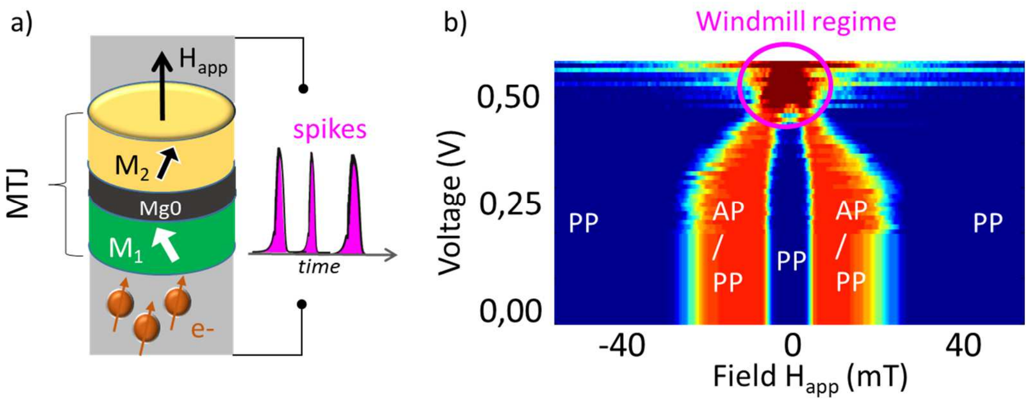

Figure 1: a) *Schematics of two free magnetic layers weakly coupled, their interaction can be controlled by the mutual spin torque effect.* b) *Experimental voltage-field state diagram of perpendicular magnetic tunnel junction pillar having 100nm diameter, showing the windmill regime.*

[1] J. C. Slonczewski, doi: 10.1016/0304-8853(96)00062-5 (1996).
[2] R. Matsumoto et al., doi: 10.1103/PhysRevApplied.11.044093 (2019).

Requested skills

Master 2 in nanophysics/solid state physics, data analysis, programming, interest in nano-electronics

Possibility to follow with a PhD : Yes

Proposal N° : 4

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Title

Magnetic MRAM memory for magnetic field sensor applications

Keywords

Spintronics, Magnetic memory, MRAM, magnetic field sensor, 3D assembly

Summary

Magnetic non-volatile memory (MRAM) is a technology being developed at Spintec. This type of memory associates non-volatility with fast switching of the order of ns. Switching the magnetization direction the storage layer results in cell resistance changes that can be greater than 100%. This 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 is higher than the switching threshold. To achieve a multifunctional cell, capable of storing information and detecting 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 critical parameters that limit the resolution of the memory in field sensor mode. We will subsequently optimize the measurement procedure to optimize it in terms of speed and sensitivity. The temperature dependence of the sensor characteristics will also be studied. Potential applications of this concept would be for example in the high precision alignment of dye-wafer required for 3D assembly, widely used in microelectronics to reduce the surface area of chips in smartphone devices.

Description

MRAM magnetic memories combine non-volatility with a writing speeds of tens of nanoseconds. These memories are being emerging as a commercial offering from major foundry companies (Samsung, TSMC, GlobalFoundries). The most advanced MRAM concepts use cells having perpendicular magnetic anisotropy layers, and current pulses to switch between two states of resistance. In a drive to achieve multi-functional memory cells, Spintec has patented magnetic field sensing concept based on a memory cell that achieves magnetic field sensing, that is compatible with the memory retention of cells storing information. To achieve this goal a special reading sequence is implemented that allows for a magnetic field measurement.

The internship work will consist in the validation of this measurement procedure and verify the compatibility with memory specifications. External parameters affecting the measurement, include the dimensions of the MRAM cell diameter (typically ranging from 30-100nm), the duration of the current pulse application and the reading time, with temperature and external field also playing a role. The objective is to obtain the sensibility of the measurement procedure to variations of the parameters, affecting the MRAM sensor sensibility. The work will consist in the identification critical parameters for sensor operation, limiting the resolution, and ways of optimizing the measurement procedure to reduce the measurement time and increase sensitivity.

To this goal, we will combine modeling and experiments. This optimization requires an accurate evaluation of the energy barrier dependence, when operating in the sensor mode. Different material stacks as well as the size of the memory element so that the magnetization of the storage layer remains stable against thermal fluctuations, while allowing for the accurate sensing of magnetic. The physics involved is well understood so that the modeling of these structures by simulation will be possible. The experiments will consist of depositing magnetic multilayers, nano-fabrication (lithography, etching) in a clean room and then characterizing their magnetic and electrical properties. It is hoped that the internship will be continued in a PhD thesis.

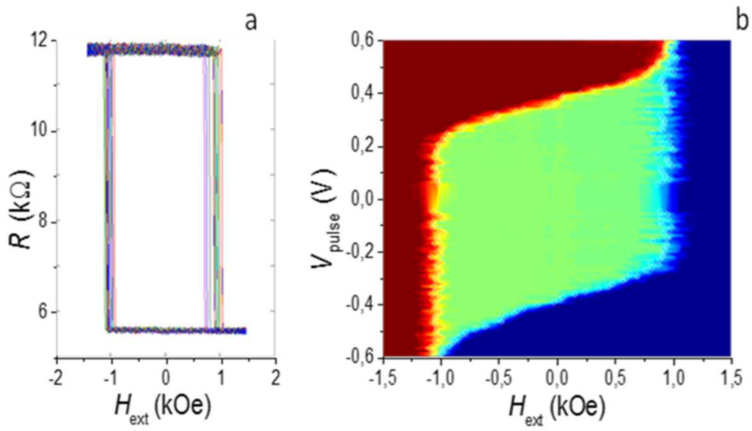

Figure 1: a) A Magneto-Resistive (MR) hysteresis cycle measured on a perpendicular anisotropy tunnel junction showing the variation of the resistance and two distinct resistance sates [1]. b) A state-phase diagram plot of the same junction when applying current pulses. The color code shows the resistance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

[1] A. A. Timopheev, R. Sousa, M. Chshiev, L. D. Buda-Prejbeanu, and B. Dieny, 'Respective influence of in-plane and out-of-plane spin-transfer torques in magnetization switching of perpendicular magnetic tunnel junctions', Phys. Rev. B, vol. 92, no. 10, p. 104430, Sep. 2015, doi: 10.1103/PhysRevB.92.104430.

Requested skills

Master 2 in nanophysics/solid state physics, knowledge of instrumentation programing (Matlab/Python), interest in microelectronics.

Possibility to follow with a PhD : Yes

Proposal N° : 5

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Title

Designing MRAM for security applications: robustness and vulnerability analysis

Keywords

spintronics, magnetic memory, MRAM, secure IoT

Summary

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. These models differ on the type of mechanism inducing the reversal, either single-domain reversal or domain-wall nucleation process. Different tunnel junction stacks and device geometries will be evaluated and modelled. The first 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 more secure MRAM cells.

Description

Commercial MRAM devices are based on magnetic tunnel junctions having perpendicular magnetic anisotropy layers, and current pulses of opposite polarity are used to switch between two states of resistance. These magnetic memories are especially adapted for “Internet of Things” applications, because they combine non-volatility with writing speeds of tens of nanoseconds and switching voltages below 1V. These memories are emerging in volume production at major foundry companies (Samsung, TSMC, GlobalFoundries).

Typical electrical characterization of MRAM bitcells consists in measurements of tunnel magnetic resistance (TMR) under applied magnetic field, to extract coercivity and estimate the cell thermal stability from switching field dispersion. An equivalent method can be implemented based on the switching voltage required for spin transfer torque (STT) switching. A wafer-level prober allows extracting these parameters in single cell arrays to provide designers with electrical corners, corresponding to the upper and lower boundaries of the observed parameters.

The internship work will first validate the different methods to extract these parameters, and verify the compatibility of the fabricated devices with memory specifications. This characterization provides accurate data for writing current density, pulse voltage, together with the device size as well as temperature dependence. In second step, physical simulation of the fabricated cells using macrospin and micromagnetic simulation codes developed at Spintec will allow understand the influence environment parameters that can be modelled by external magnetic fields (static or AC) as well as short heating pulses, generated electrically of by an external laser source. Based on the observed sensitivity to external attacks additional protections can be included, such as magnetic or thermal shielding. 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.

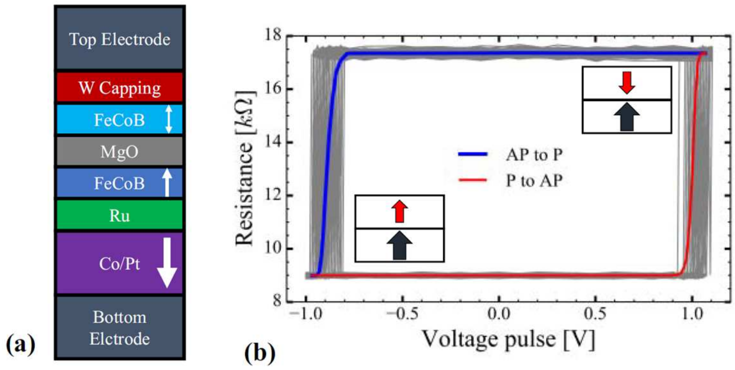

Figure 1: a) Typical magnetic stack of a perpendicular anisotropy magnetic tunnel junction used in non-volatile memory MRAM cells. b) Electrical characterization of 500 hysteresis loops showing individual voltage loops in grey and their mean value in blue-red [1]. The dispersion of the witching voltage allows for the extraction of thermal stability parameters.

[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.

Requested skills

Master 2 or Engineering School Final Year Project, knowledge of instrumentation programing (Matlab/Python), interest in microelectronics. The internship must have a minimum 5 months duration.

Possibility to follow with a PhD : No

Proposal N° : 6

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Title

Study of RF-to-DC conversion using spintronics devices

Keywords

Condensed matter, spintronics, spin transfer torque, magnetization dynamics, wireless sensor networks, nanostructure

Summary

Wireless sensor networks and smart sensors are at the core of the Internet of Things, requiring low cost, compact and low power electronic components. The most power consuming parts are the wireless communication transmitter and receiver modules, which remain active more or less permanently, while actual communication takes place only during a limited amount of time. Much energy is thus wasted. To overcome this bottleneck the idea is to switch the main communication modules off and to use a low power radio receiver to listen for wake-up signals. Spintronics devices represent microwave functionalities that respond to the need of such low power radio receivers. Notably they can convert passively an RF signal into a DC signal with the added value of being frequency selective. They thus act at the same time as frequency filters that can demodulate the information carried by an incoming wake-up signal. SPINTEC is currently coordinating a French ANR project to develop such spintronics based RF-to-DC converters to be used as radio receivers as well as for rf power harvesting, in close collaboration with CEA/LETI and UMPhy CNRS/THALES Palaiseau. The objective of the internship is to characterize the RF-to-DC conversion function for optimized spintronics devices fabricated at SPINTEC. The challenge is to study not only single devices but a small network of devices for multifunctional operation.

Description

Spintronics makes use of spin currents (either pure spin currents or spin polarized charge currents) to manipulate or detect the magnetization state of small magnetic elements. The interaction of the spin current with the local magnetization corresponds to a torque on the magnetization whose effect is to reduce or modulate the damping of the magnetization precession. This can lead to steady state oscillations (for DC currents) that have been investigated for many years at SPINTEC for realizing nano-scale rf oscillators [1,2]. Here we will investigate a second aspect, which is the ferromagnetic resonance excitation through spin polarized rf currents. The magnetization oscillations translate into resistance oscillations and the mixing of the rf resistance with the rf current then leads to a rectified DC voltage signal or in other words to the conversion of an RF signal to a DC signal. Our previous studies have shown good sensitivity to low input signals and relatively large DC signal levels for magnetic tunnel junction devices that are either in the vortex state (frequency range of 0.1-1GHz) [3] or that have out of plane magnetization such as used for magnetic memories (1-10GHz range). In order to increase the output signal level and to demodulate multifrequency signals, small arrays of devices will be realized. The magnetic tunnel junction devices are fabricated by SPINTEC at the PTA nanofabrication facility. Within the internship the student will be involved in the design of the spintronics device networks in close collaboration with CEA/LETI. The main task will be the characterization of the RF-to-DC conversion signal as a function of the array configuration and excitation schemes and to understand the excitation modes as a function of operational and device parameters. For this analytical and simulation studies will be performed using homebuilt numerical codes.

