Master Thesis Projects 2019

spintec
SPIN IN ELECTRONICS

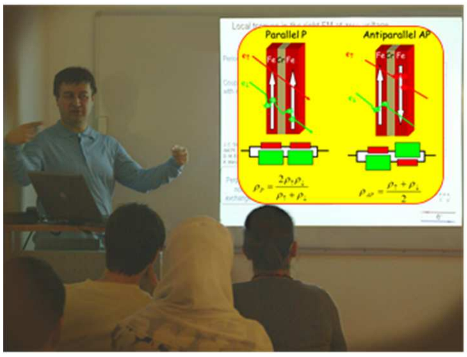
SPINTRONIQUE et TECHNOLOGIE des COMPOSANTS

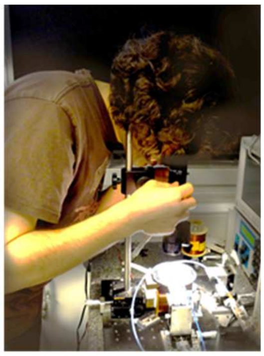
http://www.spintec.fr

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, microwave components, biotechnology. Academic research concerns spinorbitronics, spintronics in 2D materials, magnetization and spin wave dynamics, antiferromagnetic spintronics, and exotic spin textures.



SPINTEC FOR YOUR MASTER OR PHD PROJECT

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

At SPINTEC, you will find a dynamic and multicultural environment that provides all facilities to advance your research project and get yourself known in the academic world via participation at international conferences. Three years after defending their PhD, 90% of our students have a position in academics or in the industry. Come and join us to be part of those who like to revolutionize microelectronics research and applications!

Hoping to see you soon,

Lucian PREJBEANU, Director.
[ioan-lucian. prejbeanu@cea.fr / +33(0)438 78 91 43]

TOPICS FOR MASTER THESIS

MRAM memories

1. Magnetic memories optimized for ultra-low power consumption
2. Exploring the scalability of spintronics for 3D devices
3. All-optical switching in spintronic devices

Magnetic sensors

4. Miniature and ultra-sensitive magnetic sensor for space applications

Magnetization dynamics and microwave devices

5. Spintronic oscillator networks: taming a non-linear dynamical system of coupled non-isochronous and distributed oscillators
6. Long-range dynamic interaction between insulating ferromagnetic films mediated by phonons

2D Spintronics and Spinorbitronics

7. Study of magnetic skyrmion properties for spintronics applications
8. Magnetic skyrmion in ultrathin nanostructures
9. Importance of chiral phenomena for domain wall shift registers
10. Enhancing Spin Orbit torques for magnetic memory applications

Spin textures

11. Spin-Hall effect in chemically-grown metal/ferromagnetic bilayers

Health and Biology

12. 3D spheroids for the study of magneto-mechanical cancer cells destruction

Theory and Simulation

13. Theoretical studies of spin-orbit phenomena at interfaces comprising magnetic and nonmagnetic materials in a view of memory devices
14. Atomistic modeling of all-optical switchable magnetic materials

Spintronic IC design

15. Modeling and design of hybrid CMOS/magnetic circuits based on newly discovered spintronics phenomena
16. System-level simulation and design space exploration of non-volatile neuromorphic architectures

Proposal N° : 1

Contact
DIENY Bernard, bernard.dieny@cea.fr, Tel : +33(0)4 38 78 38 70
PREJBEANU Lucian, lucian.prejbeanu@cea.fr, Tel : +33(0)4 38 78 91 43

Title
Magnetic memory optimized for ultra-low power consumption

Keywords
spintronic, magnetic memories, MRAM, quantum engineering

Summary
The power consumption of electronic circuits keep on increasing with their performances. This consumption has a static part associated with the leakage of the CMOS transistors and a dynamic part due to the charge/discharge of the interconnects during data transfer between memory and logic. In this context, magnetic memory can play an important role to save energy. These memories have been studied at SPINTEC for more than 10 years. They use spintronic phenomena (tunnel magnetoresistance, spin transfer torque, spin orbit torque...). They gather several assets: non volatility (ability to keep the information without being powered), speed (write/read in a few nanoseconds), density, write endurance. In a memory, there is always a tradeoff to find between the stability of the written information (memory retention) and the energy required to write. The research goal of the internship and of the PhD thesis which will follow, will be to optimize the magnetic tunnel junctions which constitute the memory dots (composition, shape, write process) to optimize this tradeoff with the aim of minimizing the power consumption depending on the required specifications for various types of applications (Smartphones, high power computing, quantum engineering...).

Full description of the subject
The subject proposed concerns spin electronics, a rapidly developing discipline combining electronics and magnetism. It is an extremely dynamic field of magnetism combining basic research and applications. Spin electronics has made a great contribution to the hard disk industry (read heads using giant magnetoresistance phenomena or tunneling) and is about to revolutionize microelectronics by introducing a new type of magnetic memory: MRAMs (Magnetic Random Access Memory). The memory cell consists of magnetic tunnel junctions (MTJ) whose core is formed of two magnetic layers (fixed magnetization reference layer and switchable magnetization storage layer) separated by a thin insulating barrier. The electrical resistance of these structures depends on the relative orientation (parallel or antiparallel) of the magnetizations of the two magnetic layers (tunnel magnetoresistance). These junctions are written in parallel or antiparallel magnetic configuration by current pulses crossing the junction using the spin transfer phenomenon. Their magnetic state is read again by measuring their electrical resistance. SPINTEC has played a very important role at the international level in the development of these memories which are about to return to volume production in the microelectronics

industry. The first industrial application targeted is the replacement of embedded FLASH memories. But we always try to improve the properties, especially in terms of power consumption, writing speed, size of the memory points etc. to open other application fields (eg SRAM fast memories). The proposed subject aims to reduce their write power consumption by optimizing the composition, the shape of the memory points and by using recently discovered phenomena such as spin torque orbit or voltage control of magnetic anisotropy.

The proposal will combine modeling and experiments. This optimization requires an accurate evaluation of the barrier height separating the two states of the memory that must be introduced to ensure the specified retention time at the operating temperature. Then the composition of the tunnel junction, the size of the memory point and possibly its shape should be adjusted so that the magnetization of the storage layer remains stable against thermal fluctuations for the specified duration but without oversizing. To further minimize the consumption, low Gilbert damping materials are selected and spin transfer writing is combined with spin torque writing orbit and magnetic anisotropy lowering by the voltage applied across the junction.

