Master Thesis Projects 2020

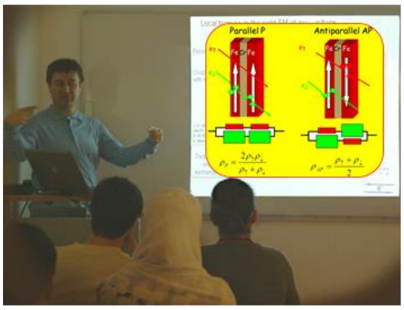
SPINTRONIQUE et TECHNOLOGIE des COMPOSANTS

www.spintec.fr

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.




https://www.linkedin.com/company/spintec-lab/

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, IDEX, IRS), academic contracts (ANR, EU,) 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!

Hoping to see you soon,
Lucian PREJBEANU, Director
Olivier FRUCHART, Deputy Director
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TOPICS FOR MASTER THESIS

MRAM memories

1 - MRAM based neuromorphic cell for Artificial Intelligence
2 - All-optical switching in spintronic devices
3 - Magnetic MRAM memory and magnetic field sensor: multi-functionality for 3D assembly

Magnetic sensors

4 - Magnetic field sensor based on magnetic tunnel junction

Microwave devices

5 - Study of RF-to-DC conversion using spintronics devices
6 - Coupling arrays of non-linear nano-oscillators: a theoretical and experimental study

2D and Semiconductor spintronics

7 - Valleytronics using light, electric fields and heat in 2D transition metal dichalcogenides
8 - 2-dimensional ferromagnets for spintronics: growth and transport in van der Waals multilayers
9 - Study of 2D materials growth using Transmission Electron Microscopy

Spinorbitronics

10 - Study of the charge current – spin current interconversion in Rashba-Edelstein interfaces and topological insulators surfaces.
11 - Magnetic skyrmion in ultrathin nanostructures
12 - Magnetic 3D topological insulators

Antiferromagnetic spintronics

13 - Probing nonlinear spin fluctuations at the nanoscale using spin-dependent transport

Health and Biology

14 - Magnetically actuated artificial membranes for biotechnology

Spin textures

15 - Spintronic samples design and electron optics for *in operando* Magnetic imaging

Spintronic IC design

16 - Modeling and design of hybrid semiconductor/magnetic circuits based on the interconversion between spin and charge currents and on the control of magnetic properties by electrical field

Theory and Simulation

17 - Micromagnetic study of a voltage controlled skyrmion chirality switch
18 - Modeling of spin Hall induced domain wall dynamics in core-shell nanowires
19 - Theoretical studies of spin-orbit phenomena at interfaces comprising magnetic and nonmagnetic materials in a view of memory devices

Proposal N° : 1

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Title

MRAM based neuromorphic cell for Artificial Intelligence

Keywords

Spintronics, Magnetic memory, MRAM, neuromorphic cell, multilevel states

Summary

Applications in artificial intelligence architectures require cell elements that can take multiple states based on different cell inputs. Hardware realizations of such elements can also be realized on magnetic non-volatile memory (MRAM) cells. This technology being developed at Spintec, associates non-volatility with fast switching of the order of a few nanoseconds. In conventional binary memory applications only two possible states are available for each cell. However, mimicking neuron behavior requires the possibility of multiple output states. This can be obtained based on individual MRAM pillar elements that are then connected as parallel or series resistors. The global measured resistance state will depend on the actual states of individual cells. The possibility to switch individual elements, while others also subjected to the same voltage maintain their original state relies on the natural dispersion of switching voltages. The goal of the internship will be to determine possible operation window to selectively switch individual memory elements and achieve stable multi-value outputs in the global cell. The sensitivity of parameters to control multilevel states will be investigated, focusing on pulse voltage and duration, applied magnetic field, and constant applied DC current. The temperature dependence of the cell characteristics will also be studied. Potential applications of this concept would be for example in memory computing that can be simulated once the electrical of multilevel cells is established.

Full description of the subject

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 conventional binary memory applications only two possible states are available for each cell. However, mimicking neuron behavior requires the possibility of multiple output states. This can be obtained based on individual MRAM pillar elements that are then connected as parallel or series resistors. The global measured resistance state will depend on the actual states of individual cells. The possibility to switch individual elements relies on the natural dispersion of switching voltages. All elements will be under the same applied voltage or current, but variability between opens the possibility to switch some elements, while other maintain their original state.

The internship work will consist in the validation multilevel output states in MRAM cell assemblies arranged in parallel or series configuration. The possibility to switch individual elements, while others also subjected to the same voltage maintain their original state relies on the natural dispersion of switching voltages. The goal of the internship will be to determine possible operation window to selectively switch individual memory elements and achieve stable multi-value outputs in the global cell. The sensitivity of parameters to control multilevel states will be investigated, focusing on pulse voltage and duration, applied magnetic field, and constant applied DC current. The work will consist in the identification critical parameters for multi-state operation to investigate and model cell operation. Different material stacks as well as the size of the memory element will be fabricated to multiple tunnel junction pillars. The experiments will consist of depositing magnetic multilayers, nano-fabrication (lithography, etching) in a clean room and then characterizing their magnetic and electrical properties.

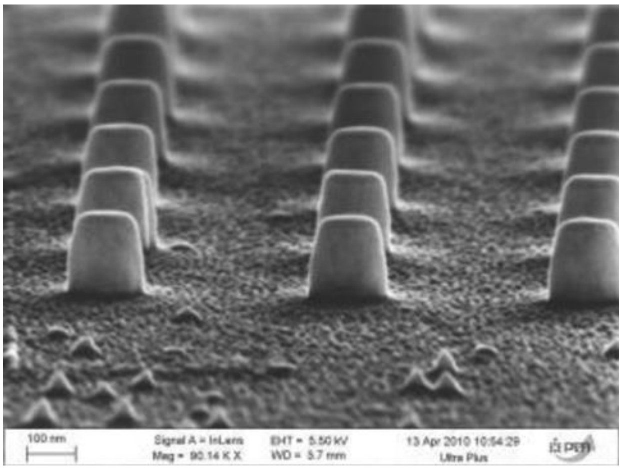

Figure: Image of magnetic tunnel junction pillars having 100nm diameter. Multiple individual cells will be connected in series or parallel to achieve a multi-level output for neuromorphic applications.

Requested skills
Master 1 or 2 in nanophysics/solid state physics, data analysis, programing, interest in nano-electronics

Possibility to follow with a PhD : Yes

Proposal N° : 2

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Title

All-optical switching in spintronic devices

Keywords

Spin-electronics, magnetic memory, MRAM, STT-MRAM, magnetic tunnel junctions, all optical magnetic switching, photonics

Summary

Spintronics, or spin electronics, revolutionized the field of magnetic data storage in the 1990's thanks to the manipulation of spin properties of devices instead of, or in addition to, charge degree of freedom. Spintronics was triggered by the discovery of Giant Magnetoresistance and led to a new generation of hard disks for data storage, of magnetic field sensors and of non-volatile memories called MRAM. It contributed largely to the new development of the Internet Of Things (IOT). However, despite these major innovations, spintronic technologies have reached a ceiling and need now a major breakthrough to be faster, more scalable as well as more energy efficient. UltraFast Opto-magneto-spintronics is an emerging field of research that combines the ideas and concepts of magneto-optics and opto-magnetism with spin transport phenomena, supplemented with the possibilities offered by photonics for ultrafast low-dissipative manipulation and transport of information. Both light and spin currents can control magnetic order, though the mechanisms as well as the corresponding time scales and energy dissipations differ.We intend to demonstrate that the study of polarised light interacting with magnetic stucture in spintronic devices will lead to a better understanding of the fundamental physics behind light-matter interaction and will potentially lead to another revolution in the field of IOT including magnetic data storage, memory, logic, computing, sensor technologies. Particularly, we intend to show that the use of polarized light as a new degree of freedom may provide a way toward more efficient spintronic devices.

Full description of the subject

The discovery of magnetization reversal by femtosecond laser pulses in thin ferrimagnetic Gd/Fe/Co films, give the possibility to improve the write speed and reduce power consumption of such spintronic memory. All-optical switching (AOS) can be achieved in the femtosecond regime, promising terabit-per-second magnetic recording, at femtojoule per bit switch energies. Most of the optically switchable magnetic materials are rare-earth (RE)-transition metal (TM) systems, such as GdFeCo, TbCo, TbFe alloys, Tb/Co and Ho/Co multilayers, but some RE-free TM multilayers like Co/Ir heterostructures are also observed to be possibly switched by laser pulses. So far, AOS with a single pulses was only observed on amorphous GdFeCo alloys, but it was also predicted on TbCo alloys through an atomistic spin model.