The internship is adapted for M1 and M2 students and can be followed by a PhD thesis. During the thesis, the student will be involved in the nanofabrication of the devices as well as in the testing of a demonstrator device that is realized by CEA/LETI.

[1] A. Ruiz-Calaforra, U. Ebels et al., Appl. Phys. Lett. 111, 082401 (2017) https://DOI.org/10.1063/1.4994892 Frequency shift keying by current modulation in a MTJ-based STNO with high data rate
[2] M. Kreissig, V. Cros, U. Ebels, et al., AIP Advances 7, 056653 (2017) https://doi.org/10.1063/1.4976337 Vortex spin-torque oscillator stabilized by phase locked loop using integrated circuits
[3] S. Menshawy, U. Ebels, V. Cros et al., AIP Advances 7, 056608 (2017) https://doi.org/10.1063/1.4973389 Spin transfer driven resonant explulsion of a magnetic vortex core for efficient rf detector

Requested skills
Master 2 in nanophysics/solid state physics, data analysis, programming, interest in nano-electronics

Possibility to follow with a PhD : Yes

Proposal N° : 7

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Title

Spin-orbit torque nano-oscillators

Keywords

spintronics, magnetization dynamics, Spin-orbit torques, nano-oscillators, machine learning

Summary

Spin currents can be used to excite persistent oscillations of a nanomagnet. This is at the origin of the concept of spin-torque nano-oscillators (STNOs) [1, 2]. STNOs are emerging spintronic devices for microwave signal generation, oscillator-based communications and computation, as well as for new neuromorphic computing [3, 4]. They combine unique properties such nano-scale size, tunable microwave frequency, and strong non-linear properties. This internship proposes to study spin-orbit torque induced magnetization dynamics in advanced nano-scaled magnetic tunnel junction (MTJ) devices for developing RF and neuromorphic applications.

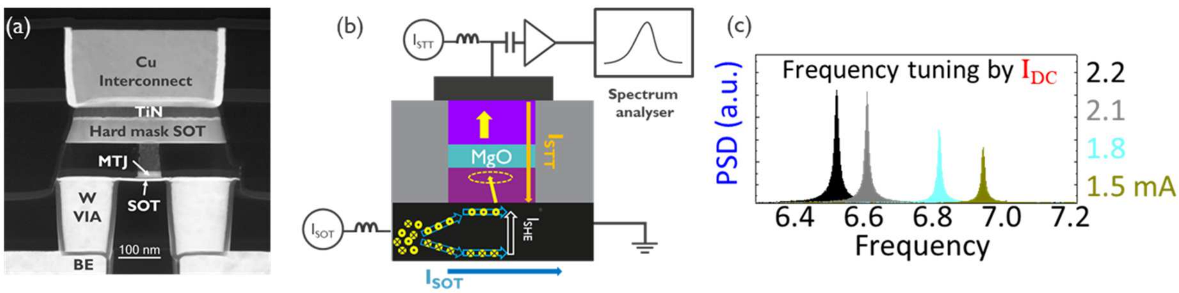

Figure 1 : (a) TEM Cross section of an SOT-MTJ that will be used in this project [6], (b) electrical scheme of a SOT/STT-STNO, (c) power spectrum of magnetization oscillation induced by STT.

Description

Typical STNOs are two terminal (2T) devices that use magnetic tunnel junction (MTJ) nanopillar structures. They rely on the spin transfer torque (STT) effect to excite and tune magnetization oscillations at microwave frequencies. Via the tunneling magneto-resistance effect (TMR) these oscillations are converted into an RF voltage signal. In these 2-terminal STT-STNOs the driving current to excite the dynamics and the sensing current to detect the dynamics are the same. This causes noise and reliability issues. Alternatively, spin-orbit torques (SOT) [5], originating from spin Hall and Rashba effects, provide the possibility to generate 3-terminal devices to separate excitation and sensing current. This is achieved by using a heavy metal track underneath the MTJ. For such configurations, SOT current driven magnetization switching has been demonstrated as an efficient and fast switching mechanism for memory applications [6]. Furthermore, SOT demonstrated the possibility to generate strong permanent oscillations of magnetization creating a so called SOT-STNO [4,7]. The flexibility to tune the excitation and sense currents independently opens many novel operational schemes for STNOS and is particularly attractive for machine-learning related concepts [4].

With the goal to develop such SOT-STNOs for both RF and machine learning applications this internship proposes a systematic study of the SOT-induced magnetization dynamics using advanced nanoscale MTJ devices. Contrary to most of literature demonstrations, we will focus our effort on perpendicularly magnetized systems with an all-electrical read-excitation scheme. The student will be involved in all steps of the characterization, starting with the magnetic stacks and materials, magneto-resistance mapping as well as RF measurements. Experimental results will be confronted to numerical simulations. Both excitation schemes SOT and STT will be compared for their efficiencies and their excitation spectra (frequency, power linewidth). The student will obtain a sound training on magneto-transport as well as RF measurement techniques, on spin transport properties and spintronics phenomena as well as on non-linear magnetization dynamics concepts.

[1] Kiselev, S. I. *et al*. *Nature* 425, 380–383 (2003).
[2] D. Houssameddine et al., Nat. Mat. 6, 447 (2007)
[3] M. Romera et al., Nature 563, 230 (2018)
[4] Akerman et. al, Nature Nanotechnology 15, p. 47–52(2020)
[5] A. Manchon et al., Rev. Mod. Phys. 91, 035004 (2019)
[6] K. Garello et al, IEEE Symp. VLSI Tech., T194-T195 (2019)
[7] Liu et. al, Phys. Rev. Lett. 109, 186602 (2012)

Requested skills
Master in physics, nanosciences or nanotechnologies

Possibility to follow with a PhD : Yes

Proposal N° : 8

Contact

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Title

Coherent transduction of magnon and phonon in suspended garnet micro-structure

Keywords

Cavitronic, coherent coupling, magnetic resonance, acoustic resonance.

Summary

The coherent transfer of information 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. While increasing the overlap integral between two spatio-temporal patterns is primarily a design issue, diminishing the internal friction inside an object is a much more complex task, which requires know-how in material research and growth technology. In this respect, yttrium iron garnet (YIG) holds a unique position in nature for having together the lowest possible magnetic damping and excellent acoustic attenuation (10x better than quartz). Thus YIG is probably the best possible coherent interlink between magnons and phonons, which all have different benefits to propose: (non-)/linear; (non-)/tunable; (non-)/reciprocal etc... One main difficulty that has always hampered the development of garnet thin films for integrated magnon phonon transducer is that their epitaxial growth could only be achieved on gadollinium gallium garnet (GGG) substrates. However for phonons, GGG substrate should be considered for all practical purposes an impedance matched medium preventing the confinement of their oscillating energy in the YIG layer. Recently, a new process developed by the group of G. Schmidt in Halle has allowed to fabricate free standing micron-size slabs from YIG with high magnon life time, hereby greatly reducing the energy leakage through the substrate of their phononic or photonic waveform. These new objects have the potential to become game-changers for the quantum information projects by allowing realistic integrated garnets solutions.

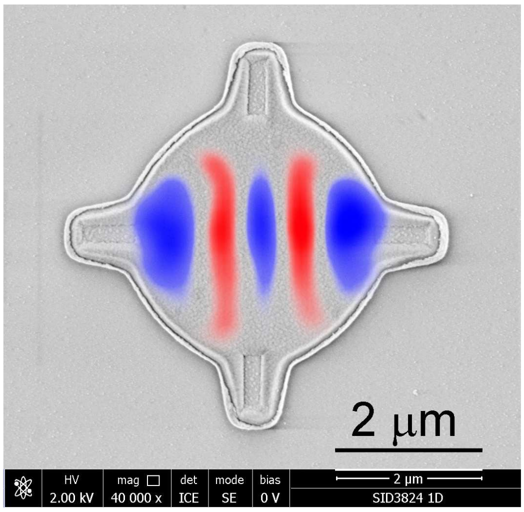

Figure 1: SEM image of a suspended drum-like YIG resonator with an overlay of a spin wave pattern measured on the same structure by TR-MOKE.

Description

The objective of this master project will be to evaluate how these suspended structures perform as magnon-phonon transducers. This will be achieved by coupling these slabs to microwave antenna or interdigited piezoelectric transducer. The project will not only try to achieve strong coupling within a micro-structure, but will also try to couple coherently the magnetization dynamics of two separate structures via a double interconversion process. The project is designed as a collaboration between the group of Spintec and Halle because inputs from both sides are needed for the realization. The coupling of magnons to phonons will be performed in France. The micropatterning and YIG deposition for both parts of the project is uniquely located in Halle while micromagnetic simulations and resonator design as well as characterization of all structures by FMR microscopy at room temperature is done at Spintec.

[1] "Long range coupling of magnetic bi-layers by coherent phonons". Kyongmo An, et al. Phys. Rev B 101, 060407(R) (2020)

[2] [2] "Measurement of the intrinsic damping constant in individual nanodisks of Y3Fe5O12 and Y3Fe5O12|Pt". C. Hahn, et al. Appl. Phys. Lett. 104, 152410 (2014)

[3] "Monocrystalline Freestanding Three-Dimensional Yttrium-Iron-Garnet Magnon Nanoresonators". F. Heyroth, et al. Phys. Rev. Applied 12, 054031 (2019)

[4] "Nutation spectroscopy of a nanomagnet driven into deeply nonlinear ferromagnetic resonance". Yi Li, et al. Phys. Rev. X 9, 041036 (2019)

Requested skills

Master 2 in condensed matter physics and a taste for hacking and working on home-made experiments

Possibility to follow with a PhD : Yes

Proposal N° : 9

Contacts

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Title

Atomic scale analysis of 2D materials using Scanning Transmission Electron Microscopy

Keywords

2D materials, Transmission Electron Microscopy, epitaxial growth, Transition Metal Dichacogenide

Summary

Two-dimensional atomically thin materials such as graphene are very promising materials for future applications. Among them, 2D transition metal dichalcogenides (2D-TMDs), such as MoS_2, have attracted tremendous attention for their exceptional optical and electronic properties. Their physical properties critically depend on the structural qualities such as crystallinity, domain size, atomic defects, etc. Molecular beam epitaxy (MBE) has appeared to be a relevant technique to provide high quality TMD layers via hetero-epitaxial growth on a single crystal substrate. To understand the epitaxial growth mechanisms and further to achieve well-controlled high quality materials, characterization of grown materials and interfaces at atomic scale is crucial. Aberration corrected scanning transmission electron microscopy (AC-STEM) is known as the most suitable technique to provide such local atomic information.

The aim of the internship will be to study the MBE growth of 2D-TMDs using AC-STEM. The student will develop an analytical process combining several atomic resolution quantitative STEM methods in order to provide detailed insights on atomic defects, boundaries, strain, crystal orientation, etc. The work will be mainly realized in the microscopy laboratory (LEMMA-IRIG) at Nano-characterization Platform (PFNC). The trainee will be also involved in MBE experiments and other characterization SPINTEC laboratory to get a more comprehensive view of the 2D systems studied.