The physics involved is well understood so that the modeling of these structures by simulation will be straightforward. The experiments will consist of depositing magnetic multilayers, nanostructuring (lithography, etching) in a clean room and then characterizing their magnetic and electrical properties.

Requested skills

nanosciences, nanotechnologies, solid state physics, basis of electronics

Possibility to follow with a PhD Yes

Proposal N° : 2

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

Title
Exploring the scalability of spintronics for 3D devices

Keywords
Magnetic random access memory, spintronics, semiconductor via, three-dimensional devices

Summary
Classical microelectronics is reaching its limits of downward scalability, reaching technological or scientific bottlenecks. Magnetic random access memories, based on magnetic tunnel junctions storing and reading bits of information, are emerging key ICT components. They are of immediate relevance for low-power and high-speed processor and mass-storage cache memory. Similar to other technologies, ways are being searched to design three-dimensional devices and thus allow long-term scalability in terms of areal density.
The scalability of single MRAM cells below 10nm lateral size has been demonstrated in the lab recently, independently at SPINTEC and at Tohoku university. The purpose of the internship is to pave the way towards integration of this concept in a viable technological process, compatible with high areal density and mass production. The principle relies on filling semiconductor vertical interconnects with a magnetic material, to be used as a storage cell. The first steps will consist in the structural, magnetic and electric characterization of such interconnects. At the scale of a PhD the work will be extended to fully functional memory cell, addressing both fundamental and technological challenges. This topic is a joint action between Spintec and LETI.

Full description of the subject
Technologies able to translate into the third dimension are expected to dominate over other technical solutions. This is the reason why flash memory, based on charge storage and reading, is the leading solution for USB and SSD storage, being able to stack tens of active layers. Nevertheless flash has limited endurance, rather high write power consumption and slow write rate. The emerging MRAM technology addresses these issues, however it is still a strictly 2D technology. The fabrication of MRAM with 3D features, starting from vertical-aspect ratio MRAM, suffers from limitations in etching technology.
Among the various technologies of non-volatile memories, STT-MRAM gathers a unique combination of assets: non-volatility, write speed (3-30ns), density (4Gbit demonstrated by Hynix/Toshiba), low consumption (a few tens of fJ/write), and very importantly an extremely long write endurance (>10^{13}cycles). Conventional STT-MRAM are based on out-of-plane magnetized magnetic tunnel junctions (MTJs) in which the storage layer magnetization is pulled out-of-plane thanks to a perpendicular anisotropy originating from the interface between the oxide barrier and the magnetic electrodes. In conventional STT-MRAM, this interfacial anisotropy is large enough to insure thermal stability of the storage layer

magnetization down to diameter of the order of 20nm. To increase the STT-MRAM downsize scalability, a novel type of MRAM with much thicker storage was developed at SPINTEC. By drastically increasing the thickness of the storage layer to values comparable to its diameter, a perpendicular shape anisotropy (PSA) is induced in the storage layer which comes on top of the previously mentioned interfacial anisotropy with no penalty on the switching current. As a result, the perpendicular anisotropy is greatly reinforced enabling to maintain magnetic thermal stability (i.e. good memory retention) down to 4nm diameter. The name PSA-STT-MRAM was coined to designate this memory.

The purpose of the internship is to pave the way towards integration of this concept in a viable technological process, compatible with high areal density and mass production. The principle relies on filling semiconductor vertical interconnects with a magnetic material, to be used as a storage cell. The study will consist in evaluating the most favorable conditions of growth according to the substrate of the cavity (liner, under layer, or not). The properties of the cobalt deposits obtained will be characterized in terms of magnetic properties and resistivity depending on the liners. The conformity of the deposit will be studied in correlation with the aspect ratio making it possible to obtain the required shape anisotropy. The magnetic properties studies of the individual dots will be carried out in collaboration LETI (holography). Micromagnetic studies of the reversal of magnetization and magnetostatic interactions between layers will complete the study.

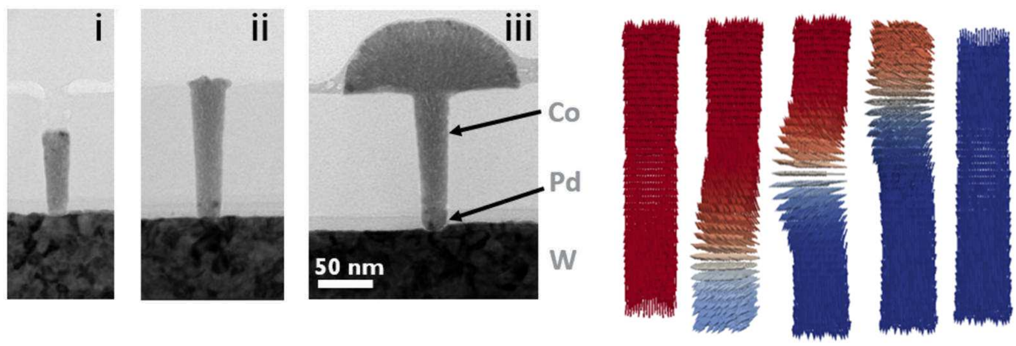


Illustration of vertical nanopillars (a) experiments and b) modeling.

Requested skills

nanosciences, nanotechnologies, solid state physics, basis of electronics

Possibility to follow with a PhD Yes

Proposal N° : 3

Contact

PREJBEANU Lucian, lucian.prejbeanu@cea.fr, Tel: +33(0)4 38 78 91 43
DIENY Bernard, bernard.dieny@cea.fr, Tel : +33(0)4 38 78 38 70

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.

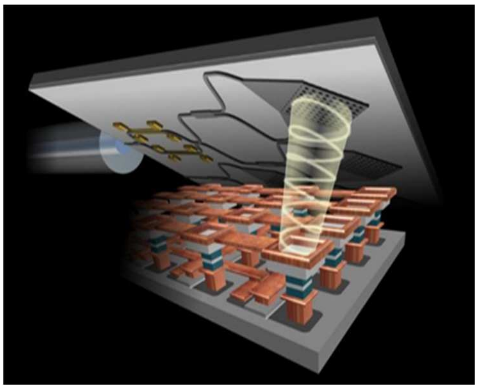
Full description of the subject

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.