Since TbCo has larger perpendicular magnetic anisotropy (PMA) or out-of-plane magnetic anisotropy than GdFeCo, which can help increase the stability of stacks and improve the scalability, it is an ideal candidate for optical switchable magnetic RAM (MRAM).

Perpendicular anisotropy, instead of in-plane anisotropy, can provide large energy barrier, which enables thermally stable elements beyond 45 nm technology node. And the perpendicular magnetic tunneling junctions (MTJs) can be pattern into circular shape rather than elongated shape. This facilitates manufacturability at smaller technology nodes. Besides, this can also reduce the dipole field interaction between neighboring cells, which contributes to increase the storage density.
The purpose of this internship will be to develop optically switchable storage layer materials that can be integrated in traditional tunnel junction pillar stacks to be used as MRAM cells.

Development of rare earth/ferromagnetic multilayers of Pt/Co or Tb/Co are the starting points to bring magneto-optic interaction to the field of spintronics. MTJ fabrication will explore various scenarios of photonics-assisted switching, where the optical pulses are used for heating up the MTJ, while simultaneously sending an electrical *write* current through the MTJ. The developed materials are to be optimized and integrated as an optically-switched layerstack. The aim is to realize an optically switchable magnetization layer in an MTJ stack, having a switching fluence comparable with state of the art for single layers. Taking advantage of the expertise of the laboratory in this field, we propose to participate in the growth of materials by sputtering, to characterize their magnetic and electrical properties. The magnetic stacks will then be nanostructured in our clean room in the form of electrically contacted nanometer pillars. The optical characterization of the MTJ stack will be done in collaboration with Radboud University using top-side illumination, using lensed fibers or high numerical aperture microscope objectives and/or SNOM. This gives the required parameters for integration with and illumination from the photonic layer. This internship or project is a part of a European Commission project: Spintronic-Photonic Integrated Circuit platform for novel Electronics (SPICE). Its objective is to realize a novel integration platform that combines photonic, magnetic and electronic components. It proposed new spintronic-photonic memory chip demonstrator with 3 orders of magnitude higher write speed and 2 orders of magnitude lower energy consumption than state-of-the-art spintronic memory technologies, which future enables petabit-per-second processor-memory bandwidths and highly energy-efficient exascale datacenters with reduced carbon footprint.

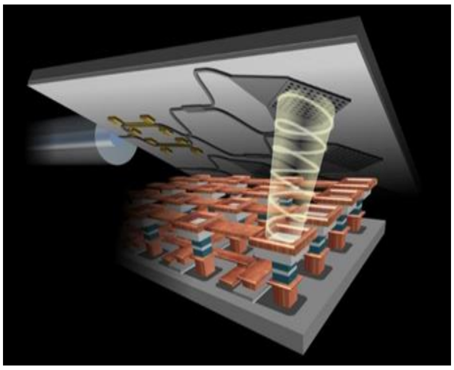

Figure: Schematic of a MRAM array with an integrated laser

Requested skills

nanosciences, nanotechnologies, solid state physics, basis of electronics

Possibility to follow with a PhD : Yes

Proposal N° : 3

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Title

Magnetic MRAM memory and magnetic field sensor: multi-functionality for 3D assembly

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 also 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 also of 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.

Full description of the subject

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 end 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.

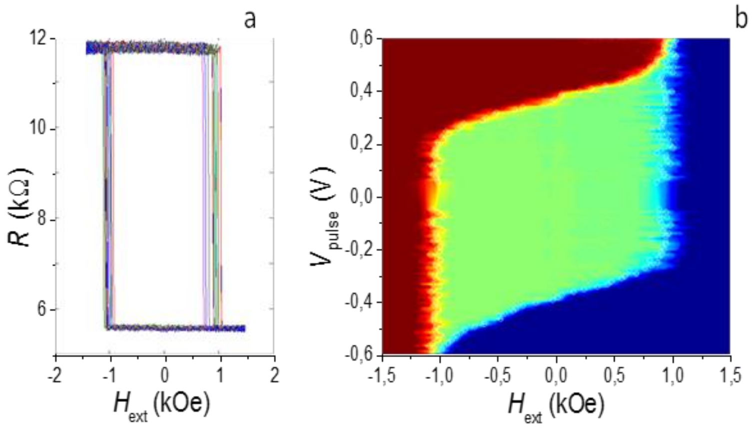

Figure: a) A Magneto-Resistive (MR) hysteresis cycle measured on a perpendicular anisotropy tunnel junction showing the variation of the resistance and 2 distinct resistance sates. b) A state phase diagram plot of the same junction when applying current pulses. The color code shows the resistance state, blue for low and red for high resistance, with green being the bi-stable region for memory cell use.

Requested skills

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

Possibility to follow with a PhD: Yes

Proposal N° : 4

Contact
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Title
Magnetic field sensor based on magnetic tunnel junction

Keywords
magnetic sensor, magnetic tunnel junction

Summary

The Spintec laboratory supports the R&D of Crocus-Technology, a company that develops magnetic field sensors. Optimizing the performance of these sensors, based on magnetic tunnel junctions, requires research on materials, micromagnetic configurations and junction transport properties, including magnetic and electrical noise. The purpose of the internship is to find ways to improve the sensors through numerical simulations as well as the measurement and analysis of the magneto-transport of samples at the state of the art in industry.

Full description of the subject

Magnetic tunnel junctions are composed of two ferromagnetic electrodes separated by an oxide barrier, of nanometric thickness, which electrons can pass through by tunnel effect. In these systems, the electrical resistance depends on the relative orientation of the magnetization of the two ferromagnetic layers. If one of the ferromagnetic layers has a fixed magnetization (reference) and the other layer has a magnetization that can be oriented according to the applied magnetic field, then the junction resistance can be used to measure the field. This is how the read heads of computer hard disks work. Nevertheless, each type of magnetic sensor requires specific developments, in terms of field range, sensitivity, detection threshold, frequency of use, etc.

Several properties are essential for a field sensor:

- *sensitivity*: it corresponds to the local slope of the sensor response curve and is directly related to two distinct characteristics of the magnetic tunnel junction, namely its tunnel magnetoresistance rate (TMR) and its saturation field (Hs). Maximizing sensitivity requires a high TMR and a low saturation field.
- *noise*: it is mainly due to thermal fluctuations of magnetization and traps contained in the tunnel barrier. It very often has a strong 1/f component that can become particularly problematic for low frequency applications. This is why it is essential to understand the different origins of noise in order to minimize it as much as possible.
- *linearity*: the sensor response must be linear over the range of use. The evolution of micromagnetic configurations in the field range considered can have a significant impact on the linearity of the response curve.

The main difficulty in improving the performance of a sensor is to find an optimal compromise between properties that sometimes evolve in the opposite direction. For example, for a given junction, increasing sensitivity also increases noise. This is why it is necessary to cross multiple approaches and play on materials, the geometry of junctions (size, shape, layer thicknesses) and the serial/parallel network architecture. The geometry of the junctions will have a considerable impact on the saturation field, the linearity of the response and potentially on the noise of magnetic origin. To anticipate these effects and propose the best geometries, it is necessary to carry out numerical simulations in order to predict the micromagnetic configuration of the sensitive layer and its evolution with the applied field. In addition, the use of a network of junctions makes it possible to reduce the overall noise by an average effect. However, we have not yet estimated all the consequences of the dipolar interaction between adjacent junctions. This question will require the implementation of numerical simulations of magnetic dots at different spacings and comparing with of the results obtained with electrical measurements of samples to the state of the art in industry. The magneto-transport measurements will be carried out using an automatic tip probe station, while the noise measurements will require the connection of a dedicated experimental set-up to the probe station.

Requested skills
Solid-state physics, nanosciences, basis on magnetism

Possibility to follow with a PhD : Yes (granted by Crocus-Technology)

Proposal N° : 5

Contact
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Title
Study of RF-to-DC conversion using spintronic 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.