Description

Two-dimensional materials such as graphene are very promising materials with applications in various domains. Thanks to their unique electronic, mechanical, and thermal properties, they are considered as materials of the future for new electronic, biodevices, super-strong materials, and energy storage. Among them, 2D transition metal dichalcogenides (2D-TMDs) have attracted tremendous attention for their exceptional electrical and optical properties. TMDs have the general formula MX_2, where M is a transition metal and X is a chalcogen: S, Se, Te. Their bulk layered structure consists in the stacking of tri-atomic layers X-M-X. The strong covalent bonding between the metal and the chalcogen inside the layers contrasts with the weak van der Waals interaction between the layers. Depending on their elemental components, their electronic properties can range from semiconducting to metallic and superconducting. When thinned down to a single layer, they exhibit drastic change of their electronic properties, for example, a transition from indirect-to-direct band gap crossover leading to very high photoluminescence emission. Combining single layers of various 2D materials offers the possibility to create a multitude of heterostructures with completely new properties and functionalities. However, despite rapid progresses in their synthesis, the quality and the size of single 2D-TMDs leaf is still unsatisfactory. Nevertheless, the expected properties depend drastically on the layer quality and the development of new well-controlled fabrication methods is needed in order to obtain large-scale and high quality 2D crystals. Molecular beam epitaxy (MBE) has the potential for enhanced quality provided by high purity elemental sources and growth in an ultrahigh vacuum system. Moreover, MBE offers more flexibility in the choice of the substrate and the transition metal. It also allows stacking of different TMDCs and growth of complex heterostructures with good control on the deposited layers.

Our research group has been developing this growth technique since several years [1-4] in association with structural observation techniques such as in-situ electron diffraction, X-ray diffraction, Raman spectroscopy. Among these techniques, transmission electron microscopy (TEM) is essential to understand the growth mode of the 2D layers on the substrate and the role of the interface with the substrate [2,4]. The combination of different microscopy techniques currently available: electron diffraction, spectroscopy, holography, etc., gives access to information at the atomic scale on the crystalline structure, the microstructure and the structural defects allowing understanding the growth mechanisms and the key parameters to improve the 2D layer quality.

The aim of the internship is to study the MBE based epitaxial growth of 2D-TMDs using AC-STEM techniques. The student will develop an analytical process combining several atomic resolution quantitative STEM methods. Structural information such as atomic defects, grain boundaries, local strain and crystal orientation will be provided to understand and control the growth mechanisms. The student will work mainly in the microscopy laboratory (LEMMA-IRIG) at the Nano-characterization Platform (PFNC) and will contribute to MBE experiments and other characterization techniques in the laboratory (SPINTEC) to get a more comprehensive view of the 2D systems studied.

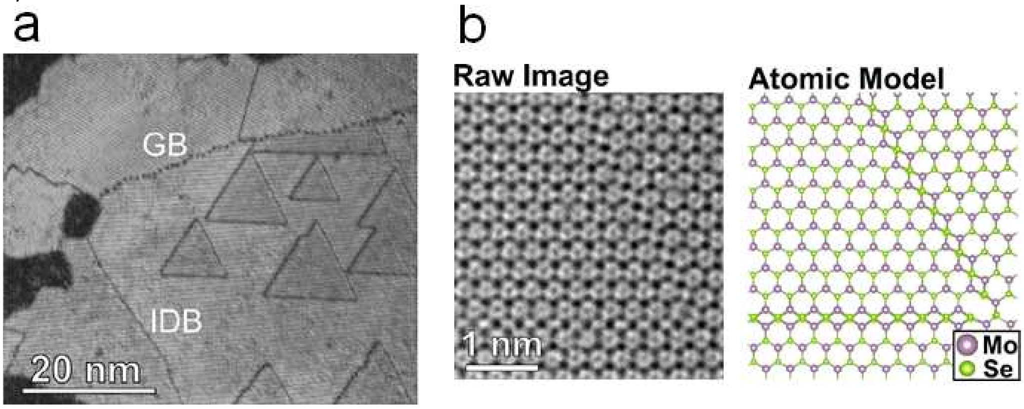

Figure 1: Aberration-corrected transmission electron microscopy (AC-TEM) image of a MoSe2 layer; (a) overview of grain and inversion domain boundaries and b) atomic structural analysis of inversion domain boundary [2].

[1] M. T. Dau et al. ACS Nano 12, 2319 (2018)
[2] C. J. Alvarez et al. Nanotechnology 29, 425706 (2018)
[3] M. T. Dau et al. APL Mater. 7, 05111 (2019)
[4] C. Vergnaud et al. Nanotechnology 31, 255602 (2020)

Requested skills

Experimental Physics, Material Science, Image analysis, Taste for group working

Possibility to follow with a PhD : Yes

Proposal N° : 10

Contact

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Title

Manipulation of magnetic skyrmion in ultrathin nanostructures

Keywords

spintronics, nanomagnetism, magnetic memories

Summary

The recent discovery of nanometer-size whirling magnetic structures named magnetic skyrmions has opened a new path to manipulate magnetization at the nanoscale [1,2]. Magnetic skyrmions are characterized by a chiral and topologically non-trivial spin structure, i.e their magnetization texture cannot be continuously transformed into the uniform magnetic state without causing a singularity (see Fig.1). Skyrmions can also be manipulated by in-plane current, which has led to novel concepts of non-volatile magnetic memories and logic devices where skyrmions in nanotracks are the information carriers. The nanometer size of the skyrmions combined with the low current density needed to induce their motion would lead to devices with an unprecedented combination of high storage density, fast operation and low power consumption. Although predicted at the end of the 1980's, magnetic skyrmions were first observed in 2009 in B20 chiral magnets thin films and later in ultrathin epitaxial films at low temperature. Recently, magnetic skyrmions were reported at room temperature in ultrathin sputtered thin films which is a first step toward the practical realization of skyrmion logic and memory based devices. In particular, Spintec recently demonstrated room temperature magnetic skyrmion in ultrathin Pt/Co/MgO nanostructure at zero external magnetic field [3] (Fig.1 (b-c)) as well as their fast current induced motion. The objective of the internship will be to push forward fundamental knowledge in view of technological applications for memory and logics. The aims will be to develop novel and unexplored material systems to achieve nm scale skyrmions stable at room temperature and allow their fast and reliable current induced skyrmion manipulation

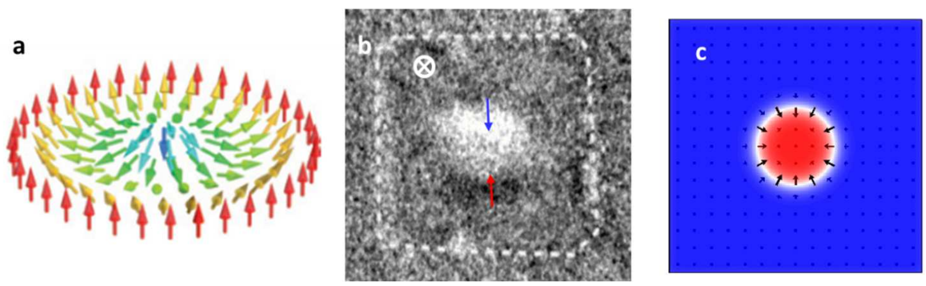

Figure 1: a) Schematic representation of a magnetic skyrmion [1]. b) XMCD-PEEM image of magnetic skyrmion (130 nm diameter) at room temperature and zero magnetic film in an ultrathin Pt/Co/MgO nanostructures [3]. c) Spin structure from micromagnetic simulations.

Description

The recent discovery of nanometer-size whirling magnetic structures named magnetic skyrmions has opened a new path to manipulate magnetization at the nanoscale [1,2]. Magnetic skyrmions are characterized by a chiral and topologically non-trivial spin structure, i.e their magnetization texture cannot be continuously transformed into the uniform magnetic state without causing a singularity (see Fig.1). Skyrmions can also be manipulated by in-plane current, which has led to novel concepts of non-volatile magnetic memories and logic devices where skyrmions in nanotracks are the information carriers. The nanometer size of the skyrmions combined with the low current density needed to induce their motion would lead to devices with an unprecedented combination of high storage density, fast operation and low power consumption. Although predicted at the end of the 1980's, magnetic skyrmions were first observed in 2009 in B20 chiral magnets thin films and later in ultrathin epitaxial films at low temperature. Recently, magnetic skyrmions were reported at room temperature in ultrathin sputtered thin films which is a first step toward the practical realization of skyrmion logic and memory based devices. In particular, Spintec recently demonstrated room temperature magnetic skyrmion in ultrathin Pt/Co/MgO nanostructure at zero external magnetic field [3] (Fig.1 (b-c)) as well as their fast current induced motion. The objective of the intnership will be to push forward fundamental knowledge in view of technological applications for memory and logics. The aims will be to develop novel and unexplored material systems to achieve nm scale skyrmions stable at room temperature and allow their fast and reliable current induced skyrmion manipulation.

The internship will be based on all the experimental methods and techniques used for the development and characterization of spintronics devices: sputter deposition of ultra-thin multilayer materials and characterization of their magnetic properties by magnetometry methods, followed by nanofabrication of nanostructures cut in these layers by electron lithography and ion etching. Nanofabrication will be performed at the PTA nanofabrication platform located in the same building as the Spintec laboratory. The nanostructures will then be characterized by magneto-transport and magnetic microscopy (MFM) methods to highlight the nucleation of isolated skyrmions and their magnetic structure. Magnetic microscopy experiments based on X-rays, STXM or XMCD-PEEM will be planned in different European synchrotrons.

[1] A. Fert, V. Cros, and J. Sampaio, Nat. Nanotechnol. 8, 152 (2013)
[2] N. Nagaosa and Y. Tokura, Nat. Nanotechnol. 8, 899 (2013)
[3] O. Boulle et al., Nat. Nanotechnol. 11, 449 (2016).
[4] R. Juge et al., Physical Review Applied, 12 044007 (2019)

Requested skills

Master 2 in nanophysics/solid state physics

Possibility to follow with a PhD : Yes

Proposal N° : 11

Contact

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Title

Spin-charge conversion in Rashba interfaces

Keywords

Condensed matter, spintronics, quantum materials, nanostructures, spin currents, Rashba, 2D electron gas, oxides

Summary

Whereas conventional spintronics uses the exchange interaction in a ferromagnetic material to manipulate spin currents, spin-orbit coupling can now be used to generate or detect spin currents, possibly in absence of any ferromagnetic element. We have shown that Rashba interfaces such as Ag/Bi [1], LAO/STO [2,3] and Al/STO|4] possess this ability, with giant conversion rates. Moreover, the spin-charge conversion can be tunable in these quantum materials by a gate voltage, and it is even possible to reverse the sign of the spin-charge conversion. Beyond fundamental questioning, the PhD project aims at exploring the possibilities offered by these features, in particular for the development of the reading part in magneto-electric spin-orbit logic devices [5]. This PhD project is funded through a Marie Skłodowska-Curie Innovative Training Networks (European grant), which provides for a competitive fellowship, and for additional funding and European mobility during the PhD.

Description

The rich physics of transition metal oxides is related to the delicate balance between charge, spin and orbital degrees of freedom. Quantum phenomena allows for the appearance of 2-dimensional electron gas at oxides surface and interfaces, with a large diversity of functional properties (insulators, metals, superconductors, ferromagnets, antiferromagnets, ferroelectrics, etc.). In recent studies [1-4] we have shown that these materials are exciting candidates for the spin-charge conversion.