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° : 4

Contact

BARADUC Claire, claire.baraduc@cea.fr, Tel : +33(0)4 38 78 42 35
BEA Hélène, helene.bea@cea.fr, Tel : +33(0)4 38 78 08 64

Title

Miniature and ultra-sensitive magnetic sensor for space applications

Keywords

magnetic sensor, magnetic tunnel junction, microfabrication

Summary

The aim is to develop a miniature and ultra-sensitive magnetometer (100 fT / √Hz), using magnetic tunnel junctions and microfabrication techniques from microelectronics. This magnetometer could replace the magnetometers currently used on space missions with a mass reduction by a factor of 100. This extreme lightness (~ 1 g without electronics) would represent a competitive advantage over inductive sensors currently used in space missions (mass > 1 kg). The proposed magnetometer combines a magnetic tunnel junction as sensing element of the sensor, a flux concentrator to amplify the field to be measured, and a magnetic field modulation system to reduce the noise of the measurement. Preliminary studies have shown the feasibility of the basic bricks of this sensor. It is now necessary to optimize the flux concentrator and the magnetic tunnel junction, in particular by developing an innovative junction that is currently the subject of a patent application. A detailed understanding of the underlying physics is necessary to optimize the sensitivity of the tunnel junction: the choice of materials and geometry (size, shape, thickness) will results from a tradeoff between increasing the sensitivity and keeping a uniformly magnetized state within the junction.The internship work will mainly be experimental (microfabrication, electrical and magnetic characterization, noise measurements, magnetic imaging) but will also include analysis and simulations.

Full description of the subject

The objective is to develop a miniature and ultra-sensitive magnetometer using magnetic tunnel junctions and microfabrication techniques derived from microelectronics. This magnetometer, if it achieves the expected performances (100 fT/√Hz detectivity), could replace the magnetometers currently used on space missions with a mass reduction by a factor 100. The device (without electronics) is fabricated on a silicon substrate of 10x4mm^2 and weighs about 1 gram. By contrast, magnetic sensors currently used in space missions are inductive sensors, and their very high sensitivity is achieved at the cost of considerable footprint and mass (1 to 2.5 kg).

The proposed magnetometer is the result of work carried out within a long-standing partnership between SPINTEC laboratory and LPC2E space laboratory (CNRS-Université d'Orléans). The sensor combines a magnetic tunnel junction as a sensitive element, a flux concentrator for amplifying the field to be measured and a magnetic field modulation system for reducing the noise of the measurement. The projections based on results already obtained suggest that a detectivity of 1pT/√Hz to 100 fT/√Hz could be obtained in the DC-10 kHz band, if the magnetic tunnel junction and the flux concentrator are optimized. Significant progress could be achieved through research on materials and a thorough study of magnetic properties.

Our goal is to develop a magnetic tunnel junction with high sensitivity and low noise. For this, we will test an innovative junction concept, which is currently the subject of a common patent application of LPC2E and Spintec.

First, we will try to optimize the materials and shape of the junction in order to obtain a coherent rotation of the magnetization at low-field: this involves combining analytical modeling, numerical simulations and experimental tests in order to determine the best parameters. These tests will require the deposition of multilayers, microfabrication in clean room and electrical characterization measurements. To analyze the magnetic behavior of the sample at a local scale, we will image the sample using magnetic force microscopy (MFM) or Kerr effect microscopy. In a second step, we will reduce the noise of the junctions obtained, by increasing the magnetic volume. This can be achieved either by increasing the junction size (provided that the magnetic uniformity is not degraded), or by connecting the junctions in a serial / parallel circuit. However, the space constraint due to the air gap of the flux concentrator will prevent to use a large number of junctions. The best form of junction and the best compromise between the number of junctions and the size of the air gap will be sought by modeling, the air-gap being approximately inversely proportional to the gain of the concentrator.

The proposed research will be carried out mainly at SPINTEC laboratory and in the PTA (clean-room in the same building) and will involve magnetic thin-film deposition, micro-fabrication, electrical and magnetic measurements and numerical simulations. Besides the junction optimization, a specific effort will be devoted to improve the reliability of a few critical technological steps of the complex microfabrication process (8 mask levels and about 50 process steps).

Requested skills

Solid-state physics, nanosciences, basis on magnetism

Experience in microfabrication is an additional valuable skill.

Possibility to follow with a PhD: Yes

Proposal N° : 5

Contact

EBELS Ursula, ursula.ebels@cea.fr, Tel: +33(0)4 38 78 53 44

Title

Spintronic oscillator networks : taming a non-linear dynamical system of coupled non-isochronous and distributed oscillators

Keywords

Spintorque driven excitations, magnetization dynamics, non-linear coupled systems, spin transfer, magnetic tunnel junctions

Summary

Spintronic oscillators are based on magnetic tunnel junctions that provide a large oscillating output voltage signal in the GHz range when driven by a spin polarized DC current. The spin momentum transfer counter-acts natural damping and drives the magnetization into large angle steady state oscillations. These are converted into an electrical signal via the magneto-resistance. A defining feature of spintronic oscillators is their non-isochronicity, i.e. their non-linear dependence of the precession frequency on the amplitude. While in the past many studies have been realized on single oscillator devices, current efforts concentrate on the coupling of different oscillators to enhance output signal levels, to reduce noise or to produce coherent magnetic fields for short distance wireless communication (e.g. inter- and intrachip). Coupling and mutual synchronization of these oscillators can occur via electrical or dipolar interactions. The challenge is to understand how the locking process, in particular the coupling phase, is influenced by the different coupling mechanisms and the excitation mode and conditions. This will be of importance when more than two oscillators will be coupled that are not identical (distributed network) and that will compete with each other.
Identifying the parameters that lead to stable coupling or chaotic states are of special interest. This is a general problem of non-linear dynamical systems applied to nanoscale spin torque oscillators. So far coupling has been demonstrated experimentally for two oscillators in the vortex configuration emitting at low frequency (<1GHz), while experimental demonstration is missing for higher frequencies (1-10GHz) using uniformly magnetized magnetic tunnel junctions. This master project, followed by a thesis, will undertake a combined experimental and theoretical study of mutual synchronization of uniformly magnetized spintronic oscillator devices that will be realized at our nanofabrication platform. They will be characterized using our microwave magneto-transport experiments, as a function of the magnetic configuration of single devices and the geometric arrangement between devices. The experimental studies will be complemented by numerical and analytical models.

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 for demonstration of such oscillators in phase locked loops. However, the output signal is too low and the phase noise still too high. The major route of improving the signal is to couple several oscillators. While coupling of two 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 open question and a severe experimental challenge. This is due in part to the fact that it is difficult to realize oscillators with exactly identical performances as well as to the strong non-isochronicity.