Full description of the subject
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
Taste for experimental condensed-matter physics and its applications, collaborative work.
Master in physics and/or nanosciences. M2 level preferred, but also adapted for M1 level

Possibility to follow with a PhD : Yes

Proposal N° : 6

Contacts

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Title

Coupling arrays of non-linear nano-oscillators: a theoretical and experimental study

Keywords

Condensed matter, spintronics, spin transfer torque, nano-oscillators, non-linear dynamics, chaos

Summary

Spin momentum transfer allows exploring and studying the non-linear magnetization oscillations in nano-sized magnetic structures and opens potential for novel applications as integrated microwave components. A defining feature of spintronic oscillators is their non-linear dependence of the precession frequency on the amplitude (non-isochronicity) that provides for additional rf functionalities and that modifies the response to external rf signals. While in the past many studies have been performed on single oscillator devices, current efforts concentrate on the coupling of different oscillators to enhance the output signal and to reduce noise. Due to their specific features (non-isochronicity, conservative and dissipative coupling mechanisms, local and/or global coupling) spintronics nano-oscillators are an interesting model system to explore different coupling scenarios such as a fully coherent state, a chimera state, or a chaotic state. All of these states would find quite different applications in either wireless communication, secure communication or neuromorphic computing. Understanding thus the dynamic state of an array, as a function of the geometrical arrangement (1D lines, 2D arrays, ..), the different coupling mechanisms as well as the role of noise, will be an interesting fundamental study with important impact for various applications. This project will undertake a combined simulation and experimental study on the coupling of spintronics oscillators. The internship will start with simulations to guide experiments and during the PhD the student will be involved in the realization of the devices and carry out the dynamic characterization.

Full description of the subject

Spin torque oscillators find potential applications as nanoscale signal sources used for stable carrier signals in transceivers. Important progress has been made by our group and collaborators in the past years for demonstration of such oscillators in phase locked loops [1], for frequency [2] and phase shift keying [3] and as fast spectrum analyzers. A major route of increasing the output signal level is to coherently couple several oscillators. While experimentally coupling of oscillators has been demonstrated for the low frequency range (<1GHz), the coupling of devices in the higher frequency range (>1GHZ) and of more than two oscillators remains an experimental challenge.

The objective of the Master project, followed by a PhD, is to undertake a combined experimental and theoretical study on the coupling of spin torque oscillators. A main question concerns the role and efficiency of different coupling mechanisms such as dissipative (electrical via spin transfer torque) and conservative (via dipolar interaction) coupling, that can act locally or globally and that can act together or compete with each other when the oscillators are not identical (in frequency, in volume, in their non-linear response etc). Depending on these coupling mechanisms and on the geometrical configuration (lines, arrays…) different dynamical states may occur such as a fully coherent state, chimera state or chaotic state. This is a general problem of non-linear dynamical systems applied to nanoscale spin torque oscillators.

The studies will be realized for spin torque oscillators with different magnetization configurations that can be an in-plane or out of plane magnetization. This will lead to different oscillation amplitudes and dynamic dipolar interaction profiles (isotropic or anisotropic). The experimental studies will be guided by numerical simulations starting with two spin torque oscillator devices and then increasing the number. For the theoretical description an adequate model of the dipolar coupling or coupling via rf current will be established. This will be then implemented in the numerical simulation to investigate under what conditions a coherent, chimera or chaotic state will occur with an attempt to classify the different states as a function of: coupling mechanism (dissipative, conservative or both), coupling strength (modified through the distance between oscillators), symmetry of the coupling (identical and non-identical oscillators) as well as geometrical configuration and oscillation mode. The role of thermal noise on the robustness of the coupled state will be investigated. This theoretical description will guide the experimental realization of a network of coupled spintronic oscillator devices using our nanofabrication facilities (PTA cleanroom). The student will be trained to use the clean room facilities to realize the devices, will characterize the devices using our microwave laboratory and compare the experimental results to the theoretical descriptions.

The project provides multidisciplinary training on spintronics concepts (spin polarized transport, spin momentum transfer), linear and non-linear magnetization dynamics, on non-linear dynamical systems, nanofabrication and microwave measurement techniques.

[1] 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
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https://DOI.org/10.1063/1.4994892
Frequency shift keying by current modulation in a MTJ-based STNO with high data rate
[3] https://arxiv.org/abs/1905.02443

Requested skills

Taste for condensed-matter physics, nanoscience and collaborative work, interest to combine theoretical simulation studies to guide experimental work. Master in physics and/or nanosciences

Possibility to follow with a PhD : Yes

Proposal N° : 7

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Title

Valleytronics using light, electric fields and heat in 2D transition metal dichalcogenides

Keywords

2D materials, valleytronics, molecular beam epitaxy, semiconductors, thermoelectric effects

Summary

In the monolayer limit, two dimensional (2D) transition metal dichalcogenides (2H-MX_2, with M=Mo, W and X=S, Se) are semiconductors with a sizeable (1-2 eV) and direct electronic bandgap as well as (degenerate) valleys at the K+/K- corners of the Brillouin zone. Beyond their use as classical semiconductors, this peculiar electronic structure opens new and exciting possibilities for information processing that exploit the quantum degree of freedom known as the valley index. This emergent field of research is known as « valleytronics ». The valley degree of freedom is known to be more robust than the spin one. It has been established that K+/K- valleys can be selectively addressed by using circularly polarized light and electric fields by the valley Hall effect that allows resolving the valley polarization of charge carriers. More recently, we could show that temperature gradients also allow resolving the valley polarization through the valley Nernst effect (article under review in Nature Nanotechnology). The purpose of this master 2 internship is to generate and detect pure valley currents in WSe_2 using either electric fields or the absorption of circularly polarized light or both. The interplay between the valley degree of freedom and temperature gradients will be studied during the PhD.

Full description of the subject

Following the discovery of graphene, the properties of layered transition metal dichalcogenides (TMDs) **MX_2 (M=Mo, W and X=S, Se)**, especially when thinned down to a single monolayer (ML), make them very attractive for applications such as data processing (transistors), gas sensors, light detection (photodetectors), conversion (non-linear optics or solar cells) or emission (LEDs) [1]. While data processing and storage relies mainly on the charge and spin of the electron – sometimes exploited together in spintronic devices - MX_2 provide a unique access to the electron valley degree of freedom in reciprocal k-space. This new field of research, called valleytronics, may offer new functionalities for future devices both in classical and quantum data processing. For instance, for quantum computation, qubits constructed out of valley quantum dots may benefit from long coherence times and higher working temperatures thanks to valley protection of the spin states [2]. The generation, manipulation and detection of valley polarized carriers still remains a real challenge nowadays and an intense field of research. The *2D and Semiconductor Spintronics* team of Spintec is deeply involved in this topic.

To date, the TMDs are mostly studied in microflakes prepared by the "Scotch tape method", a manual and poorly reproducible top-down approach. Our team is one of the first European groups able to fabricate 2D materials [3,4] by molecular beam epitaxy (MBE). MBE enables the growth of extended single crystals (cm^2) in ultra-high vacuum and guarantees sharp interfaces at the atomic level (see Fig. 1a and 1b). Our team has also developed state-of-the-art optical and electrical techniques to study these 2D materials.

During the master 2 internship, the student will first grow WSe_2 mono or multilayers by molecular beam epitaxy and transfer the layers on SiO_2/Si substrate. The second step consists in processing simple devices like simple bars with source and drain (Fig. 1c) or double Hall crosses (Fig. 1d) by electron beam lithography to perform electrical and optical measurements and observe valley-related effects. The student will be trained to the molecular beam epitaxy of WSe_2 on mica and graphene substrates and to the layer transfer by well-established wet processes. Then, he/she will participate to the electron beam lithography process. For the physical measurements, the student will have full access to an OXFORD cryostat with optical access (1.6-300 K, 7 Tesla) and to a dedicated microscope equipped with an OXFORD Microstat (4-300 K), an electromagnet (0.3 Tesla) and circularly polarized light sources.

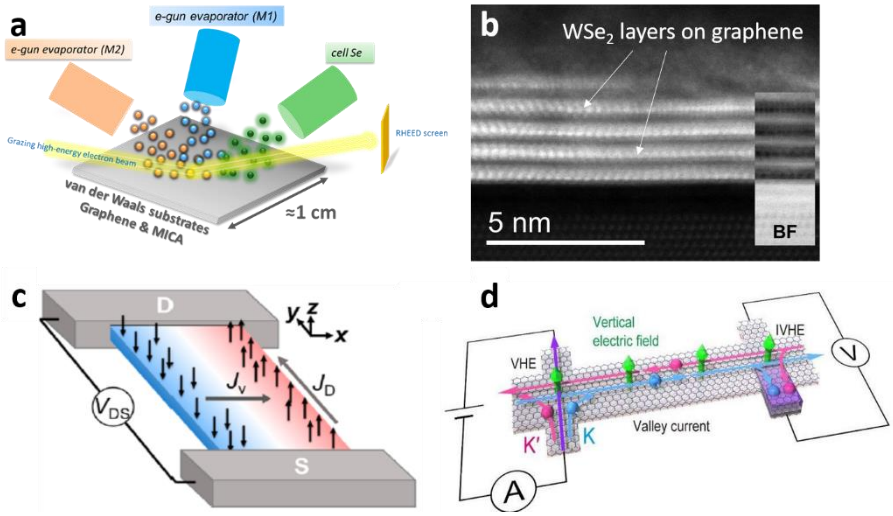

Figure: (a) Principle of MBE, with in situ electron diffraction. (b) Cross section transmission electron microscopy image of WSe_2 multilayers grown by MBE on graphene. (c) Illustration of the valley Hall effect that allows to generate a transverse valley current (J_V) applying a longitudinal electrical current (J_D) between source (S) and drain (D). Valley-polarized carriers are then accumulated at the edges of the track (red and blue contrasts). (d) Example of a simple valleytronic device where the valley current is generated (VHE) and detected (inverse VHE or IVHE) electrically in a TMD layer.