A very active field of research for information processing is spintronics, which has traditionally relied on ferromagnetic metals as generators and detectors of spin currents. A new approach called spin-orbitronics exploits the possibility offered by the spin-orbit coupling (SOC) in non-magnetic systems to generate pure spin currents from charge currents, and vice versa. In particular, a quantum phenomenon called the Rashba effect allows spin-charge interconversion with great efficiency. It typically occurs at surfaces and interfaces where spatial symmetry breaking results in an out-of-plane electric field. In the presence of SOC, this leads to a locking of the momentum and spin degrees of freedom along two inequivalent Fermi contours with opposite chiralities (Fig. 1a). The flow of a charge current in such a system induces a shift of these Fermi contours, which produces a transverse spin accumulation diffusing as a spin current in an adjacent material; this is the Edelstein effect (EE) (Fig. 1b). Conversely, injecting a spin current generates a net charge current (by inverse Edelstein effect IEE, Fig. 1c). Importantly, the Edelstein effect yields spin-charge interconversion efficiencies much larger than the spin Hall effect (with record values in $SrTiO_3$-based structures).

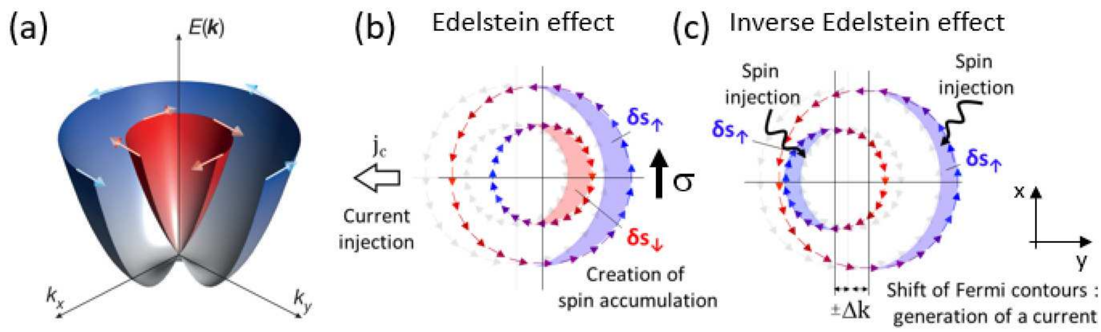

Figure 1: a) Band structure of a Rashba system, with two Fermi contours having opposite spin helicities. Charge-spin (b) and spin-charge (c) conversion: in (b) the injection of a charge current J_C along y shifts the Fermi contours and generate a spin-density $\sigma=\delta s\uparrow-\delta s\downarrow$ along x. In (c) the injection of a spin density σ along x shifts the contours along y, creating a finite charge current.

The PhD project aims at exploring the possibilities offered by these features, in particular for the development of the reading part in magneto-electric spin-orbit logic devices recently proposed by Intel [6]. The gate dependence of the conversion and the material characterization and optimization will be done by spin pumping. The PhD student will realize the device nanofabrication in order to measure the spin-charge interconversion electrically [7]. He will explore the potential offered by the electric-field control of the spin-orbit conversion and by the unidirectional magnetoresistance to create new devices. The PhD students will develop skills in nanofabrication, and in magnetotransport (at room and low temperature) in thin films and in nanodevices. Transport simulations will be performed if necessary, in order to analyse the data. We already possess on this topic a PhD funding via a Marie Skłodowska-Curie Innovative Training Networks (European grant), which also provides for additional funding and European mobility during the PhD, with training period and 3 months stay in another lab of the consortium during the PhD.

[1] Rojas, Attané et al., Nature communications 4 (2013): 2944.
[2] Lesne, Attané et al., Nature materials 15.12 (2016): 1261.
[3] Vaz, Attané et al., Nature materials, 18(11), (2018) 1187-1193.
[4] Noël, Attané et al., Nature 580.7804 (2020): 483-486.
[5] Manipatruni et al., Nature 565.7737 (2019): 35.s
[6] Manipatruni et al., Nature 565.7737 (2019): 35.
[7] Avci et al., Nature Physics 11.7 (2015): 570.

Requested skills
Taste for experimental condensed-matter physics, and collaborative work.

Possibility to follow with a PhD : Yes. We already possess the funding via a Marie Skłodowska-Curie Innovative Training Networks (European grant), which also provides for additional funding and European mobility during the PhD.

Proposal N° : 12

Contact

Laurent VILA laurent.vila@cea.fr +33(0)4 38 78 03 55

Title

Spin-charge conversion in topological insulators

Keywords

condensed matter, spintronics, quantum materials, nanostructure, spin currents, topological insulators, Rashba, 2D electron gas, oxides

Summary

Whereas conventional spintronics uses the exchange interaction in a ferromagnetic material to 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. Spin-dependent transport effects can thus be observed in a class of recently discovered materials, topological insulators.

We will use the spin pumping phenomenon, which takes place at the ferromagnetic resonance, to inject a spin current from a ferromagnet into topological insulators such as HgTe [1,2] and Sb_2Te_3. The conversion of this spin current into a charge current will be detected electrically for different experimental parameters: temperature, gate voltage, layer thickness, presence of a tunnel barrier or of a metal layer, stoichiometry of the materials ... This will allow studying the physics of spin-orbit coupling in these materials, such as the hybridization of surface states in topological insulators, or the role of interfaces in spin-dependent transport.

Once the optimal systems have been identified, we will fabricate nanodevices to realize this interconversion electrically (see Figure 1), in both possible directions (charge to spin or spin to charge). These devices will also allow studying the Bilinear Magnetoresistance, a novel and intriguing phenomenon leading to symmetry breaking (the electrical resistance of a nanowire is depends on the sign of the applied current). This subject is a rather fundamental research topic, with transport effects specific to spin-orbit coupling appearing in new materials. We already possess the PhD funding, via a Marie Skłodowska-Curie Innovative Training Networks (European grant), which provides a competitive fellowship, and additional funding and European mobility during the PhD (with training period and 3 months stay in another lab of the consortium during the PhD).

Description

The conversion of a conventional charge current into a spin current, carrying not charges but angular momentum, can be done in non-magnetic systems using the spin-orbit coupling [3]. Over the past ten years, the use of this coupling has caused a radical transformation of spin electronics. Whereas conventional spintronics uses the exchange interaction in a ferromagnetic material to manipulate spin currents, spin-orbit coupling can now be used to generate or detect spin currents, possibly in absence of any ferromagnetic element. Spin-dependent transport effects can thus be observed in topological insulators. A topological insulator is a material that behaves as an insulator in its interior but whose surface contains conducting states, meaning that electrons can only move along the surface of the material.

We will use the spin pumping phenomenon, which takes place at the ferromagnetic resonance, to inject a spin current from a ferromagnet into topological insulators such as HgTe [1] and Sb_2Te_3. The conversion of this spin current into a charge current will be detected electrically for different experimental parameters: temperature, gate voltage, layer thickness, presence of a tunnel barrier or of a metal layer, stoichiometry of the materials ... This will allow studying the physics of spin-orbit coupling in these materials, such as the hybridization of surface states in topological insulators, or the role of interfaces in spin-dependent transport. These experiments will also optimize materials and systems in order to obtain the highest possible spin conversion rates possible.

Once the optimal systems have been identified, we will fabricated nanodevices to realize this interconversion electrically (see Figure 1), in both possible directions (charge to spin or spin to charge). This subject is a rather fundamental research topic, with transport effects specific to spin-orbit coupling appearing in new materials. The PhD student will develop skills in device characterization, nanofabrication, and in magnetotransport (at room and low temperature) in thin films and in nanodevices. Transport simulations will be performed if necessary, in order to analyse the data. The work will is currently done in collaboration with Albert Fert (Nobel Prize, UMR CNRS-Thales), Tristan Meunier (Néel Institute) and Philippe Ballet (CEA LETI).

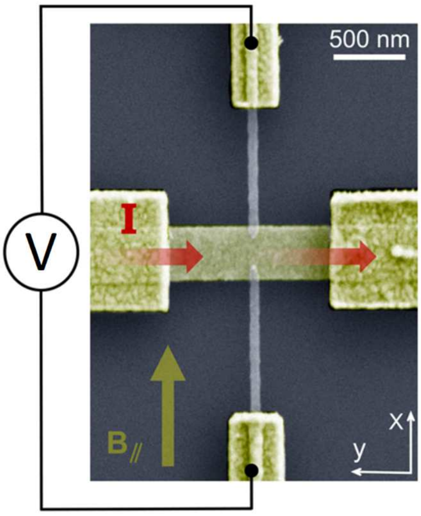

Figure 1 : Example of a nanodevice made in our team allowing the electrical measurement of the charge current - spin current conversion [4]. The charge current travels along the horizontal track in the spin-orbit material, generating a spin accumulation, and the vertical ferromagnetic electrodes probe this accumulation.

[1] P. Noel, L. Vila et al., Physical Review Letters 120, 167201 (2018)
[2] J.C. Rojas Sanchez, L. Vila et al., Physical Review Letters 116, 096602 (2016)
[3] J.C. Rojas Sanchez, L. Vila et al., Nature Communications 4, 2944 (2013)
[4] V.T. Pham, L. Vila et al., Nano Letter 16, 6755 (2018)

Requested skills
Taste for experimental condensed-matter physics and collaborative work.

Possibility to follow with a PhD : Yes. We already possess the funding via a Marie Skłodowska-Curie Innovative Training Networks (European grant), which also provides for additional funding and European mobility during the PhD.

Proposal N° : 13

Contacts

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Laurent VILA	laurent.vila@cea.fr	+33(0)4 38 78 03 55

Title

Ferroelectric spintronics for memories, low-energy post-CMOS logic, and AI

Keywords

Post-CMOS electronics, spintronics, architectures, memories, neuromorphic, quantum materials, 2D electron gas

Summary

Spintronics devices involve ferromagnetic elements that are intrinsically nonvolatile, but still require high switching energies. Contrastingly, the polarization of ferroelectrics can be easily switched by an electric field, at energies typically 1000 times lower. We recently demonstrated in a Nature article that combined with high spin-orbit coupling elements, ferroelectrics have also a natural potential to generate a strong Rashba effect, which allow obtaining an electrically-switchable, highly efficient spin-charge interconversion[1]. The aim of this PhD is to study this ferroelectric control of the charge-spin conversion in Rashba heterostructures, and to explore its potential for applications along three directions: memories, post-CMOS computing (in particular for the development of the reading part in magneto-electric spin-orbit logic devices [2]), and neuromorphic computation for artificial intelligence.

At the fundamental level, the ambition of this PhD is to merge the fields of ferroelectricity and spin-orbitronics. In particular, for spintronics devices the project will allow replacing the ferromagnetism by ferroelectricity as the source of non-volatility.

Description

To contain the ever-increasing power consumption of information and communication systems, resorting to ferroic systems with collective switching behaviour and non-volatility appears essential, in order to bring memory into logic and to alleviate energy-costly on-chip data transfer. Spin-orbitronics memory, neuromorphic and logic concepts still involve ferromagnetic elements, whose switching energy far exceeds the requirements of beyond-CMOS technologies. In addition, the way charge and spin are interconverted is inherently set by the stack, without the possibility to tune it by an external stimulus. In contrast with ferromagnets, the order parameter in ferroelectrics (polarization) can be easily switched by an electric field, at a power typically 1000 times lower. Ferroelectrics have been used in commercial non-volatile data storage for two decades (in FERAMs). At the cross-road between spintronics, ferroelectricity and quantum materials physics, this PhD will pioneer new devices in which spin currents can be generated, manipulated and converted by electric fields in a non-volatile way, without resorting to ferromagnets and their energy-costly magnetization switching.