The objective of the Master project, followed by a PhD, is to undertake a combined experimental and theoretical study to understand the conditions for stable coupling of a network of non-isochronous and distributed spin torque oscillators. A main question concerns the role and efficiency of different coupling mechanisms (electrical and dipolar interaction), that act together and that can compete with each other. This competition in the coupling is of particular importance when considering the coupling of more than two oscillators that are not identical (in frequency, in volume, in their non-linear response etc). It is not clear whether the coupling will be mutual or whether one oscillator will drive the other and what is the role of the noise on the coupling. Coupling of several oscillators can lead to a fully coherent oscillation but can also result in a chaotic state. This is a general problem of non-linear dynamical systems applied to nanoscale spin torque oscillators.

The studies will be realized for oscillators with different orientation of magnetization that can be in-plane or out of plane magnetization. This will lead to different oscillation amplitudes and dynamic dipolar interactions strengths.

To guide the experimental studies, a numerical analysis will be made on the synchronisation of the spintorque oscillator to an external rf signal, which can be an rf current signal or an rf field signal. First synchronisation to one or the other source will be considered and then for both signal sources, to mimic the different coupling mechanisms and to understand how they cooperate or compete with each other. Here the strength of the coupling can be varied. In addition the effect of thermal noise on the robustness of the coupling will be considered. The numerical results will be compared to analytical models developed in a previous thesis. These theoretical studies will then be compared to experiments, for the different oscillator configurations (in-plane vs out-of-plane) leading to different excitation modes.

In a second step the mutual synchronization of two and more spin torque oscillators will be addressed. 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 the conditions of the coupling as a function of several parameters: coupling strength and symmetry of the coupling (i.e. identical and non-identical oscillators). The role of thermal noise will be investigated on the robustness of the coupling. This theoretical description will guide the experimental realization of a two and if successful a network of coupled spintronic oscillator devices. These will be developed at our nanofabrication facilities (PTA cleanroom). The student will be trained to use the clean room facilities to realize the devices. The student will then 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.

Requested skills

Master in Physics and/or Nanosciences; Skills in programming for developing data analysis protocols;

Possibility to follow with a PhD Yes

Proposal N° : 6

Contact

KLEIN Olivier, olivier.klein@cea.fr, Tel: +33(0)4 38 78 58 02

Title

Long-range dynamic interaction between insulating ferromagnetic films mediated by phonons

Keywords

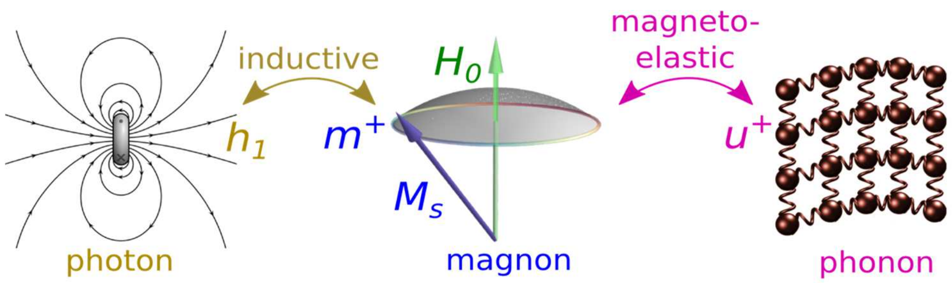
spintronics, nanophysics, wireless communications, condensed matter, magnonics

Summary

The proposed research project inserts itself in the emerging field of insulator spintronics whose vision is to fully replace the moving electrical charge with the friction-free propagation of the spin degree of freedom using electrical insulators. In this novel paradigm, low damping magnetic insulators are good spin-conductors by allowing the long-range propagation of the spin information trough spin-waves. In this project we shall investigate the ability to transfer orbital angular momentum using circularly polarized acoustic-waves. The project shall focus on Yttrium Iron Garnet (YIG) thin films grown on Gadolinium Gallium Garnet (GGG) substrate because i) of the strong magneto-elastic constant in YIG, which should allow efficient interconversion of magnetic energy into acoustic; ii) of the small acoustic impedance mismatch between YIG and GGG; and iii) of the ultra-low acoustic damping in garnets (better than quartz). The target here is to demonstrate dynamical exchange coupling mediated by phonons between between two spatially separated YIG layers intercalated by a non-magnetic dielectric GGG spacer. This will be measured by performing frequency and time-domain spectroscopic studies on YIG thin films prepared by liquid phase epitaxy, which consists of having two almost identical YIG layers of variable thickness on both side of a GGG substrate. We believe that these progresses on hybrid transducers exploiting the magneto-elastic coupling could be beneficial for the development of the future microwave analog front-end technology (e.g. delay lines and filters) used in the wireless industry. The efficiency of this interconversion process could help removing the high frequency limitations of piezo transducers found in acoustic devices.