The project will involve collaborations with teams at Spintec, the CEA LETI, the Politecnico of Milan in Italy and the ICN2 in Barcelona.

[1] Novoselov *et al.*, *Science* 353, 462 (2016); arXiv:1608.03059
[2] Whitepaper from Valleytronics Materials, Architectures, and Devices Workshop, 22-23 August 2017
[3] Dau, Jamet *et al.*, *APL Materials* 7, 051111 (2019); arXiv:1906.04801
[4] Vergnaud, Jamet *et al.*, *2D Materials* 6, 035019 (2019); arXiv:1906.03014

Requested skills
M2 level in condensed matter physics, taste for experimental work and material growth, good communication skills.
Possibility to follow with a PhD: Yes, a funding is already secured for the thesis starting in 2020.

Proposal N° : 8

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Title
2-dimensional ferromagnets for spintronics: growth and transport in van der Waals multilayers

Keywords
2D materials, spintronics, molecular beam epitaxy, topological insulators

Summary
Research on graphene and 2D materials is currently very dynamic, as these materials show high potential for future 2D electronics. Due to their high surface-to-volume ratio and unique electronic structure, 2D materials show radically new proximity effects when they are combined into multilayers. Very recently, the first 2D ferromagnets have been discovered. This opens important opportunities for spintronics, in particular for making energy saving magnetic memories. The project aims at pioneering the fabrication of 2D ferromagnets with molecular beam epitaxy, a technique used to grow high quality materials and multilayers. The student will also employ various experimental techniques to perform material and magnetic characterizations. We will then study multilayers combining these films and other 2D materials such as transition metal dichalcogenides ($PtSe_2$, $MoSe_2$, WTe_2, etc.) and topological insulators (Bi_2Se_3, $BiSbTe_3$). By using magnetotransport and optical measurements, we will investigate proximity effects and demonstrate the electrical control of magnetization in all-2D spintronics devices.

Full description of the subject
Following the discovery of graphene, a large number of 2D nanomaterials have been discovered, in which confinement gives rise to extraordinary electronic, optical and magnetic properties. These materials span a wide range of properties: metals, insulators, semiconductors, superconductors, etc. Thanks to their layered structure and van der Waals interlayer bonding, they can be stacked in multilayers in order to design devices with completely new functionalities for 2D microelectronics [1,2].

In this family of 2D materials, ferro/antiferromagnets have been experimentally discovered only very recently (CrI_3 and $CrGeTe_3$ in 2017, VSe_2 and Fe_3GeTe_2 in 2018) [3]. Their strong perpendicular magnetic anisotropy and ultimate thinness make them choice materials for low power magnetic memories, based either on exotic magnetic order (skyrmions) or on electrical control of the magnetization (conversion between spin and charge). In addition, interfacing them with other 2D materials is expected to give rise to new phenomena, for instance the "ferrovalley" polarization with transition metal dichalcogenides (TMDs: $PtSe_2$, $MoSe_2$, WTe_2, etc.) and the quantum anomalous Hall effect with topological insulators (TIs: Bi_2Se_3, $BiSbTe_3$). The discovery of 2D ferromagnets has therefore opened huge opportunities for both fundamental and applied physics.

However, these materials are mostly studied in microflakes prepared by the "Scotch tape method", a manual and poorly reproducible top-down approach. The *2D and Semiconductor Spintronics* team at Spintec is one of the first European groups able to fabricate 2D materials (both TMDs [4,5] and TIs [6]) by molecular beam epitaxy (MBE). MBE enables the growth of extended single crystals in ultra-high vacuum and guarantees sharp interfaces at the atomic level (Fig. 1). Our team has also developed state-of-the-art optical and electrical techniques to study these 2D materials.

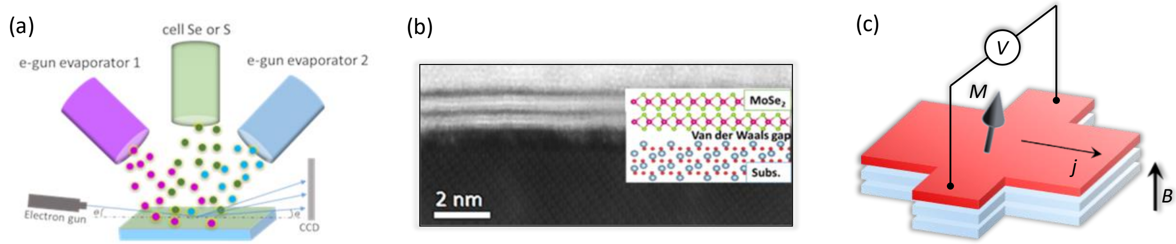

Figure. (a) Principle of MBE, with in situ electron diffraction. (b) Transmission electron microscopy image of a $MoSe_2$ bilayer grown by MBE. (c) Sketch of a Hall device that will be used to study 2D ferromagnets and multilayers with magnetotransport.

The objective of the internship is to pioneer the growth of high quality 2D ferromagnets by MBE, study their magnetic properties, then interface them with TMDs/TIs in order to realize all-2D spintronics devices.

We will first optimize the growth of Fe_3GeTe_2 by MBE with input from various material characterizations (electron and x-ray diffraction, atomic force microscopy, x-ray photoelectron spectroscopy). Magnetic properties will be studied with magnetometry (SQUID), magnetotransport (Hall effect), and optical measurements (MOKE). In a second step, we will enhance the spin-orbit interaction (SOI) by combining 2D ferromagnets with other 2D materials (TMDs, TIs) in fully epitaxial multilayers. The SOI couples the magnetization with electric fields and makes it possible to control the magnetism optically and electrically. We will investigate these effects in devices patterned by lithography. Our goal will be to evidence proximity effects specific to these 2D materials, and to demonstrate the efficient control of their magnetization. The project will involve collaborations with teams at Spintec and at ICN2, Barcelona.

[1] Novoselov *et al.*, *Science* 353, 462 (2016); arXiv:1608.03059
[2] Benitez, Bonell *et al.*, *Nature Physics* 14, 303 (2018); arxiv 1710.11568
[3] Gibertini *et al.*, *Nature Nanotechnology* 14, 408 (2019)
[4] Dau, Jamet *et al.*, *APL Materials* 7, 051111 (2019); arXiv:1906.04801
[5] Vergnaud, Jamet *et al.*, *2D Materials* 6, 035019 (2019); arXiv:1906.03014
[6] Guillet, Jamet *et al.*, *AIP Advances* 8, 115125 (2018); arXiv:1808.00979

Requested skills
M2 level in condensed matter physics, taste for experimental work, good communication skills

Possibility to follow with a PhD : Yes

Proposal N° : 9

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Title

Study of 2D materials growth using 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 and $MoSe_2$, have attracted tremendous attention for their exceptional optical and electronic properties ranging from semiconducting, to metallic or superconducting. The physical properties of these 2D layers are first defined by elemental components but also critically depend on their structural qualities such as crystallinity, domain size, atomic defects, etc. Since a few years our team has been developing the fabrication of high quality 2D-TMDs by hetero-epitaxial growth using molecular beam epitaxy (MBE). This growth technique using single crystal substrate and high purity elemental sources might lead to well-oriented large crystal formation with a great flexibility in the choice of the metals and low contamination. To understand the growth mechanisms and further to achieve well-controlled high quality materials synthesis, multidimensional and multiscale structural analysis are essential. Aberration corrected transmission electron microscopy (AC-TEM) is one of the most powerful techniques to study the structure of atomically thin 2D layers, allowing structural analysis from micron down to atomic scale. The aim of the internship will be to study the MBE based epitaxial growth of 2D-TMDs using AC-TEM techniques. For this purpose, the student will develop an analytical process to investigate the structural correlation between grown materials and growth substrate, requiring a combination of plan-view and cross-sectional analysis. The student will work mainly in the microscopy laboratory (LEMMA-IRIG) at Nano-characterization Platform (PFNC) and will also contribute to MBE experiments and other characterization techniques in the laboratory (SPINTEC) to get a more comprehensive view of the 2D systems studied.