A very active field of research for information processing is spintronics, which has traditionally relied on ferromagnetic metals as generators and detectors of spin currents. A new approach called spin-orbitronics exploits the possibility offered by the spin-orbit coupling (SOC) in non-magnetic systems to generate pure spin currents from charge currents, and vice versa. In particular, a quantum phenomenon called the Rashba effect allows spin-charge interconversion with great efficiency. We have already shown that Rashba interfaces such as Ag/Bi [3], LAO/STO [4,5] and Al/STO [6] possess record spin-charge conversion rates. The PhD tudent will design and invent new devices, realize material characterization and optimization, and measure the devices properties, with the aim of providing a proof of concept for the three technological axis. The PhD student will develop skills in device characterization, nanofabrication, and in magnetotransport (at room and low temperature) in thin films and in nanodevices. Transport simulations will be performed if necessary, in order to analyse the data. Note that the team is currently trying to develop a start-up based on this activity.

Figure 1. Non-volatile memory device patented in our group operated by ferroelectricity and Rashba SOC. Through the inverse Edelstein effect a charge current J_C is generated by the conversion of a spin current J_S injected from the ferromagnet. The sign of Jc changes with the direction of the ferroelectric polarization. The large white arrows show the ferromagnet magnetization, the small black arrows the spin σ, the brown arrows the direction of the generated charge current Jc, and the red arrow the direction of the spin current Js. The small black-and-white arrows correspond to the ferroelectric polarization.

[1] Vila, Attané et al., Nature 580.7804 (2020): 483-486.
[2] Manipatruni et al., Nature 565.7737 (2019): 35.
[3] Rojas, Attané et al., Nature communications 4 (2013): 2944.
[4] Lesne, Attané et al., Nature materials 15.12 (2016): 1261.
[5] Vaz, Attané et al., Nature materials, 18(11), (2018) 1187-1193.
[6] Noël, Attané et al., Nature 580.7804 (2020): 483-486.

Requested skills
Imagination, interest towards innovative microelectronics applications and condensed-matter physics, possible will to pursue a career in a start-up environment

Possibility to follow with a PhD : Yes

Proposal N° : 14

Contacts

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Title

New scheme for SOT-MRAM switching

Keywords

Spin-orbit torques, MRAM, spinorbitronics

Summary

While the capacity of data centers and servers continues to grow, digital technologies as a whole is already one of the main sources of global energy consumption (notably due to the "big data" revolution driven by IOT and IA and the ever-increasing role of these technologies in our lives), and its environmental impact is currently a major challenge. Most of this energy consumption stems from the physical separation of the memory and the processor and the data transfer between the two units. One of the best solutions is to integrate non-volatile memory at all levels of the "memory hierarchy", especially as close as possible to the processors, and as such reduce the data flow. However, mainstream memories are limited in terms of speed, energy consumption and endurance (Flash, EEPROM) or cannot retain data without power (SRAM, DRAM). In addition, they are all approaching physical scaling limits. Magnetic Random Access Memory (MRAM) has been identified as the most promising technology for integrating non-volatility into the memory hierarchy. In particular, the latest generation of these MRAMs, the SOT-MRAM[1–3], based on the manipulation of magnetization by means of spin-orbit torques (SOT), is currently the only technology that allows the design of ultra-low power and ultra-fast devices[4]. Nevertheless, this concept still suffers from crucial limitations for practical applications.

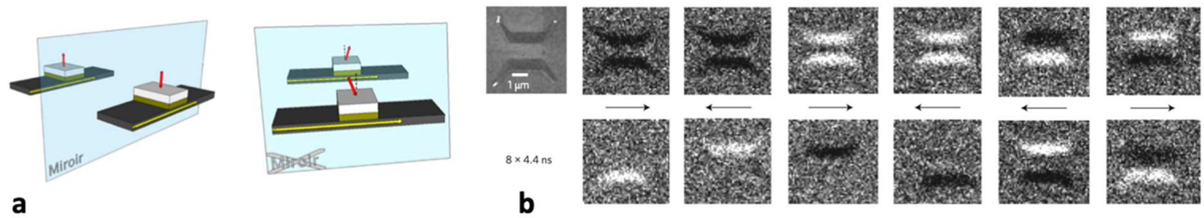

Figure 1: a) Without additional symmetry breaking, the two magnetization states "up" and "down" are perfectly symmetrical. An in-plane magnetic field, by tilting the magnetization, breaks this symmetry and allows a deterministic reversal. b) Bipolar switching of U-shaped devices. The first row contains a scanning electron microscopy image (left) of the magnetic structure sitting on top of the much wider rectangular Pt electrode (not visible). The subsequent differential Kerr images correspond to the initial magnetic state of the devices (bright, down; dark, up). The second row of images correspond to the final magnetic configuration of the devices after the injection of eight pulses (4.4 ns at $j = 1.87 \times 10^{12}$ A m^{-2}). The electric current is indicated by black arrows. Comparison of the initial and final images confirms that the two objects behave as bipolar switches with reversed polarity (from [6]).

Description

One of the most important is the need for a magnetic field during the writing phase. As shown in figure 1.a, the external in-plane magnetic field is used to break the mirror symmetry between the magnetization "up" and "down" magnetizations (the "0" and "1") that are, otherwise, completely equivalent. Several solutions have been proposed recently in the literature to break this symmetry but, apart from the generation of a magnetic field at the heart of the memory point[5] (which raises other questions), none seems compatible with industrial industrialization.

Very recently, SPINTEC has patented an approach using specific magnetic configuration to switch SOT-MRAM without field. This approach relies on the tuning of the physical shape of the memory cell, and more specifically on the pillar and/or the track shape (fig. 1.b). A deterministic reversal was also shown to be compatible with fast writing[6].

If the proof of concept has thus been realized on a particular material, many studies remain to be carried out in order to validate, or not, this approach for the integration of "field-free" SOT-MRAM. The first is to show that this solution is compatible with the materials typically used in SOT-MRAM. The second is to show that the magnetization reversal mechanism responsible for this "shape-controlled switching" remains the same when the memory point size decreases to sub-50nm sizes (scalability).

In order to carry out these studies, we will use Kerr effect optical microscopy (MOKE) to probe the reversal mechanisms. In parallel, we will electrically characterize SOT-MRAM cells with different shapes of pillars and current track and with dot dimensions down to 50nm. These SOT-MRAM will be either nanofabricated at the PTA (Plateforme de Technologie Amont) or supplied by an industrial partner of the laboratory. The validity of this approach will be characterized by the writing characteristics (critical current, success rate for various writing speeds) and the equivalence to an external magnetic field (immunity of the writing under the perturbation of an external magnetic field).

1. Miron, I. M. *et al.* Perpendicular switching of a single ferromagnetic layer induced by in-plane current injection. *Nature* 476, 189–93 (2011).
2. Cubukcu, M. *et al.* Spin-orbit torque magnetization switching of a three-terminal perpendicular magnetic tunnel junction. *Appl. Phys. Lett.* 104, 042406 (2014).
3. Garello, K. *et al.* SOT-MRAM 300MM Integration for Low Power and Ultrafast Embedded Memories. in *2018 IEEE Symposium on VLSI Circuits* 81–82 (IEEE, 2018). doi:10.1109/VLSIC.2018.8502269
4. Garello, K. *et al.* Ultrafast magnetization switching by spin-orbit torques. *Appl. Phys. Lett.* 105, 212402 (2014).
5. Garello, K. *et al.* Manufacturable 300mm platform solution for Field-Free Switching SOT-MRAM.
6. Safeer, C. K. *et al.* Spin–orbit torque magnetization switching controlled by geometry. *Nat. Nanotechnol.* 11, 143–146 (2016).

Requested skills

Master 2 in nanophysics/solid state physics

Possibility to follow with a PhD: Yes

Proposal N° : 15

Contacts

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Title

Mechanical response of cells under local magneto-mechanical vibrations

Keywords

mechanobiology, cell biology, magnetic nanoparticles

Summary

The proposed internship aims to study the mechanical response of cells subjected to magnetic stimulation. The aim is to analyze the impact of the duration of exposure and the frequency of magnetic stimulation on cell contractility. Preliminary results obtained at the SPINTEC laboratory show that certain combinations of frequencies and amplitude direct cells towards apoptosis, which should lead to a rapid decrease in their contractility. During the internship, the evolution of cell contractility will be linked to the parameters of magnetic stimulation and the degree of apoptosis obtained by biochemical labeling. Moreover, since the particles are internalized by cells, the effect of their surface chemistry (metal, PEG, protein) on the cellular response will be analyzed.

Description

The SPINTEC laboratory has been pursuing for several years research on the development and implementation of magnetic nanoparticles for biomedical applications. The interest for these particles lies in the possibility of setting them in motion, or in vibration, by the remote application of a magnetic field. When the particles are in close contact with a cell this generates a localized mechanical force or torque on the cell membrane or in the cytoplasm, depending on whether the particle is internalized or not. In particular, it has been observed in previous in vitro experiment that after a few minutes the magneto-mechanical vibration leads to the death of cancer cells, with a significant increase in apoptosis.[1] These observations pave the way for the development of innovative therapeutic approaches. However, the understanding of the mechanisms involved in mechanical stimulation and the signaling pathways leading to apoptosis remain largely misunderstood.

For its part, the LTM Micro & Nano Technologies for Health research team is developing analytical and technological tools for the study of cell mechanics. This theme includes the study of the effect of the rigidity of the cellular environment on cellular behavior and the development of tools for quantifying cellular forces. For this purpose, a methodology has been implemented which makes it possible to dynamically measure the contractility of cells with a micrometric resolution.[2] Cellular contractility is indeed a marker of cellular activity. Many signaling pathways are directly linked to it, such as mitosis, differentiation of stem cells or cancerous phenotypes, migration, apoptosis, etc. The proposed technique is based on a mechanical analysis of the interaction of cells and their substrate, without any hypothesis on the signaling pathways involved. Thus, when a cell goes into apoptosis, its contractility decreases significantly over a period of time and this can be detected with mechanical measurement.

[1] C. Naud, C. Thébault, M. Carrière, Y. Hou, R. Morel, F. Berger, B. Diény, and H. Joisten, *"Cancer treatment by magneto-mechanical effect of particles, a review"*, Nanoscale Adv., https://doi.org/10.1039/D0NA00187B.
[2] M. Moussus, C. der Loughian, D. Fuard, M. Courçon, D. Gulino-Debrac, H. Delanoë-Ayari, and A. Nicolas, *"Intracellular stresses in patterned cell assemblies"*, Soft Matter 10, 2014 (2014).

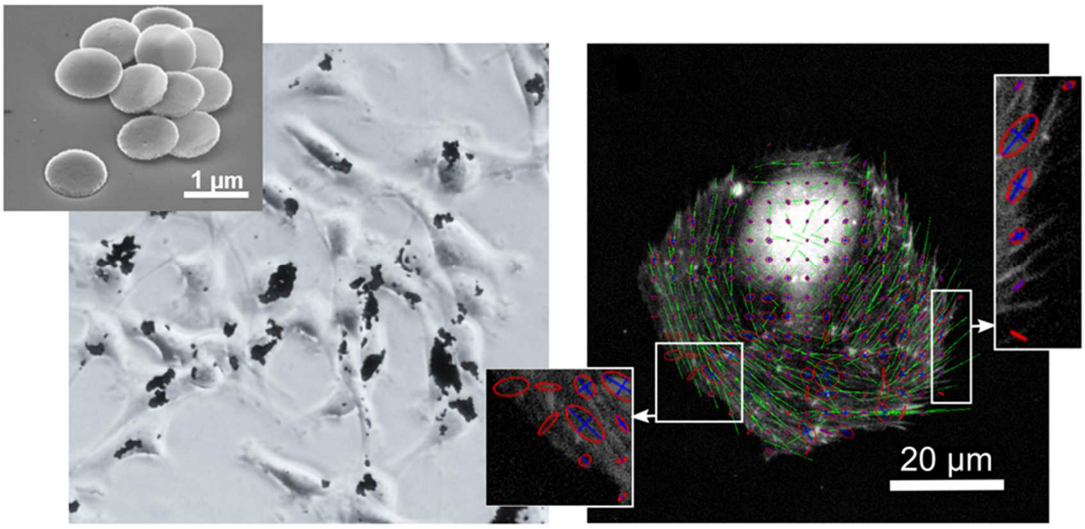

Figure 1: Left: Glioblastoma brain cancer cells incubated with magnetic nanoparticles.Right: Intracellular stress tensor in human umbilical vein endothelial cell, represented as a set of ellipses, aligned with actin filaments (stained in green).