Full description of the subject

The emerging field of insulator spintronics is attracting a lot of attention. Its long-term vision is to replace the moving electrical charge with the friction-free propagation of the spin signal using electrical insulator media. This novel information platform promises higher energy efficiency and higher fidelity, while remaining adaptive and miniaturized. The research on pure spin conductors has so far concentrated on the exploitation of coherent and incoherent spin-waves, or their quanta magnons, propagating inside magnetic insulators with characteristic frequencies ranging from GHz to THz and wavelengths from µm to nm. For this research effort, which falls into the field of magnonics, the ideal material is Yttrium Iron Garnet (YIG), a material known for its record low magnetic damping coefficient. YIG samples are available in the form of epitaxial thin film grown on Gadolinium Gallium Garnet (GGG) substrate. The current state of the art is the exploitation of spin-orbit effects (spin torque, spin-charge conversion, etc) with the aim to excite, detect and control magnons. A recent accomplishment was the demonstration that their decay time can be controlled electrically by injecting a dc current (~mA) into an adjacent platinum (Pt) layer, a metal with strong spin-orbit coupling, that could potentially lead to the magnetization auto-oscillation of a coherent mode at radio-frequencies (rf). But a crucial function still missing in this toolbox for electrical insulators is the ability to transfer the corresponding angular momentum information across a non-magnetic (NM) dielectric spacer, which is key to the operation of spintronics devices. The spacer is required to decouple from the multilayer stack a free magnetic layer, whose orientation can be controlled by transport. The spin conductance of the spacer is captured by the characteristic decay length of the spin signal in the non-magnetic material. In metals, this quantity is called the spin diffusion length whose value lays in the sub-micron range. Currently the longest spin diffusion length has been reported in graphene, which lays in the micron range. In this paper we propose to investigate a novel and original channel to efficiently transfer angular momentum between two distinct YIG layers separated by GGG using circularly polarized phonons. The concept relies on the magneto-elastic coupling Ω between the Larmor precession of the magnetization and the corresponding circular elastic deformation of the lattice (see FIG1), which can carry orbital angular momentum. There are 3 reasons that make such proposition very promising: i) the magneto-elastic coupling in YIG is known to allow efficient energy transfer from spin-waves (SWs) to acoustic-waves (AWs), ii) AWs excited in YIG should be transferred efficiently into GGG due to small impedance mismatch, iii) acoustic waves in GGG have amongst the lowest damping in nature (the ultra-sonic attenuation coefficient of garnets is ten times smaller than quartz) and the expected decay length of circularly polarized phonons in GGG is expected to be in the millimetric range. This will be measured by performing frequency and time-domain spectroscopic studies on YIG thin films prepared by liquid phase epitaxy, which consists of having two almost identical YIG layers of variable thickness on both side of a GGG substrate. We believe that these progresses on hybrid transducers exploiting the magneto-elastic coupling could be beneficial for the development of the future microwave analog front-end technology (e.g. delay lines and filters) used in the wireless industry. The efficiency of this interconversion process could help removing the high frequency limitations of piezo transducers found in acoustic devices. Among the targeted applications are the development of a new generation of microwave analog front-end functions (e.g. delay lines and filters), which can enhance the potential of CMOS based electronics by complementing the deficiencies of the digital signal processing, in particular in terms of sensitivity or dynamical range, while remaining compatible with the long-term evolution of wireless telecom standards, which foresees an increase of the carrier frequency well above 5 GHz.



Requested skills

The candidate must have solid knowledge in solid-state physics. 'Parcours nanoscience' organized by Univ. Grenoble Alpes is the perfect academic preparation.

Possibility to follow with a PhD Yes (financing secured)

Proposal N° : 7

Contact
BEA Hélène, helene.bea@cea.fr, Tel : +33(0)4 38 78 08 64
BARADUC Claire, claire.baraduc@cea.fr, Tel : +33(0)4 38 78 42 35

Title
Study of magnetic skyrmion properties for spintronics applications

Keywords
Perpendicular magnetic anisotropy, Dzyaloshinskii-Moriya interaction, electric field effects, skyrmions

Summary
Skyrmions in thin films are spin textures across which magnetization follows a cycloid, rotating in one or the other direction, which defines skyrmion's chirality. These specific magnetic domains can appear in ultrathin trilayers with no inversion symmetry such as heavy metal/ferromagnet/oxide, where an interfacial interaction called Dzyaloshinskii-Moriya (DMI) appears. These topological solitons currently attract a considerable interest both for the underlying physics and for their applicative potential. Since they can be set in motion by electrical current, they could be used as dense storage nanoscale data bits, or for magnetic logic. Furthermore, the possibility to tune magnetic interfacial properties by a gate voltage allows 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 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 experimental internship, we target to observe the change of DMI sign and to demonstrate the 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 (chirality). 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 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 envisioned 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 field 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: by successively applying positive and negative voltages, the skyrmions appear and disappear[6]. Moreover, we have recently demonstrated that the DMI itself can be tuned by gate voltage[7]. Our result was the first direct proof of an influence of gate voltage on DMI. 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.

In previous studies, we have observed the formation of skyrmions under various material and magnetic field conditions. They present different thermal stability and different behaviour under the application of magnetic field or electric current.

Within this experimental internship, we thus propose to better understand skyrmion formation in the various conditions. We also plan to study the electric field effects on magnetic properties, and more particularly DMI, for these different types of skyrmions. Finally, we target to observe the change of DMI sign and to demonstrate the chirality switch. This breakthrough would open new possibilities for skyrmion manipulation.

The experimental techniques that will be used are magnetic characterizations (vibrating sample magnetometer), magnetic imaging (magneto-optical Kerr effect microscopy) and electrical characterizations. The candidate will also fabricate samples using micro- and nanopatterning techniques (UV or laser lithography, atomic layer deposition, lift-off). The candidate will be integrated in a team of 3-4 people with daily support and weekly meetings. This project is part of a collaboration with Néel Institute where some experiments will be conducted.

[1] A.N. Bogdanov et al. *J. Exp. Theor. Phys*. 95, 178 (1989)
[2] U.K. Roßler et al., *Nature* 442, 797 (2006) ; N. Nagaosa and Y. Tokura, *Nat. Nanotech.* 8, 899- 911 (2013)
[3] W. Jiang et al., *Science* 349, 283 (2015), S. Woo et al., *Nat. Mater*. 15, 501 (2016)
[4] M. Weisheit et al., *Science*, 315, 349 (2007)
[5] K.L. Wang et al. , *J. Phys. D*, 46, 074003 (2013)
[6] M. Schott et al. *Nano Lett*., 17, 3006 (2017)
[7] T. Srivastava et al., *Nano. Lett.,*18, 4871 (2018)

Requested skills
Basis in solid state physics, nanosciences and on magnetism

Possibility to follow with a PhD Yes

Proposal N° :8

Contact

BOULLE Olivier, olivier.boulle@cea.fr Tel : +33(0)4 38 78 21 56

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.

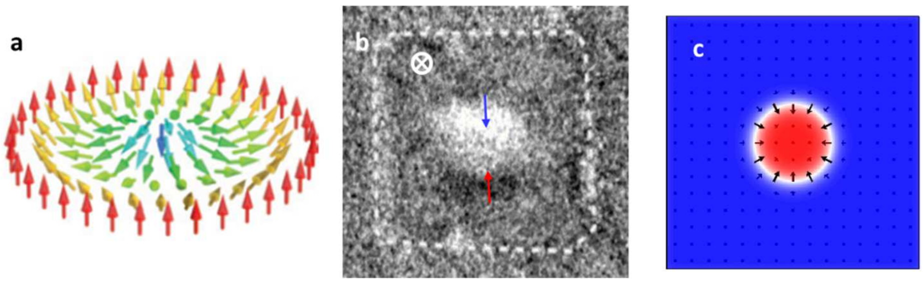


Fig. 1. a - Schematic representation of a magnetic skyrmion [1]. b XMCD-PEEM image of magnetic skyrmion (130 nm diameter) at room temperature and zero magnetic film in an ultrathin Pt/Co/MgO nanostructures [3]. *c. Spin structure from micromagnetic simulations.*

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° : 9

Contact

MIRON Mihai, mihai.miron@cea.fr , Tel : +33(0)6 18 07 61 40

Title

Importance of chiral phenomena for domain wall shift registers

Keywords

Magnetic Domain walls, spin Orbit Torque, racetrack memory, chiral damping

Summary

Magnetic shift registers have been proposed as a better alternative for hard-disk technology. They would be two orders of magnitude denser and faster than hard-disk technology[1]. Their realization relies on the possibility to shift the magnetic domain walls (transition areas that separate the uniformly magnetized domains) by the application of an electric current. We study in detail the interactions governing the physical process of current induced DW motion. For experiments we rely on the magneto-optical imaging techniques as well as electric magneto-transport detection. In order to understand our observations, we model our findings using macro-spin and micro-magnetic simulations.