Full description of the subject

Two-dimensional materials such as graphene are very promising materials with applications in various domains of the industry. 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 sheets 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 to stack 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 - 3] 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]. 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 to understand the growth mechanisms and the key parameters to improve the 2D layer quality. The aim of the internship will be to study the MBE based epitaxial growth of 2D-TMDs using AC-TEM techniques. For this purpose, the student will develop an analytical process to investigate the structural correlation between grown materials and growth substrate, requiring a combination of plan-view and cross-sectional analysis. In order to understand the detailed growth mechanisms from nucleation to crystal enlargement, these structural analysis will be applied for the samples obtained at each step of the growth process. The student will work mainly in the microscopy laboratory (LEMMA-IRIG) at the Nano-characterization Platform (PFNC) and will also contribute to MBE experiments and other characterization techniques in the laboratory (SPINTEC) to get a more comprehensive view of the 2D systems studied.

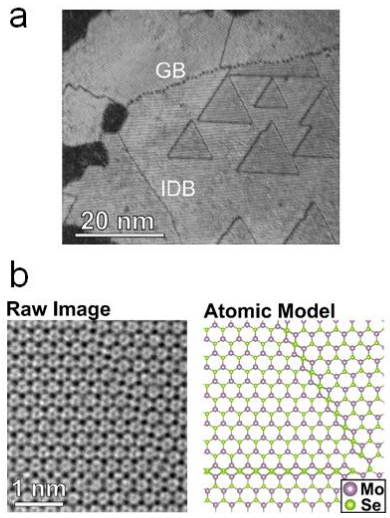

Figure: Aberration-corrected transmission electron microscopy (AC-TEM) image of a $MoSe_2$ layer; (a) overview of grain and inversion domain boundaries and (b) atomic structural analysis of inversion domain boundary [2].

[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)

Requested skills

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

Possibility to follow with a PhD : Yes

Proposal N° : 10

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Title
Study of the charge current – spin current interconversion in Rashba-Edelstein interfaces and topological insulators surfaces.

Keywords
Condensed matter, spintronics, nanostructure, spin currents, topological insulators, Rashba, 2D electron gas, oxides

Summary
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. Spin-dependent transport effects can thus be observed in very wide ranges of materials and interfaces, allowing spin manipulation in metals, oxides [1], semiconductors, Rashba interfaces, topological insulators, 2D materials, etc.

We will use the spin pumping phenomenon, which takes place at the ferromagnetic resonance, to inject a spin current from a ferromagnet into STO [2] and KTO-based Rashba systems [3], and into topological insulators such as HgTe [4] 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, nanodevices will be manufactured 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. It could however lead to beyond-CMOS logic and/or memory devices.

Full description of the subject
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. 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 very wide ranges of materials and interfaces, allowing spin manipulation in metals, oxides [1], semiconductors, Rashba interfaces, topological insulators, 2D materials, etc.

We will use the spin pumping phenomenon, which takes place at the ferromagnetic resonance, to inject a spin current from a ferromagnet into STO [2] and KTO-based Rashba systems [3], and into topological insulators such as HgTe [4] 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 load current spin conversion rates possible.

Once the optimal systems have been identified, nanodevices will be manufactured 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. However, this physics opens up new applications: in particular, our team has just received funding from Intel to study the potential of our systems for beyond-CMOS magnetoelectric spin-orbit logic [5], in collaboration with Albert Fert and Manuel Bibes (UMR CNRS-Thales).

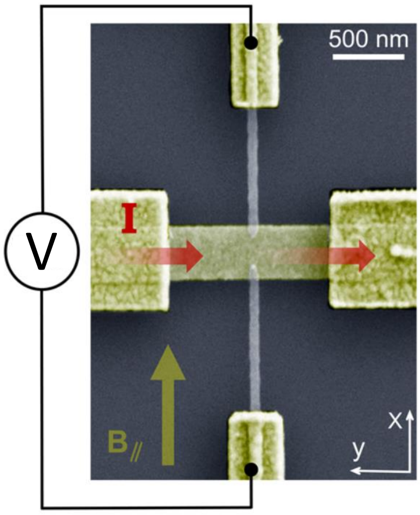

Figure 1 : Example of a nanodevice made in our team allowing the electrical measurement of the charge current - spin current conversion. The charge current travels along the horizontal track in the spin-orbit

[1] Vila, Attané *et al.*, *Nature Materials* 15.12, 1261 (2016)
[2] Vila, Attané et al., *Nature Materials* (2019)
[3] Vila *et al.*, *Nature Physics*, *14*(4), 322 (2018)
[4] Attané, Vila *et al.*, *Physical Review Letters* 120.16, 167201 (2018)
[5] Manipatruni *et al.*, *Nature* 565.7737, 35 (2019)

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

Possibility to follow with a PhD : Yes

Proposal N° : 11

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Title

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 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.

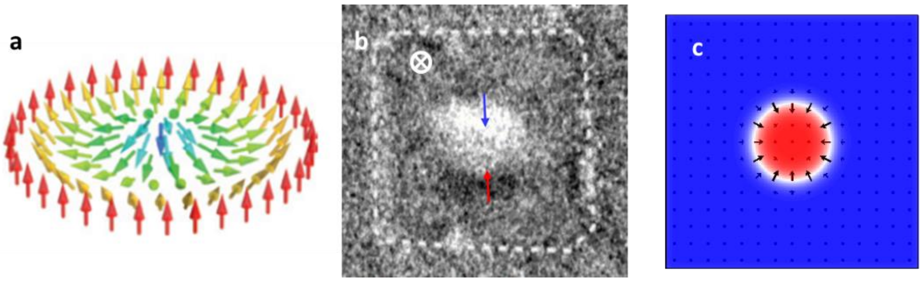

Fig. 1. a - Schematic representation of a magnetic skyrmion [1]. b XMCD-PEEM image of magnetic skyrmion (130 nm diameter) at room temperature and zero magnetic film in an ultrathin Pt/Co/MgO nanostructures [3]. *c. Spin structure from micromagnetic simulations.*

Full description of the subject

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).

Requested skills

Master 2 in nanophysics/solid state physics

Possibility to follow with a PhD : Yes

Proposal N° : 12

Contact

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Title

Magnetic 3D topological insulators

Keywords

Magnetism and Topology, Nanostructures, Nanofabrication, Magneto-transport measurements, Quantum anomalous Hall effect

Summary

Nanostructures of the magnetic 3D topological insulators $MnBi_2Te_4$ and $MnBi_4Te_7$ are candidates to realize novel chiral electronic states, similar to the quantum Hall state, but without the need of magnetic fields. The modification of the band structure by the exchange interaction is also predicted to generate axion insulators, with topological properties that can be tuned by the magnetization. Both antiferromagnetic and ferromagnetic topological insulators will be investigated by magneto-transport measurements, after nanostructures are prepared by mechanical exfoliation of high-quality single crystals and processed by standard clean-room techniques. In particular, the aim will be to reveal the quantum anomalous Hall state at higher temperatures than observed with diluted magnetic insulators.

Full description of the subject

Can a physical system resemble the quantum Hall state but in zero magnetic field?

In a magnetic 3D topological insulator, the coexistence of long-range magnetic order (exchange field) with topological electronic states (2D spin-helical Dirac fermions) leads to a metal-insulator transition (band-gap opening), which indeed generates dissipationless 1D spin-polarized edge states [1]. This novel electronic state, known as the quantum anomalous Hall effect, hold promises for ballistic spintronics and low-power interconnects in electronic devices. It was discovered in diluted magnetic insulators, but only at very low temperatures, due to both a rather small energy gap (small magnetization) and inhomogeneous magnetic properties. Yet, outstanding transport properties were evidenced, with a quantization of the Hall resistance already being very close to metrology standards [2].

A new family of van-der-Waals layered magnetic topological insulators, not diluted, now offers the possibility to investigate the rich interplay between the magnetic structure and topological electronic states [3,4]. $MnBi_2Te_4$ is an antiferromagnetic topological insulator with a Néel temperature T_N=23K and a perpendicular-to-plane magnetization. In ultra-thin nanostructures, novel electronic states are predicted (axion electrodynamics, QAH) with properties that can be tuned by applying small magnetic fields [4]. $MnBi_4Te_7$ is further a ferromagnetic-like topological insulator below about 2K, therefore being a candidate to evidence the QAH state with unprecedented accuracy.

During this master internship, nanostructures of MnBiTe compounds will be prepared by mechanical exfoliation of high-quality single crystals, and then processed using clean-room facilities (e-beam lithography, metal contacts, Hall-bar patterning). The magneto-transport properties will be investigated down to 1.8K, and eventually down to 50mK in a vector-field magnet (collaboration with the IFW Dresden, Germany).