Requested skills
Master 2 in Nanophysics with a strong interest in cell biology.

Possibility to follow with a PhD: Yes

LTM LABORATOIRE DES TECHNOLOGIES DE LA MICROÉLECTRONIQUE

LTM Micro & Nano Technologies for Health research lab

Proposal N° : 16

Contacts

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Title

Magnetic particle dynamics in an agarose gel for biomechanics application

Keywords

magnetic nanoparticles, magnetic actuation, gel viscosity, gel model, substitute brain, substitute tumor

Summary

Magnetic micro-nanoparticles are widely studied 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 Herz), preserving neighboring healthy cells. This purely magneto-mechanical effect - without heat production - has attracted a great deal of attention. However, in the numerous studies still exploratory, physical and biological aspects remain to be investigated and understood. In particular, the behavior of magnetic particles, widely investigated in a fluid (microfluidics, blood flow…), remains uncertain in media of larger viscosity. A remaining key issue, for an effective magneto-mechanical treatment, is thus the ability of the magnetic particles to move, rotate, or vibrate within a tumor site or in organic tissues. 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 a 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. Magnetic particles will be prepared in clean room PTA and magnetically characterized. Their dynamic behavior will be studied in particular under optical microscopy and applied field, in various agarose gel preparations to develop. The study will be mainly experimental, and may include a part of magneto-mechanical modeling.

Description

Magnetic micro- nanoparticles are more and more studied for biotechnological and biomedical applications, in crucial biomedical fields, such as magnetic resonance imaging (MRI) as contrast agents, tissue engineering, targeted drug delivery, magnetic hyperthermia for anti-cancer therapies, etc. Classical magnetic iron oxide nanoparticles, fabricated by chemical routes, have been studied for several decades. In a more recent approach developed in particular at Spintec, magnetic particles are fabricated by photolithography techniques in clean room facilities (top-down approach). A large variety of particles have emerged, including permalloy vortex disks currently studied at Spintec. Their large magnetization and magnetic anisotropy can lead to particularly efficient magneto-mechanical actuations, as highlighted in studies using the mechanical vibrations of particles for destroying cancer cells [1,2]. However, as detailed in our recent review [3], most of the studies demonstrate the induction of cancer cell death by magneto-mechanical effect in *in vitro* conditions, that is in fluidic solutions containing the cancer cells. Likewise, in our earlier works, agglomeration or redispersion of particles in zero field had been studied in fluids (acetone or water-based solutions) [4], far from tumor density.

We propose here to develop a purely physical model, based on the use of agarose gels, without involving biological cells or living organisms. Gel will mimic the density and firmness of viscous media, in which the particles have to act, close to those of tumors or brain matter [5]. The aim is to make a step further towards the reality of potential clinical cases, where particles are not immersed in a fluid.

The work will consist in developing appropriate agarose gels, and installing the experimental set-up. Based on earlier studies conducted at SPINTEC consisting in magnetic actuation of particles in fluidic solutions, the particles behavior will be observed in gels under the dedicated optical microscope (Figure 1).

The intern will explore different agarose gels concentrations, mimicking various tumors density. The particles dynamics and behavior in gel will be characterized to study in particular their tendency towards dispersion or agglomeration in zero field, their oscillations as a function of the field amplitude and frequency, their tendency to orient in specific directions.

The magnetic micro-nanoparticles studied at SPINTEC will be prepared by a top-down approach in the clean room PTA. This work will benefit from SPINTEC's expertise in nanomagnetism and nanofabrication. The intern will thus be trained on the various techniques required for the fabrication of magnetic particles as well as the magnetic and optical characterizations of the particles. The behavior of the particles will be correlated to magnetic forces calculated through existing analytical models. Models of particles response versus the gels viscosity will also be developed.

The internship will be conducted mainly at Spintec, in collaboration with the laboratory IRIG-SyMMES/Creab for the chemistry issues, in particular the particle surface functionalization or coating. Contact at SyMMES/Creab : Yanxia Hou-Broutin. yanxia.hou-broutin@cea.fr

[1] D.-H. Kim *et al.*, Nat. Mater., 2010, 9, 165–171.
[2] S. Leulmi *et al.*, Nanoscale, 2015, 7, 15904–15914
[3] Naud C. *et al.*, Nanoscale Adv, 2020.
[4] H. Joisten *et al.*, Appl. Phys. Lett., 2010, 97, 2–4.
[5] Pomfret R. *et al.*, Annals of neurosciences, 2013, 20, 118-122

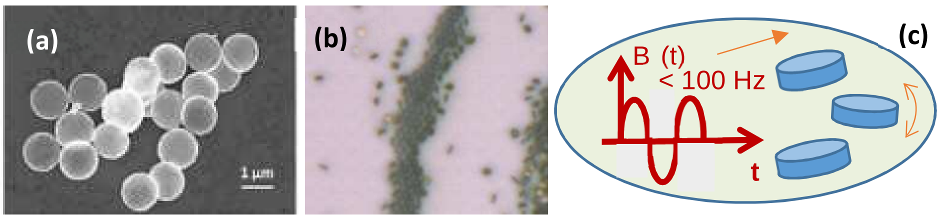

Figure 1: Magnetic particles imaging. ***(a)*** *SEM image of magnetic particles (Ø 1.3 µm, 60 nm-thick) from PTA, Spintec [2])* ***(b)*** *Optical image of self-polarization of particles in a fluid (acetone) in zero magnetic field [4]* ***(c)*** *Sketch of particles actuation by alternating magnetic field in an agarose gel.*

Requested skills

Master 2 in nanophysics/solid state physics, knowledge/approaches of lithography technics, microelectronics, physico-chemical processes, magnetism and biotechnological applications interest.

Possibility to follow with a PhD: Yes

Proposal N° : 17

Contacts

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Title

Multi-platform Image processing for Quantitative Magnetic Imaging

Keywords

Image acquisition, Data Processing, Transmission Electron Microscopy, X-Ray based imaging (STXM, XPEEM)

Summary

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 e. 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 for 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.

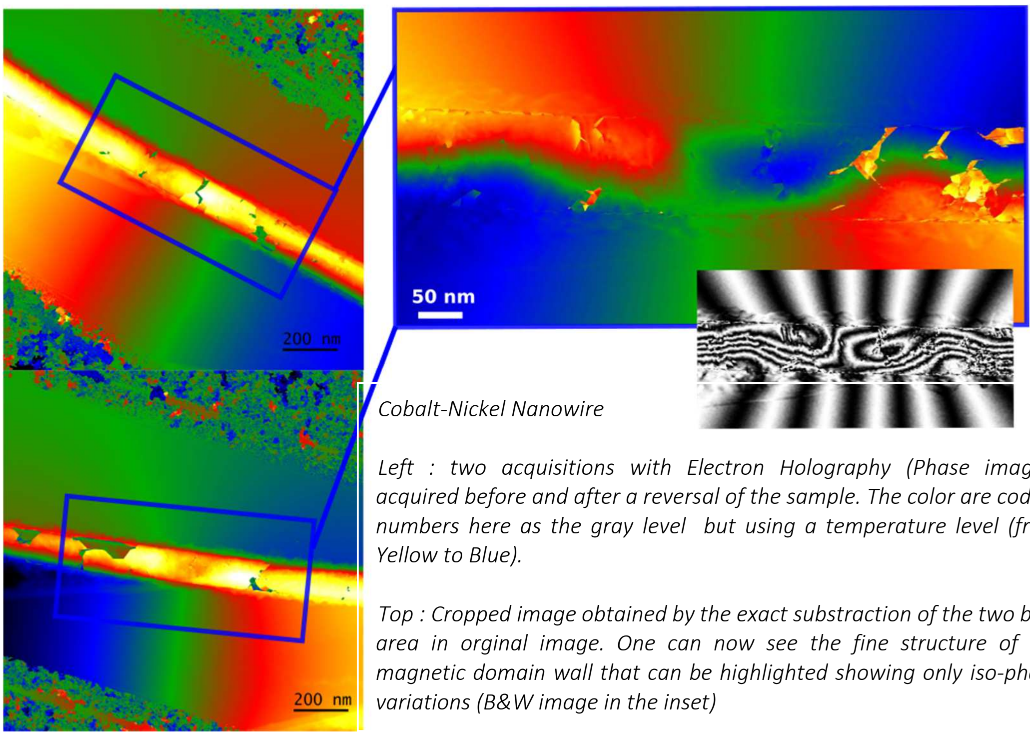
Description

We are interested in the observation of magnetic fields at the nanoscale, as it is of fundamental importance for the design of future memory and logic devices. The main challenges at that time is to modify the paradigm of memory storage and logical operation processing that mainly relies on charge displacement in devices. Among the main challenges of Spintec laboratory, new ways of storing information and new routes for addressable devices at higher rate and lower energy consumption are developed by the use of magnetic materials. One of these ideas is to use the magnetic domain walls (frontier in between magnetic domains that appears in a soft magnet to reduce its own energy) in a tunable fashion and to move them not only with a help of an external magnetic field but by the action of a current (see Racetrack memory). We thus need to precisely know the inner structure of domain walls prior and during their displacement with magnetic imaging capacities at spatial resolution down to the characteristic dimension of such objects: from few to tens of nanometers.

We are mastering in Spintec the techniques based on either X-ray or electron probes. Using the intrinsic characteristics of the radiation (polarization of the X-rays, charge of the electrons) we are sensitive to the magnetic properties of the matter. Our main results are images where each pixel (< 1 nm) contains a magnetic (vectorial) information. To achieve this magnetic sensitivity one always need at least two images to subtract the structural (or chemical) information. Particular attention is needed to subtract the exact same portion of space for not blurring if not cheating in the final data and requires a sub-pixel alignment. We also need to realign not only two images but more than hundread that we use to record movies of magnetic dynamic at the nanoscale (automated procedure). Last but not least, various instruments and detection are using various output format that are not natively able to be read by the same program.

The work in such training will be to tackle this re-alignment procedure on various type of scientific images, various quantity of images and in various environment. The student will be part of the SpinTextures team but will interact with various team of Spintec as well as outside : some routines of re-alignment have been already developed for specific experiments and one need to build a data treatment platform that could be used and developed hereafter by the scientists. The student will thus interact with people from various community : modeling of magnetism at the nanoscale (@SPintec and Institut Néel), experimentalists on X-ray techniques (participating to synchrotron time slots) and on TEM (in the Nano-Characterization platform of Minatec). This training will be thus a very good overview of the Research field ranging from theory to post-treatment of experiments including time in front of the machines.

It will be of real interest that the candidate could exhibit a good knowledge in coding, preferably under Python language and demonstrate an ease with image processing (not mandatory). Such training could thus lead to the extension of the work toward a PhD thesis onto magnetic imaging.