Full description of the subject

The racetrack memory is an original memory concept where the information is coded by the relative positioning of magnetic domain walls (DWs) in a magnetic nano-wire[1]. The working principle of this device relies on the possibility to shift all DWs in the same direction without modifying the distance separating them. While this is not possible by magnetic field (pushes any two adjacent DWs in opposite directions thus modifying the distance) the current induced DW motion exhibits this special feature.

We observed that current induced DW motion is extremely efficient in materials composed of a very thin ferromagnet sandwiched between a heavy metal and an oxide[2]. The initial explanation of this phenomenon, in terms of spin transfer torque, has proven inadequate, and it has been shown that this remarkable feature is entirely linked to the spin orbit interaction.

Namely the simultaneous occurrence of large spin orbit interaction and the structural inversion asymmetry (SIA) of these materials leads to a conspiracy of phenomena that can explain the extraordinary efficiency of the current induced DW motion. On one hand in the presence of the SIA, the electric current produces large spin orbit torques[3] and on the other hand, the SIA produces a chiral energy that forces the DWs to adopt a fixed chirality, making them extremely susceptible to be displaced by SOT[4].

Besides these two phenomena playing a dominant role for the DW motion, we have discovered a third component that affects their motion: the dissipative counterpart of the chiral energy. The observation of chiral damping[5] makes the picture even more complex. Disentangling the roles of these components is very difficult and challenging. However, the full understanding is necessary to control and improve the efficiency of this process to the extent required for memory applications. For this purpose, we study the current and field induced DW motion using magneto-optical microscopy.

The ideal candidate should have a taste for the deep understanding of complex physical phenomena and also be interested by the potential applications of their discoveries.

1. S.S.P. Parkin, M. Hayashi, and L. Thomas. "Magnetic domain-wall racetrack memory." *Science* 320.5873 (2008): 190-194.
2. I.M. Miron et al. "Fast current-induced domain-wall motion controlled by the Rashba effect." *Nature materials* 10.6 (2011): 419.
3. I.M. Miron et al. "Perpendicular switching of a single ferromagnetic layer induced by in-plane current injection." *Nature* 476.7359 (2011): 189.
4 K.-S. Ryu et al. "Chiral spin torque at magnetic domain walls." *Nature nanotechnology* 8.7 (2013): 527.
5. E. Jué et al. "Chiral damping of magnetic domain walls." *Nature materials* 15.3 (2016): 272.

Requested skills : general physics; team spirit; sense of humor;

Possibility to follow with a PhD Yes

Proposal N° : 10

Contact

MIRON Mihai, mihai.miron@cea.fr, Tel: +33(0)6 18 07 61 40

Title

Enhancing Spin Orbit torques for magnetic memory applications

Keywords

Spin Orbit Torque, MRAM

Summary

A promising way to improve the energy efficiency and performance of microprocessors is the integration of non-volatile random access memories (MRAM). While many different technologies are currently developed there is only one possibility for creating non-volatile high-level SRAM. This is a type of magnetic random access memory, where the writing is achieved by a newly discovered phenomenon called Spin Orbit Torque (SOT). This relies on the electric switching of the magnetization by transferring angular momentum from the crystal lattice. While this phenomenon has been clearly evidenced, and its efficiency proven, its physical origin remains debated. We work towards understanding this phenomenon, with the goal of improving its efficiency and integrate it in MRAM applications.

Full description of the subject

The ability of ferromagnetic materials to maintain their magnetic orientation over extended periods of time is what allows using them for information storage. However, this is not the sole condition. A magnetic memory stores information but it also has to be read and written. Recent developments in spintronics have allowed to address both this problems: while reading a magnetic memory relies on the tunnel magnetoresistance effect, the writing can be achieved through different strategies. The most successful strategy so far relies on the transfer of spin angular momentum (Spin Transfer Torque - STT) by injecting an electric current from another ferromagnet .

Recently we discovered a new physical phenomenon allowing to switch the magnetization by means of in-plane electric current[1]. Contrasting with STT where the electric current transfers spin angular momentum from an adjacent ferromagnet, we showed that it is possible to reverse the magnetization by transferring angular momentum directly from the crystal lattice. The Spin-Orbit Torque (SOT) only occurs in magnetic materials that lack structural inversion symmetry and that have strong spin orbit coupling.

Our goal is to develop new materials with enhanced SOT efficiency, which are also compatible with industrial standards. For this purpose we design the materials, fabricate the devices and quantify the torques[2]. We are looking for a person genuinely interested both in the fundamental understanding of the physical phenomena as well as in using this understanding for real world applications. The successful candidate is expected to collaborate with a PhD student in all aspects of this work.

1. I.M. Miron et al. "Perpendicular switching of a single ferromagnetic layer induced by in-plane current injection." *Nature* 476.7359 (2011): 189.
2. K. Garello et al. "Symmetry and magnitude of spin–orbit torques in ferromagnetic heterostructures." *Nature nanotechnology* 8.8 (2013): 587.

Requested skills : general physics; team spirit; sense of humor;

Possibility to follow with a PhD Yes

Proposal N° : 11

Contact

FRUCHART Olivier, olivier.fruchart@cea.fr, Tel: +33(0)6 84 20 68 71
MIRON Mihai, mihai.miron@cea.fr, Tel : +33(0)4 38 78 02 79

Title

Spin-Hall effect in chemically-grown metal/ferromagnetic bilayers

Keywords

Atomic layer deposition, electroless plating, spin-Hall effect

Summary

The integration requirements of the semiconductor industry pushes the development of three-dimensional technologies, such as the highly-multilayered NAND flash for charge memories. A similar push is perceptible for the emerging magnetic RAM, which otherwise would face limits of areal density in the mid-term future.