[1] S. Oh, “The Complete Quantum Hall Trio”, *Science **340**, 153 (2013)*

[2] M. Götz *et al*., “Precision measurement of the quantized anomalous Hall resistance at zero magnetic field”, *Appl. Phys. Lett*. **112**, 072102 (2018)

[3] J. Li et al., “Intrinsic magnetic topological insulators in van der Waals layered MnBi2Te4-family materials”, Science Advances ***5**,* 5685 *(2019)*

[4] M.M. Otrokov *et al*., “Unique Thickness-Dependent Properties of the van der Waals Interlayer Antiferromagnet MnBi2Te4 Films”, *Phys. Rev. Lett*. **122**, 107202 (2019)

Requested skills

The candidate should have no allergy to scotch tape and show tenacity to exfoliate ultra-thin flakes and a taste for experimental physics in general.

Possibility to follow with a PhD : Yes

Proposal N° : 13

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Title

Probing nonlinear spin fluctuations at the nanoscale using spin-dependent transport

Keywords
Spin pumping, magnetic phase transition, spin Hall effect, ferro- and antiferro- magnets

Summary

In the field of spintronics, spin correlations due to *sd* exchange and spin-orbit interactions have attracted considerable attention, facilitating advances in basic physics along with the emergence of closely related applications. One of the related effect is known as the inverse spin Hall effect (ISHE), and is commonly used for spin-charge conversion in devices. The object of this experimental internship is to demonstrate the decisive exacerbating impact on the ISHE of non-linear spin fluctuations near magnetic phase transitions. Conversely, we will investigate how efficient the ISHE can be as a detector of these fluctuations in materials of different magnetic types: ferro- and antiferro-magnets. This internship will benefit from two SPINTEC teams' knowhow and state of the art techniques of fabrication and characterization at the nanoscale.

Full description of the subject

The generation of a spin current and its further conversion to a charge current are key to facilitating characterization and engineering of new materials for spintronics. In this context, an electrical current can be converted to a spin current and vice versa as a result of the spin-orbit interaction (SOI), which links the spin and the orbital angular momentum of an electron. As a result of SOI, a flow of charges (spin) causes transverse spin (charge) to accumulate. One of the related effects of this phenomenon, known as the inverse spin Hall effect (ISHE), is commonly used to study SOI in materials inserted into archetypal ferromagnetic-spin-injector/(spacer)/spin-absorber bilayers. In some of these studies, a spin current is pumped from the ferromagnetic spin-injector at resonance (FMR), and the ISHE ensures spin-charge conversion in the spin-absorber under test. This is known as FMR spin-pumping experiment.

The efficiency of spin injection was explored through studies of interfacial spin mixing conductance, a parameter quantifying the amount of spin-angular momentum absorbed at magnetic interfaces upon reflection and transmission. Deeper investigations of the influence of the static vs. fluctuating magnetic order for the case of magnetic spin absorbers indicated that spin fluctuations make spin injection more efficient as they open new conduction channels across the interface. As a result, spin injection was shown to be most efficient near the ordering transitions, i.e., near the Curie and Néel points for a ferromagnet and an antiferromagnet, respectively. This enhancement of spin injection actually relates to linear spin fluctuations (zeroth order in dynamic magnetic susceptibility). Among others, this topic was pioneered by SPINTEC.[1-3] Recent theoretical models predicted that the ISHE relates to second-order nonlinear spin fluctuations (third-order spin correlations), being therefore very sensitive to tiny variations of magnetic moments.[4)] A pioneering experimental study in the so-called non-local geometry validated the proposed mechanisms in weak ferromagnetic NiPd alloys.[5)] We recently identified one the main reasons why the targeted effect is scarcely reported in spin pumping experiments. It can be masked by self-induced spin-charge conversion in the spin-injector.[6)] (Fig.)

Using appropriate spin-injector/(spacer)/spin-sink multilayers, the object of this internship is to demonstrate how efficient the ISHE can be as a detector of nonlinear spin fluctuations in materials of different magnetic types: ferro- and antiferro-magnets. This internship is experimental. It will build on the techniques of fabrication and characterization at SPINTEC and benefit from the collaboration with the CEA-SYMMES laboratory for experiments with a resonant cavity.

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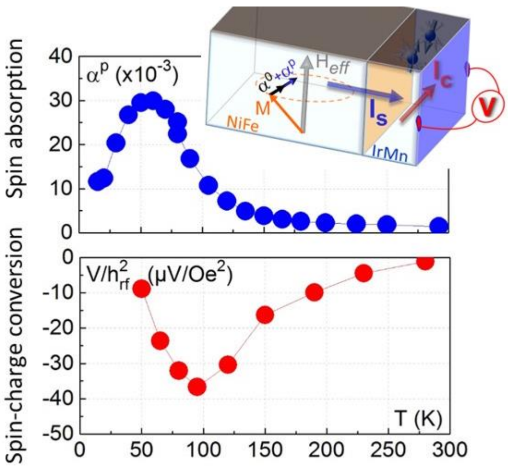

Fig. Increased spin absorption due to the linear spin fluctuations of the absorber near its magnetic phase transition (here, the IrMn antiferromagnet).2) Self-induced spin-charge conversion in the injector (here, the NiFe ferromagnet).6)

Requested skills

M2 level, experimental physics, material science, solid state physics

**Possibility to follow with a PhD : ** Yes

Proposal N°: 14

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Title

Magnetically actuated artificial membranes for biotechnology

Keywords

Magnetic microparticle, nanoparticle, flexible membrane, photonics, optics, magnetic actuation, biocompatible

Summary

New biocompatible magneto-elastic membranes have recently been developed at SPINTEC, based on the integration of magnetic microparticles previously investigated in biological studies [1]. Our earlier studies aimed at cancer cells destruction, through the low frequency magneto-mechanical vibrations of the particles dispersed among the cells [2). Here, on the contrary, magnetic particles are patterned in an array embedded in a transparent polymer film, the whole membrane being partially released and free to be deformed by application of a magnetic field. The great potential of such elastic magnetic membranes lies in their ability to be remotely actuated by an external magnetic field. The fabrication process of these membranes has already been established in the PTA clean room located in our building (Plateforme de Technologie Amont). For understanding the membranes behavior in an applied magnetic field, the magnetic state of the embedded particles will be investigated by vibrating sample magnetometry (VSM) and Magnetic Force Microscopy (MFM) (See Fig.1). Membranes with various compositions and dimensions will be then optically characterized with the objective of determining their micrometric deformations versus applied field. This study will be mostly experimental but may also include a modeling of the micromagnetic behavior of the particles and of the optical diffraction pattern produced by the deformable membrane. Such magneto-elastic membranes may be used as building blocks in a variety of applications combining magnetism, biology, biophysics, optics such as bioreactor cores for stimulating living cell functions, artificial muscles, components in adaptive optics, etc.

Full description of the subject

Artificial membranes are more and more explored for various applications. In particular in biology, for understanding the living or acting on it with therapeutic purposes, or in optics-related fields as flexible photonic devices. Biology and optics being potentially linked for instance in vision studies. Based on the magneto-elastic membrane recently developed at SPINTEC, the internship work will consist in deepening and broadening results that could be expected from optimized flexible devices, magnetically actuated. The intern will be first train in the various techniques required for the fabrication of magnetic particles / magneto-elastic membranes in the clean room (PTA). Membranes will consist of arrays of permalloy ($Ni_{80}Fe_{20}$) particles/pillars embedded in a polymer (PDMS). PDMS films are indeed known for their tunable elastic modulus, biocompatibility and optical properties (high transparency). The study will then include magnetic characterization through VSM measurements and MFM imaging of the magnetic response of the NiFe particles. The purpose will be here to precisely understand the magnetic behavior of the array of particle to be able to evaluate the force applied to the membrane under magnetic field. The MFM results will be compared to micromagnetic simulations.

In a second step, the fabricated membranes, suspended over a ring-shaped substrate, will be characterized by optical experiments. The resulting diffraction patterns in reflexion and transmission will be compared to analytical model predictions. This will allow to derive the membrane deformation versus applied magnetic field. We already showed that membranes, flat or deformed by the applied magnetic field, illuminated by a laser beam, produced a very strong optical response to the magnetic field in reflection, depending on their microstructure and concavity. The membranes turned out to constitute therefore magnetically tunable optical diffraction gratings for visible light wavelengths. For instance, the diffraction patterns of ~1cm-diameter-membranes could be significantly modified by slight membrane deflections, in the range of 50 µm down to a few hundreds of nm. Following earlier studies conducted at SPINTEC in the field of magnetic actuation for biotechnology [3] [4] [5], various applications could be envisioned for the present membranes: **i)** in biology, they could help to understand phenomena in the living, and to act on it with therapeutic purposes, or as in "artificial muscles" **ii)** in optics, the membranes could be used in flexible photonic devices.