Cobalt-Nickel Nanowire

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 substraction of the two blue area in orginal 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)

Requested skills
Python coding, Micromagnetism, Image processing skills would be appreciated

Possibility to follow with a PhD : Yes

Proposal N° : 18

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Title

Electron Optics for Stroboscopic Magnetic imaging

Keywords
Instrumentation, Electron Optics, Electrostatic, Instrumental design

Summary
Lorentz Microscopy is an advanced technique of Transmission Electron Microscopy that consists in reconstructing the full electron wave to access its phase. The phase of an electron wave is modulated by the presence of electro-magnetic fields that may be quantitatively mapped, once the phase is fully reconstructed. Beyond the possibility of describing magnetism (and more particularly micromagnetic objects such as domain walls or vortices) at the nanometer scale, it is now of fundamental importance to observe devices during their operation (*in operando*). We thus want to observe them in a TEM (that require electron transparency, below 100 nm thickness) still preserving their initial functions. The possibility of quickly changing the physical state of the samples allows to imaging them in a stroboscopic mode if one can modulate the electron beam accordingly. The student will help the scientists and engineers of Spintec in designing an electron blanker that should be operated at high frequency. The topics covered are ranging from the modelisation of a blanker using dedicated software along with technical drawing, design of the final solution that will be made in-house with the TechniLab available and operation of such stroboscopic TEM with the drawing of the first figure of merit.

Description

The emergence of magnetic memories in a fast access fashion is a key for joining together their robustness, low consumption and long term stability to the microelectronic chipsets design standards for mass production. Among numerous challenges and locks still to open, the way to write/read this memories using single current (by transferring spin properties of the electron flow to the magnetic state of the memories) and the micromagnetism at play (coding of the data in terms of magnetic domain or domain wall, reversal of the bit by domain wall mediation or vortex nucleation) still need to be chosen. It is thus mandatory to possess a tool that can at the same time scrutinize the inner magnetic structure of these new memories and operate them in a dynamical fashion.

The subject proposed here aims at developing the Transmission Electron Microscope (TEM) which is an unavoidable tool for the nanoscale characterization bringing spatial resolution, now in the picometer range, and sensitivity ranging from atomic chemistry to nanomagnetic fields. Still, temporal resolution is actually limited to the low millisecond range as TEM requires long time exposure for detector to exhibit a significant Signal-to-Nose Ratio (SNR). A common way to overcome such time limitation is to use stroboscopic methods where the detector is opened quickly (time windows in the nanoseconds range) after the process starts (tunable delay), then the process is restarted to sum the same time windows until SNR is significant. It is more convenient to push the electrons away from the detector as the dynamic that we expect to probe is in the MHz regime. Only electrostatic deflection may reach such values. So to speak, we need to implement in an existing TEM, that will be dedicated to that project, a system of high energy electron deflection that could be operated at high frequency (> MHz).

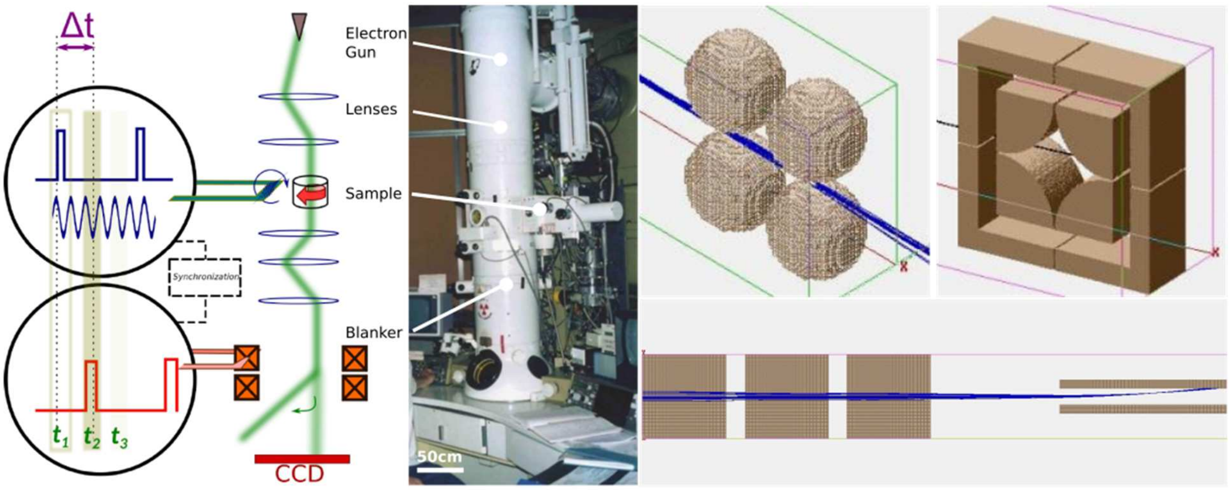

Figure 1: (Left) Principle of the stroboscopic instrument: the sample (here a magnetic vortex) is excited with a pulse at t_1. At t_2 (after Δt) the electron beam is released and hit the CCD (electron detection). The process is reproduced over a long number of repetitions to enable enough statistic in the final image. Other times (e.g. t_3) may be probed during another acquisition. (Middle) Photography of the TEM used for the training. (Right) Various blanker geometries explored through modelling (SIMION software) to achieve the blanking.

The Master internship will tackle together (i) the design of a high energy electrons blanker in static and dynamic mode, (ii) the fabrication supervision of the selected design and (iii) the first experiments of the stroboscopic method in the TEM. Each of these three goals will be conducted with the help of the exceptional scientific environment of Spintec in CEA : the experts in TEM and e-beam lithography (that used similar commercial blanker but at lower energies), the PFNC characterization platform fitted with a TEM dedicated to the project and a TechniLab offering a full set up of tools for prototyping the blanker. Moreover we aim at implementing such a system within CEMES lab in Toulouse (worldwide known as expert in electron optics) and the internship will also be made in strong collaboration with CEMES scientists (travels to be expected). Once the system will be installed the student will have the available tool to promote high frequency magnetic imaging within a fruitful PhD in Spintec Lab.

Requested skills
Nanosciences knowledge (TEM, electromagnetism, high frequency)
Instrumentation (mastering a drawing tool as SolidWork would be strongly appreciated)
Computation and modelling (dedicated software for electron trajectory – SIMION – will be learnt)
Handy with practicals (Vacuum, Electrical connexions, Instrumental)

Possibility to follow with a PhD : Yes

Proposal N° : 19

Contacts

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Bernard DIENY bernard.dieny@cea.fr +33(0)4 38 78 38 70

Title

Modeling and design of hybrid CMOS/magnetic circuits based on newly discovered spintronics phenomena

Keywords

Spin electronics, compact models, CADENCE, circuits design, spin orbit

Summary

Spin electronics is a merging of microelectronics and magnetism which aims at taking advantage of the best of the two worlds. Magnetism is very appropriate for memory functions since it allows encoding information in a nonvolatile way via the direction of magnetization of magnetic nanostructures. Magnetic memories called MRAM (Magnetic Random Access Memories) are about to be launched in volume production at several major microelectronics companies. For readout, these memories use the magnetoresistance of magnetic tunnel junctions while the writing is performed by using the magnetic torque that a spin-polarized current exerts on the magnetization of a magnetic nanostructure (spin transfer torque). But spinelectronics keeps on progressing and new phenomena have been discovered since then on which our laboratory is actively working. These new phenomena rely on spin-orbit interactions and on the control of the magnetic properties of magnetic nanostructures by electric field rather than magnetic field or spin transfer torque. They enable the conception of memories and non-volatile logic circuits working at multiGHz frequency and exhibiting extremely low power consumption. The purpose of this internship will consist in integrating these new devices in the standard design flow of electronics and evaluate their use in simple circuits like non-volatile standard cells for digital design, small memory matrix or radiofrequency spintronics oscillators. These circuits' performances will be benchmarked with those of equivalent circuits using standard technologies.

Description

Spintec lab aims at making the bridge between upstream research in magnetism and microelectronics applications. Spintronics consists in using magnetic devices in addition to standard microelectronics devices to push forward the physical barriers that limit integrated circuits scaling. These devices are the basic blocs of an emerging memory technology, called MRAM for Magnetic Random Access Memory. These memories are part of resistive non-volatile memories. They combine several advantages for logic circuits, that are not gathered by any other memory technology: intrinsically non-volatile, they have an operation speed close to the one of SRAM, a density close to the one of DRAM and a quasi-infinite endurance.

A lot of academic studies have shown the advantages in terms of performance, power consumption and new functionalities that can be expected in computations systems for various applications. The biggest actors of microelectronics are investigating this technology in its standard version, with Spin Transfer Torque (STT) writing scheme. However, while STT becomes more and more mature and close to industrialization, new generations are studied in laboratories and in particular at Spintec, like electric field assisted writing scheme of spin/charge current interconversion by spin orbit effect. These new technologies promise still better performance but are actually at the stage of theoretical studies, from fundamental understanding to materials developments.

The aim of the internship is a preliminary evaluation of the advantages that can be expected from memory and logic circuits using these new concepts. It will be necessary to develop compact models of the devices and integrate them in the standard tools of microelectronics for electrical simulations. These models will then be used to design elementary circuits which will allow in the long term an evaluation of the gains for more complex circuits. The internship could address the following tasks :

- Compact model development for electrical simulations using the design suite CADENCE.
- Validation of these models by comparison with experimental results obtained in the lab or from the literature.
- Design of elementary circuits like non-volatile logic gates (NOR, NAND ...), small memory blocks or spintronics RF oscillators.
- Evaluation of the performance of these circuits compared to the equivalent state of the art.
- Writing of scientific articles an internship report.

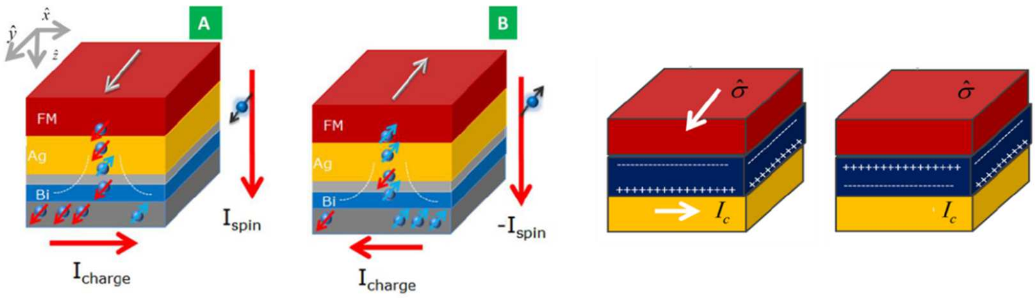

Figure 1: Spintronics devices associating two types of components : ISHE/Rashba metallic pillars converting vertical spin current into horizontal charge current (left) and Magnetoelectric insulating capacitors allowing to switch the magnetization of nanomagnets (right)

Requested skills

The candidate should have a master degree or equivalent, from university or engineer school. His skills should cover microelectronics full-custom/circuit level design preferably using Cadence. VerlilogA language programing 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 which could be made in English. An attraction for research and multidisciplinary are very important for this internship.

Possibility to follow with a PhD : Yes

Proposal N° : 20

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Title

Theoretical studies of spin-orbit phenomena at interfaces comprising two-dimensional and magnetic materials

Keywords

spin-orbit phenomena, 2D materials

Summary

This internship project aims on unveiling microscopic mechanisms of spin-orbit phenomena including Dzyaloshinskii-Moriya Interaction (DMI) and perpendicular magnetic anisotropy (PMA) in magnetic nanostructures comprising 2D materials (graphene etc) in order to help optimizing spintronic and provide the scientific underpinnings of next generation energy efficient, ultrafast and ultrasmall spintronic devices.

Description

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 or Dzyaloshinskii-Moriya interaction have become of tremendous interest since they play a major role in particular for magnetic random access memories such as based on spin transfer torque (STT-MRAM) and spin-orbit torque (SOT-MRAM). At the same time, 2D materials such as graphene or two-dimensional have been of major interest in recent years since they may serve as an efficient alternatives for these and next generation of spintronic devices.

The purpose of this Master internship is to address spin-orbit phenomena with focus on perpendicular magnetic anisotropy and Dzyaloshinskii-Moriya Interaction mechanisms including its temperature dependence and possibility of electric field control (VCMA). The calculations will be performed on Spintec computer cluster nodes using first-principles packages based on density functional theory (DFT) combined with other simulation techniques. Results obtained will be analysed with possibility of publication in international scientific journals. Strong collaboration with labs in France and abroad is previewed.