The purpose of the internship, which is fundamental and exploratory, is to investigate the suitability of chemically-grown metallic/ferromagnetic bilayers to exhibit a sizeable spin-Hall effect. Indeed, the spin-Hall effect is a key in efficient spintronic devices, allowing the conversion of charge current in a heavy-metal layer, into a transverse spin current in the adjacent ferromagnetic layer. On the other hand, this effect in metallic bilayers has only been demonstrated based on physical deposition, while truly three-dimensional spintronic requires alternative synthesis processes to deliver vertical structures with a high aspect ratio.

The work will involve interaction with chemists for the synthesis, structural and magnetic characterization, and transport measurements to extract the spin-Hall angle. The internship is an exploratory step coming with the perspective of a PhD to demonstrate new building blocks for three-dimensional spintronic, in the form of core-shell tubes, with application to current-induced domain-wall motion and magnonics in these novel structures. This action is done in a joint group between SPINTEC and Institut Néel, as well as expert chemistry groups in Germany (Erlangen and Darmstadt).

Full description of the subject

In order to fulfill Moore's law describing the expected exponential growth of areal density of semiconductor devices, there is a rising trend to build devices making use of the third dimension, so that more functions can be packed in terms of areal density, even though the lateral pitch remains constant when facing technological or physical limits. In spintronics, a proposal raised considerable attention about ten years ago: the race-track memory, a mass-storage device that would make use of dense arrays of vertical cylindrical wires. Domain walls would be the basis for coding bits of information, to be moved with spin-polarized current from/to write/read cells patterned at the surface of the array. So far, academic knowledge has been greatly developed on flat structures deposited and patterned by physical methods on wafers. Generally, the synthesis of a dense three-dimensional scaffolds is not possible by physical methods, and requires the use of various bottom-up techniques. The consideration of cylindrical wires is only emerging, fabricated by electrodeposition, as they are more challenging to fabricate and investigate. However, there is a need to fabricate multilayered structures, which are the basic building block of spintronics. This leads to the concept of core-shell and multilayered tubes in three dimensions, which is the background of the present proposal.

The Master internship will consider the demonstration of the spin-Hall effect in heavy metal/ferromagnetic metal bilayers grown by chemical methods. We will consider deposits on wafers for the first step, before shifting to tubes fabricated in nanoporous templates.

The first aspect concern material development and characterization. The first layer will be Pt, deposited using atomic layer deposition. The second layer will be Co, deposited using electroless plating. Both processes are compatible for implementation in tubes at a later stage. These bilayers will be characterized structurally and magnetically. This involves atomic force microscopy for roughness, magneto-optical microscopy and magnetic force microscopy for domains and domains wall, magnetometry for magnetization and coercivity characterization.

The second aspect concerns characterization of the spin-Hall effect, which will be done with the harmonic hall voltage measurement technique, a robust method to quantify the spin orbit torques. We inject a low frequency ac charge current and detect the anomalous Hall effect. If the magnetization is fixed, the response is linear, and the hall voltage is oscillating exactly at the frequency of the current. If the charge current injected exerts a torque on the magnetization due to the injection of a spin current, the magnetization will no longer be fixed, but oscillate at the frequency of the current. This leads to a non-linear response, and hence to higher harmonics in the Hall voltage. The analysis of the higher harmonics response allows (by comparison to an external field) to quantify precisely the magnitude and the vectorial orientation of the Spin Orbit Torques, here, the spin-Hall effect and possibly interfacial Rashba effect.

The work lies in the frame of a tight and longstanding collaboration with Institut Néel and the Universities of Erlangen (Prof. J. Bachmann) and Darmstadt (Prof. W. Ensinger) as regards chemical synthesis. In practice, the student will participate in the chemical synthesis, assisted by chemical experts. The structural, magnetic and transport properties ate the core of the internship, and will be under the direct responsibility of the student. The student will be part of a larger group of persons working on the topic of magnetic nanowires and nanotubes between Spintec and Institut Néel, giving rise to regular group meetings.

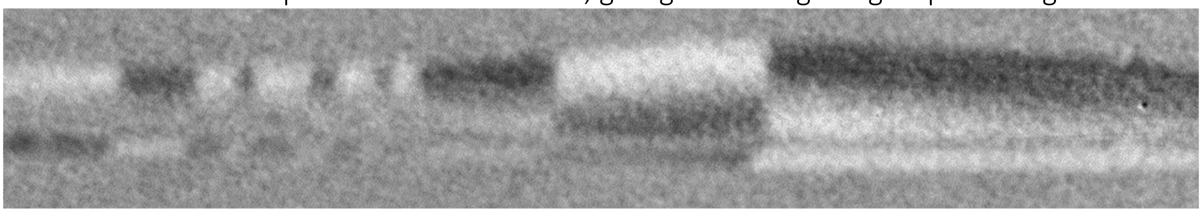


Illustration of the magnetic state observed in ferromagnetic single-shell tubes of ours, made by photo-emission electron microscopy (PEEM, a synchrotron-based techniques), demonstrating the existence of azimuthal domains of alternating circulation.

Requested skills

Experimental physics, taste for interdisciplinary interaction, understanding of material science and condensed matter physics.

Possibility to follow with a PhD Yes

Proposal N° : 12

Contact
MOREL Robert, robert.morel@cea.fr, Tel: +33(0)4 38 78 55 03

Title
3D spheroids for the study of magneto-mechanical cancer cells destruction

Keywords
3D spheroids, cancer cells destruction, magnetic nanoparticles

Summary
The objective of this internship is to develop a 3D spheroid model of cancer cells, in gel, to study the destruction of cancer cells by application of magneto-mechanical vibrations. Cell death is achieved by mixing cells with magnetic nanoparticles, which vibrates when a rotating magnetic field is applied. These effects were first studied in vitro, on 2D cultures of cancer cells. The transition to in vivo studies on mice allows to realize that the differences in the mechanical properties of the liquid medium (in vitro) and the in vivo medium could lead to significant differences in the vibration of the particles. The internship that we propose is to develop a spheroidal model of cancer cells with mechanical properties closer to those of a real tumor. It will thus be possible to study in a more realistic way the mechanisms that allow the triggering of cell death by mechanical vibrations.

Full description of the subject
The CEA INAC /SPINTEC and BIG/ Biology of Cancer and Infection/ Invasion Mechanisms in Angiogenesis and Cancer research labs offer an internship opportunity on the development of a 3D spheroid model for the study of mechanically-induced cancer cells death.