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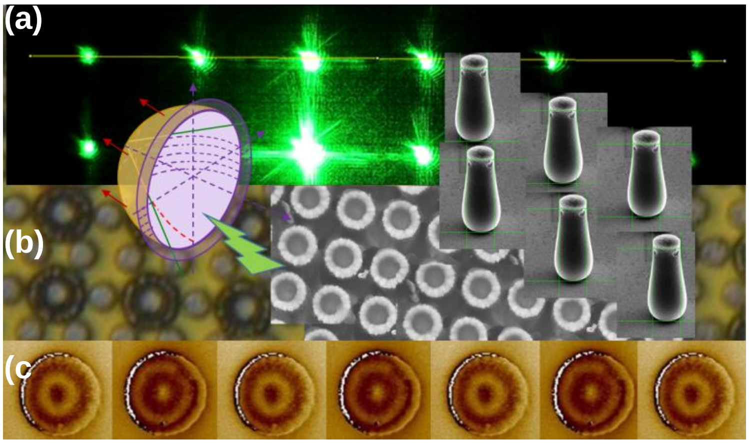

Figure: Sketch and microscopy images of suspended magnetoelastic membranes (polymer films with embedded magnetic particles of various shapes and thicknesses), yielding flexible and magnetically tunable diffraction gratings. (a) optical response of embedded magnetic micro-pillars arrays: diffraction pattern. (b) Optical/SEM (Scanning Electron Microscope) images of various magnetic particles/pillars arrays. (c) Example of magnetic particles MFM (Magnetic Force Microscopy) imaging.

Requested skills

Master 2 in nanophysics/solid state physics, knowledge/approaches of lithography technics, microelectronics, magnetism and optics applications interest.

Possibility to follow with a PhD : Yes

Proposal N°: 15

Contact

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Title

Spintronic samples design and electron optics for *in operando* Magnetic imaging

Keywords

Transmission Electron Microscopy, Nanofabrication, Magnetic Imaging

Summary

Electron Holography 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 obtained. 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 real devices (Magnetic Random Access Memories as a single example among others) during their operation (in operando). We thus need to prepare existing nano-devices for being able to observe them in a TEM that require electron transparency (below 100 nm thickness) still preserving their initial functions being addressable within the TEM. Moreover the possibility of quickly changing the physical state of the samples requires the capacity to handle and understand dynamical imaging via a continuously increasing set of images that need to be automatically acquired and numerically processed.

This internship will offer an important background and know how on nanoscale characterization, nanofabrication tools and data processing, thus enabling to discover various aspects of scientific research. The field of spintronics associated to such method offers the opportunity to understand and tailor an very broad panorama of physical phenomena in condensed matter, such as spin-orbit effects, Dzyaloshinskii-Moriya interactions and other interfacial effects.

Full description of the subject

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. However, TEM limits strongly the sample environment and design due to the necessary high vacuum, high voltage, limited space and also very low thickness (< 100 nm) that is mandatory for electrons to travel through the sample. So to speak, it is of fundamental importance to develop fabrication processes on "electron transparent" supports. Among various methods for preparing samples to fit into a TEM, the bottom-up approach of nanotechnologies enables to build at the same time a TEM-sample that fulfills all of the experimental constraints and to design the electrical circuit of the sample at the same time. We now use a combination of nanofabrication tools to promote such high level of engineering at the nanoscale but still need exploration of new routes of fabrication that fulfills TEM constraints. Last but not least, TEM is an integrative technique where the magnetic signal gained by the electron wave is integrated over the whole electron trajectory. It is thus necessary to simulate this integration from micromagnetic models to compare with the obtained phase signal of TEM. Image formation mechanism has thus to be mastered to compute the resulting signal, especially with a dynamical sensitivity and low experimental SNR.

The Master internship will tackle together (i) the electron microscopy methods for magnetic characterization (Electron Holography) in static and dynamic mode (ii) experimental design of the samples via a combination of nanofabrication tools and conventional microfabrication and (iii) image simulation for the understanding of experimental images. Each of these three goals will be conducted with the help of the exceptional scientific environment of Spintec in CEA : the PTA cleanroom facility and the PFNC characterization platform fitted with various TEM. Moreover the presence of experts in the various required field will bring to the Master student an efficient and interactive environment for promoting these ambitious objectives. We thus hope to continue this project during a PhD project.

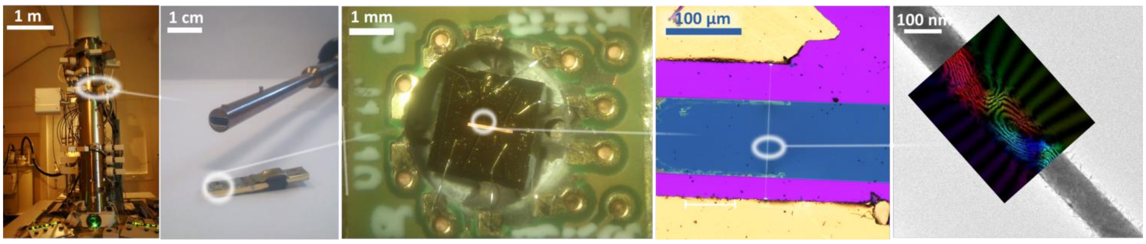

Figure : Length scales explored during the internship : from the m-scale electron microscope instrument (left) to the nm-scale resulting magnetic image (right displaying magnetic flux lines)

Requested skills
Nanotechnologies, Instrumentation, Handy with practicals, Solid State Physic, Computation

Possibility to follow with a PhD : Yes

Proposal N° : 17

Contacts

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Title

Micromagnetic study of a voltage controlled skyrmion chirality switch

Keywords

skyrmions, Dzyaloshinskii-Moriya interaction, perpendicular magnetic anisotropy, electric field effects, micromagnetic simulations

Summary

Skyrmions in thin films are spin textures across which the magnetization follows a cycloid with a unique sense of rotation, known as chirality. These specific magnetic patterns can be stabilized in various kinds of materials, and particularly in ultrathin trilayers with no inversion symmetry (e.g. heavy metal/ferromagnet/oxide) exhibiting simultaneously an interfacial interaction called Dzyaloshinskii-Moriya (DMI) and a strong perpendicular magnetic anisotropy (PMA). Since they are ideally topological solitons, skyrmions are currently attracting considerable interest both for the underlying physics and for their applicative potential. Their ability to be set in motion by electrical current opens the way to imagine them as dense storage data bits or magnetic logic operations. Furthermore, the possibility to tune magnetic interfacial properties by a gate voltage enables low power control of spintronic devices and provides a versatile, local and dynamic degree of freedom that can be implemented in innovative designs.In this context, in collaboration with Institut Néel, we have recently shown that a gate voltage can not only switch skyrmions *on* and *off* but also tune the interface properties (PMA and DMI). The new mechanism leading to DMI revealed by our experiments allows expecting a control of DMI sign, which would lead to an inversion of the skyrmion's chirality. In this internship, we target to study by micromagnetic simulations the possibility to change DMI sign and to demonstrate voltage controlled skyrmion chirality switch. This breakthrough would open new possibilities for skyrmion manipulation, as a change of chirality would invert the direction of current-induced motion. It will also open new and rich physics on the dynamical control of the topology of these solitons.

Full description of the subject

Topologically non-trivial magnetic structures called skyrmions[1] are magnetic bubbles with domain walls of a given chirality: when crossing the skyrmion radially, the magnetization rotates by 360° with a given sense of rotation. They can appear at room temperature in ultrathin trilayer systems, for example consisting of a heavy metal, a ferromagnet and an insulator such as Ta/FeCoB/TaOx, Pt/Co/AlOx and Pt/Co/MgO. Broken inversion symmetry and spin orbit coupling in these trilayers lead to antisymmetric exchange called interfacial Dzyaloshinskii-Moriya interaction (DMI)[2]. This exchange interaction gives rise to non-collinear magnetic textures and its sign determines skyrmion chirality. Skyrmions are currently attracting a wide interest as they could be used as dense bits of information that can be shifted with an electric current via spin-orbit torques: they are thus valuable candidates for memory or logic applications[3]. In 2007, interfacial magnetic anisotropy has been shown to be controllable with an electric field[4]. This breakthrough has opened a whole new research area and paved the way towards new gate-controlled spintronic devices. This new degree of freedom provides a versatile, local and dynamic tuning that can be implemented in innovative designs. Moreover, controlling by a gate voltage does not require a current flow and is thus energy efficient[5]. In this context, in collaboration with Néel Institute, we have shown the first proof-of-concept of a room temperature skyrmion switch device controlled by a gate voltage[6]. Moreover, we have recently demonstrated the first direct proof of an influence of gate voltage on DMI [7] (see Fig below). It also revealed a theoretically predicted mechanism leading to DMI (called Rashba-DMI) that had not yet been experimentally observed. Hence we can expect a sign reversal of DMI for appropriate gate voltages that could ultimately lead to a dynamic chirality inversion. Such chirality switch is very interesting, as it would change the direction of current-induced motion of the skyrmions. It would also open new and rich physics on the dynamical control of the topology of these solitons.