Requested skills

Good background in solid state physics, condensed matter theory and numerical simulations

Possibility to follow with a PhD : Yes

Proposal N° : 21

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Title

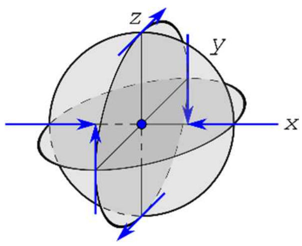
Multiscale modeling of a Bloch point, the only singularity in a ferromagnetic body

Keywords
Bloch-point, Micromagnetism, Ab initio modeling, Domain wall, Topology

Summary

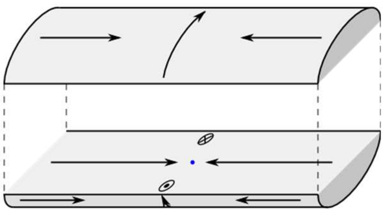
The distribution of magnetization at the nanoscale in matter, such as magnetic domains, domains walls and skyrmions, display a rich physics while providing an excellent basis for non-volatile data storage in the semi-conductor industry. Micromagnetism is the theory describing magnetization at this scale, based on a continuous vector field. While its success in describing reality is outstanding, an exception has been remaining stubbornly since decades: the Bloch point. The latter represents a singularity in the vector field for magnetization, predicted by topology to exist for certain boundary conditions [FIG. (a)]. Its existence is proven experimentally, e.g., in domain walls in cylindrical nanowires [FIGs. (b), (c)], resulting in both unique physical properties, and interest for domain-wall-based memory devices.

The purpose of the internship is to provide for the first time a faithful description of the Bloch point at all scales, from tens of nanometers down to the scale of atoms. The former will be described with various micromagnetic codes, all developed in the lab and thus customizable, while *ab initio* simulations (first principles) will describe the latter. Ab initio is indeed required to address properly the local quenching of magnetic moment in band magnetism. The student will conduct both types of simulations under the guidance of experts, while being in contact with a team of experimentalists working on real systems hosting Bloch points. The continuation as a PhD is encouraged.



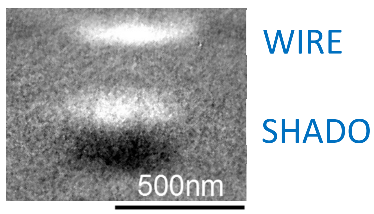
(a)

Sketch for the topology of magnetization around a Bloch point



(b)

Open sketch of a domain wall in a cylindrical nanowire, embedding a Bloch-point at its core



(c)

Experimental observation of a Bloch-point domain wall in a nanowire. The dark/light contrast highlights the circulation of magnetization around the Bloch point

Description

The specific properties of magnetism at the nanoscale have fueled most of the advances in modern magnetism over the past decades: spintronics, bringing together delocalized charge transport and localized magnetism; unusual magnetic anisotropy at interfaces, for instance promoting perpendicular magnetization; the statics and dynamics of spin textures such as domain walls and more recently skyrmions. Besides the advancement of knowledge, the resulting new properties resulted in novel functions for devices: spintronics has become a key in magnetic sensors; allowed great progress in the density of hard disk drives, and has made the development of random access memory possible. Perpendicular magnetic anisotropy has been crucial to increase the thermal stability of magnetic data storage solutions to smaller sizes; spin textures are being investigated as new ways to store and process data, especially in the framework of artificial intelligence.

The understanding and prediction of the statics and dynamics of spin textures (the distribution of magnetization in space) is crucial in both the fundamental and applied aspects mentioned above. Theoretical and numerical micromagnetism are now routinely applied to all aspects of nanomagnetism and spintronics. However, the Bloch point, the only expected singularity in a ferromagnetic body, cannot be described by micromagnetism. Yet, Bloch points are known to be involved in realistic spin textures of prominent interest, such as a transient objects during the sub-nanosecond nucleation and annihilation processes of magnetic skyrmions (a chiral type of circular magnetic nanodomain), or even at rest in so-called Bloch-point walls. These are magnetic domain walls specifically found in cylindrical magnetic nanowires. These walls have been predicted to be unique compared with their counterpart in thin film samples, in the sense that their topology should prevent them from suffering of dynamic instabilities, reaching large speed up to 1 km/s. This is a key topic being investigated experimentally in the spin textures team.

The proposed internship will be conducted largely in the theory group. It aims at contributing to a better theoretical understanding of this exotic micromagnetic object, the Bloch point. The student will perform *ab initio* simulations of a Bloch point in a 3d element, to understand to which extent the band splitting related to the ferromagnetic order is quenched, both in strength and spatially. Co and Fe will be both investigated as they display a very different sensitivity on competing energies favoring ferromagnetic versus antiferromagnetic orders. These are demanding computations, as the lack of translational symmetry requires a sphere of a few nanometers to be considered, including tens to hundreds of atoms. The boundary conditions of the ab initio calculations will be provided as the output of micromagnetic simulations at a larger scale. In parallel, micromagnetic simulations will be performed to estimate the impact of the existence of a Bloch point within a domain wall on the macroscopically relevant phenomenon of pinning (the domain wall does not move, feeling a local potential well related to a defect). The student will remain in close interaction with the experimental spin textures group. Through the internship, we expect to gather first results to improve our fundamental understanding of the Bloch point. Beyond the scientific curiosity of the frustration of ferromagnetic order by topology, the knowledge of the atomic-scale distribution of spin and band splitting is expected to be a key in macroscopic phenomena such as domain-wall pinning. The full extent of the open questions on Bloch points extends much beyond the scope of an internship, and would be tackled at the scale of a PhD. Questions extend to the magnetization dynamics of Bloch points and its truly multiscale modeling. Further modeling tools shall be used and/or implemented, such as atomistic calculations and the Landau-Lifshitz-Bloch formalism, allowing the local cancelation of the magnetization vector in micromagnetism.

Requested skills

Students are expected to come with a reasonable background in condensed-matter magnetism, and display a taste for computer-based physics and teamwork.

Possibility to follow with a PhD : Yes

Proposal N° : 22

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Title

Modeling of domain wall dynamics in core-shell nanowires: towards 3D spintronics

Keywords

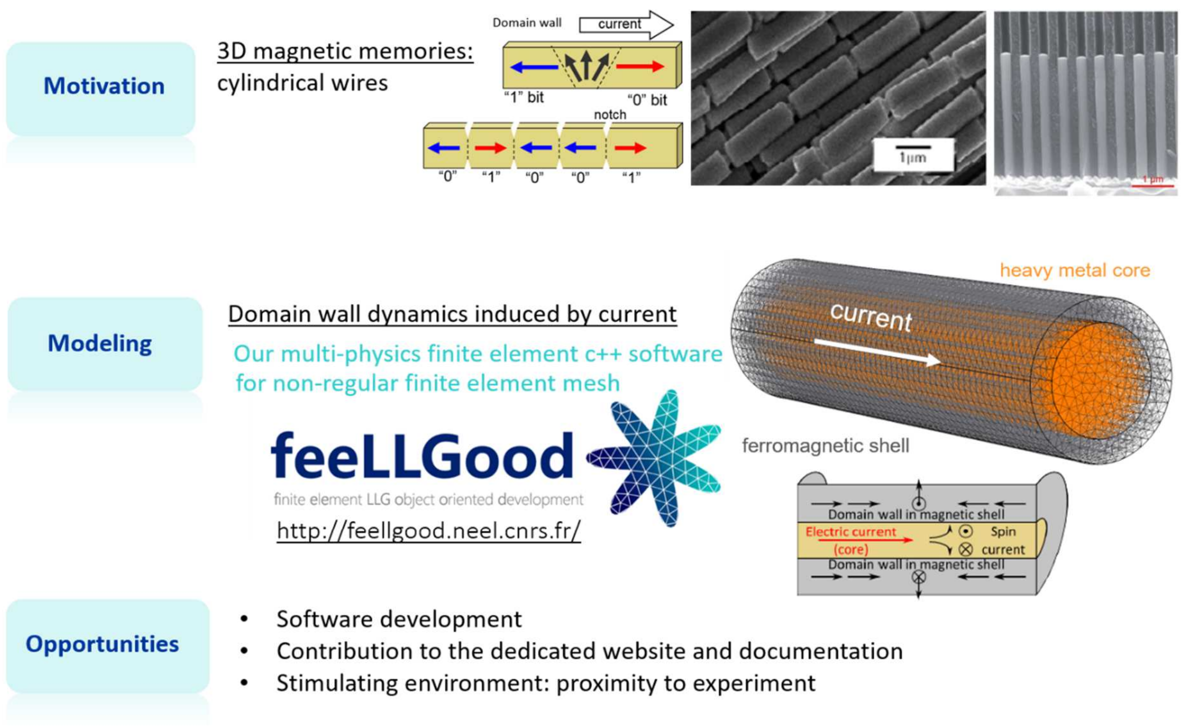
Finite element modeling, magnetic nanowires, domain wall, spin Hall effect

Summary

Recent progress in domain wall nucleation and its control in cylindrical nanowires makes them fascinating objects for fundamental research as well as for data storage advanced technologies. In these systems the interplay between magnetization and 3D properties results in novel physical phenomena such as unconventional spin textures, additional energy terms due to curvature or spin wave non-reciprocity. Three-dimensional spintronics exploits the interaction of magnetization with spin polarized currents in such cylindrical objects in view of designing the 3D building blocks for magnetic storage devices. The advancements of experimental techniques in this field 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 multipurpose micromagnetic finite element C++ software jointly in Spintec and Néel Institute. Our software is permanently enlarged with new physics to accompany experimental development. The first release of our open source code with basic functionalities is available on a dedicated website http://feellgood.neel.cnrs.fr/. The purpose of this PhD project is to model the domain wall dynamics in so-called core-shell cylindrical wires induced by spin-orbit effects. It will require the appropriate extension of our software which is an excellent opportunity to get familiar with finite element modeling and contribute to the development of the multi-physics software for spintronics. Given that, we are looking for a candidate who has affinity for numerical modeling and analytical calculations.

Description

The objective of this internship project is to model physical phenomena induced by applied current in core-shell cylindrical nanowires and to contribute to the development of dedicated open source cross-platform simulation framework *feeLLGood*. Cylindrical nanowires and tubes are studied experimentally and theoretically in our laboratory in a view of designing the building blocks for 3-dimentional low-power and high-density magnetic memories. Three-dimensional spintronics based on cylindrical wires and tubes exploits the interaction of magnetization with spin polarized currents. The information stored in a single material wire, for example, 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. Our recent experimental advances done in nanowire elaboration and characterization contribute to stimulating environment and strong interaction between experimentalists and theoreticians on this topic. For example, we showed that cylindrical geometry favors very high domain wall velocities which is beneficial to low-power and high-speed memory applications [M. Schöbitz et al, Phys. Rev. Lett. 123, 217201 (2019)]. In addition to 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 theoretically in the frame of this internship. In parallel to experiments, our group is working of the development of the novel finite element multi-physics software combining magnetization dynamics and spin transport for spintronics modeling [M. Sturma et al. Phys. Rev. B 94, 104405 (2016)]. The first release of our open source code with basic functionalities and corresponding documentation are available on a dedicated website http://feellgood.neel.cnrs.fr/. This internship will contribute to extend our software with spin-orbit coupling induced effects particularly relevant in heavy metal/ferromagnet core-shell nanowires. Moreover, we aim to complete our development with specific post-treatment and imaging modules in order to propose consistent cross-platform simulation framework for large number of users.



Requested skills
M2, affinity for numerical modeling, solid state physics, magnetism, spintronics

Possibility to follow with a PhD : Yes