Within this internship, we thus propose to study the electric field effects on magnetic properties, and more particularly on DMI using micromagnetic simulations. First, we plan to explore the effect of a modification of DMI on the domain wall and skyrmion current-induced velocity. By creating local high-energy barriers with a gate voltage, the skyrmions propagation is likely to be strongly modified, possibly leading to gate voltage induced acceleration/deceleration of skyrmion motion under current. Besides, if DMI sign is changed by the gate voltage, an inversion of the most stable chirality is expected. It will thus destabilize the already present skyrmions. In particular, the dynamics of the chirality switching is expected to be strongly dependent on the rate of the electric (and magnetic) field changes with respect to the typical time scale of skyrmions evolution (nanosecond range). Depending on the electric field pulses rise time, different behaviours are expected between quasistatic and dynamic behaviours. The mechanism and time scale of the change of chirality of skyrmions will be thus studied. Furthermore, the use of patterned nanostructure in a real device could strongly modify this dynamic behaviour under gate voltage as lateral confinement might play a crucial role in stabilizing skyrmions during the rise time. Our simulations are thus expected to answer these dynamic behavior and confinement effect questions. Finally, these simulations will be used to design a chirality switch device and its operation methodology. This breakthrough would open new possibilities for skyrmion manipulation.

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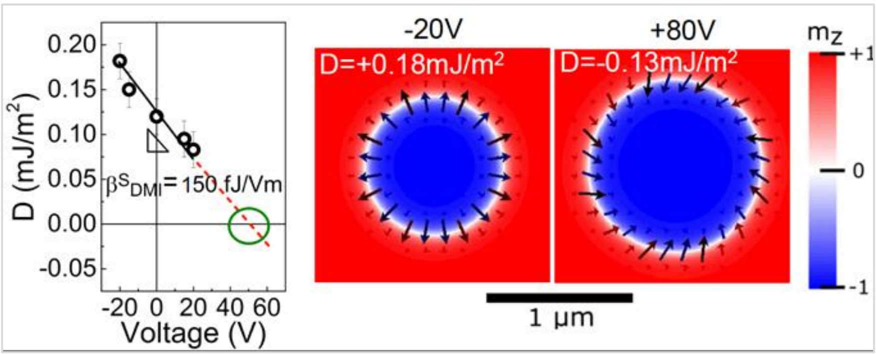

Figure: (left) Evolution of DMI with gate voltage on Ta/ FeCoB/ TaOx trilayers. Extrapolation (dashed line) of experimental points (circles) gives sign reversal of DMI for +50V. (right) Skyrmionic bubble configurations issued by micromagnetic simulation using experimental magnetic parameters (-20V) and extrapolated parameters (+80V).

Requested skills

Master 2 in nanophysics/solid state physics

**Possibility to follow with a PhD : **Yes

Proposal N° : 18

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Title

Modeling of spin Hall induced domain wall dynamics in core-shell nanowires

Keywords

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

Summary

Recent progress in domain wall nucleation and its control in nanostructures with tubular shape [see Figure 1] 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 in cylindrical geometries we have developed the multipurpose micromagnetic finite element C++ software [1] jointly in Spintec and Néel Institute. Our software is permanently enlarged with new physics to accompany experimental development. This internship is an excellent opportunity to get familiar with finite element modeling and contribute to the development of the multi-physics software for spintronics.

Full description of the subject

The objective of this internship is to model physical phenomena induced by applied current in core-shell cylindrical nanowires [see Figure1] – building blocks for 3-dimentional spintronics. The information stored in single material wire, for example, would be encoded by magnetic domains separated by magnetic domain walls. Domain wall motion in wires in order to write information may be achieved, for example, by applying an external magnetic field [2,3] or spin-polarized current [4,5]. The cylindrical geometry favors very high domain wall velocities which is beneficial to low-power and high-speed memory applications. 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. Moreover, recent experimental advances done in nanotube elaboration and characterization in our laboratory jointly with Neel Institute [6] will contribute to stimulating environment for the internship and possibly for further PhD project.

In this context, several aspects should be treated theoretically in order to understand the properties measured and further to guide the design using analytical modeling as well as our finite element based micromagnetic software [1], combined with the description of spin polarized current effects.

First, we plan to draw a panorama of domain wall types for a single material ferromagnetic tube as a function of material parameter and tube dimensions, since the domain wall dynamics subjected to field and current is expected to crucially depend on the orientation of magnetization in the domain wall. At this stage we will also quantify the contribution of the exchange interaction to favor the orthoradial magnetization, a possibility recently shown [6] and never considered before.

Second, we will focus on the core-shell structures with ferromagnetic shell and normal metal or heavy metal core. In the case of the normal metal core we will take into account the effect of the Oersted field generated by the flowing current and producing a torque on the magnetization of the shell, to move domain walls. This aspect have been recently included into our multi-physics software and does not require supplementary code development. In the case of heavy metal material core with high spin-orbit coupling, the direct injection of spin-polarized electrons inside the ferromagnetic shell due the spin Hall effect allows one to combine the spin-orbit torque efficiency with the high domain wall velocities within the same object. This step requires the extension of physical model used in the current version of our software. In particular, we will focus on the implementation of the bulk spin Hall effect completed with Rashba-Edelstein boundary conditions leading to a spin-orbit torque contribution in heavy metal/ ferromagnet bilayers. With this development we will be able to quantify the ability and the efficiency of the current to move domain walls within core-shell structure.

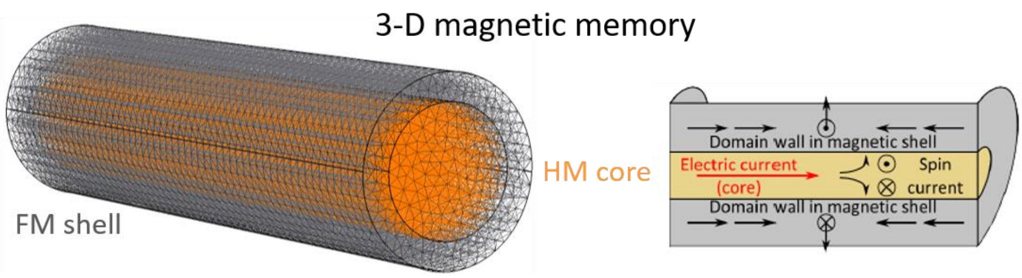

Figure 1 : Illustration of the novel core-shell based 3-D magnetic memory to be studied by our finite element software.

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[6] M. Stano, PhD thesis, https://www.theses.fr/2017GREAY063

Requested skills
M2, affinity for numerical modeling and programming, solid state physics

**Possibility to follow with a PhD : **Yes

Proposal N° : 19

Contact

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Title

Theoretical studies of spin-orbit phenomena at interfaces comprising magnetic and nonmagnetic materials in a view of memory devices

Keywords

spin-orbit phenomena, magnetic random access memories, first-principles and tight-binding approaches

Summary

This internship project aims on unveiling microscopic mechanisms of spin-orbit phenomena including perpendicular magnetic anisotropy in order to help optimizing spin-based memory applications and provide the scientific underpinnings of next generation energy efficient, ultrafast and ultrasmall spintronic devices.

Full description of the subject

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 solid-state storage class magnetic memory devices known as magnetic random access memories (MRAM). Among the latter, spin-transfer-torque MRAM (STT-MRAM) based on out-of-plane magnetized magnetic tunnel junctions (pMTJ) has become in recent years a subject of tremendous interest due to a number of advantages which could allow addressing, for instance, embedded FLASH and static random access memory-type of applications. However, there are fundamental problems to be addressed arising from two main critical requirements for these devices in which information is encoded in the form of magnetization orientation. First, in order to ensure good memory retention, magnetic layers used in pMTJs must preserve magnetic orientation against thermal fluctuations (thermal stability). Second, free layer's magnetization has to be manipulated efficiently, i.e. with lowest energy consumption.

The purpose of this Master internship is to address fundamental phenomena and properties, which will help ensuring aforementioned requirements, with focus on perpendicular magnetic anisotropy (PMA) 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.

Most importantly, during this internship you will learn/improve your theoretical/computational skills and will prepare yourself for future career.

Requested skills

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

Possibility to follow with a PhD : Yes