Identification of the anti-tumor effect associated with the magnetic-field induced mechanical vibrations of nanometric magnetic particles has been achieved in 2010. Since then, several studies have demonstrated the likely applicability of this approach for cancer therapy, with both in vitro and in vivo experiments. The INAC /SPINTEC lab has been involved in these studies with the development of suitable magnetic nanoparticles, using optical lithography or powder technology. Our past and present activities are also devoted to the application of this technique for the development of a therapy for glioblastoma, an aggressive form of brain cancer.

Up to now, for the in vitro studies, magnetic particles were incubated with 2D cell culture in a liquid medium. Depending on the case, the particles may either attach to the cell membrane or undergo endocytosis. The application of a rotating external magnetic field induces mechanical vibration of the nanoparticles, leading to cell death in a matter of minutes. One important observation is that under these experimental conditions, a significant rate of apoptotic cell death is often detected. In vivo studies with mice proceed in a similar way, with the magnetic particles injected in a tumor.

From a physical point of view, one key parameter for the understanding of this effect is the efficiency of the mechanical energy transfer, from the particle, to the cell. Among other things, this depends on the viscosity of the liquid growth medium (for a 2D cell culture) or the stiffness of the cell tissue (for in vivo experiments). Because they differ significantly, it is difficult to extrapolate, to in vivo case, the observation collected from in vitro experiment.

The internship we propose consists in the development of a 3D spheroid model of breast cancer cells, with mechanical properties closer to that of a real tumor. Organoid cultures in 3D matrices are relevant models to mimic the complex in vivo environment that supports cell physiological and pathological behaviors. While traditional 2D cultures on rigid surfaces fail to reproduce in vivo cell behavior, 3D matrices are becoming increasingly popular supports for cell cultures because they allow mimicking the complex environment that supports cell physiological functions to better predict in vivo responses and thus to limit the need for animal models.

For this study, we will use spheroids generated from highly metastatic MDA-MB-231 breast cancer cells. Spheroids grown in gels will be incubated with magnetic nanoparticles and the impact of their mechanical vibration, as a function of the magnetic field intensity and duration, will be assessed by fluorescence imaging using cell viability, apoptosis assays (time lapse confocal microscopy). This internship is intended to be followed by a PhD thesis where a more detailed study on the effect of magneto-mechanical vibration on breast cancer cells will be undertaken, including in vivo studies with animal.

Requested skills
Cell biology, cell culture and testing, microscopy. Hepatitis B vaccination is required.

Possibility to follow with a PhD Yes, according to funding.

Proposal N° : 13

Contact

CHSHIEV Mairbek, mair.chshiev@cea.fr, Tel : +33(0)4 38 78 02 80

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 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 quantum mechanics, solid state physics and condensed matter theory

Possibility to follow with a PhD Yes

Proposal N° : 14

Contact

BUDA-PREJBEANU Liliana, liliana.buda@cea.fr , Tel : +33(0)4 38 78 44 19

Title

Atomistic modeling of all-optical switchable magnetic materials

Keywords

magnetic moments, ultra-fast dynamics, Landau-Lifshitz-Gilbert equation, atomistic model

Summary

The world of electronics is actively looking for smaller and compact components, which consume very little energy, capable of performing a huge number of operations. For the information storage and processing, magnetic materials based on rare earths and transition metals offer the possibility of manipulating information using laser pulses of a few femto seconds and thus aim at operating frequencies of the THz. This process of ultra-fast dynamics is the result of the combined action of several phenomena on magnetic moment carriers at the atomic scale. The purpose of the master proposal is to analyze by numerical modeling the process of the reversal of the magnetization according to the composition of the materials and their crystalline structure. For this, the Landau-Lifshitz-Gilbert equation that describes the dynamics of magnetic moments will be coupled to heat diffusion equations by involving electrons and phonons. This atomistic model will make it possible to understand the mechanisms of magnetic moment switching as well as to identify the most promising materials for their fabrication.

Full description of the subject

The reversal of magnetization under the action of laser pulses was experimentally demonstrated in 2007 for amorphous thin layers of GdFeCo alloy [1]. Laser pulses circularly polarized of a few femto-seconds are sufficient to switch the magnetization of some rare-earth-transition metal compounds without the need to apply an additional magnetic field. The research activity around this remarkable property is very intense given the strong application potential targeting ultra-fast memory devices with very low consumption by integrating active parts all-optical switchable. The practical object is to combine a memory function (long-term information retention) with an ultra-fast write speed (~ THz). It is imperative to demonstrate that switching is deterministic and perfectly reproducible despite the multiple physical phenomena that are involved: exchange interaction, phono-electron coupling, photon-magnetization coupling. The success of the concept involves simultaneously experimental efforts and extensive modeling.

During this project, we propose to participate in the development of an adapted, efficient and powerful numerical model able to take into account several interactions to describe at the atomic scale the mechanisms of ultra-fast reversal of the magnetization. The formalism is based on the coupling between the dynamics of the magnetization and the ultra-fast heating induced by the laser pulse [2]. For each magnetic moment, composing the material, the phenomenological equation of Landau-Lifshitz-Gilbert motion will be numerically integrated taking into account the ultra-very fast variation of the local temperature during the duration of the laser pulse.

After a test / validation phase compared to the results reported in the literature, the model will be exploited for an in-depth analysis of the properties of new rare earth-transition metal compounds. The goal is twofold: to understand and master the mechanisms that drive the ultra-fast reversal in order to identify the best materials for the applications. The various material parameters necessary for a realistic modeling of a certain compound will be extracted from ab-initio calculations in connection with the theoretical team of Spintec. Confrontations with the experimental studies will be conducted in parallel with the MRAM team.

[1] C. Stanciu et al, Phys. Rev. Lett. 99, 047601 (2007).
[2] I. Radu et al., Nature 472, 205 (2011).

Requested skills
condensed matter physics, nanosciences, basis in magnetism and programming

Possibility to follow with a PhD Yes

Proposal N° : 15

Contact

PRENAT Guillaume, guillaume.prenat@cea.fr, Tel : +33(0) 4 38 78 63 15

Title

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

Keywords

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

Summary

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

Full description of the subject

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

A lot of academic studies have shown the advantages in terms of performance, power consumption and new functionalities that can be expected in computations systems for various

applications. The biggest actors of microelectronics are investigating this technology in its standard version, with Spin Transfer Torque (STT) writing scheme. However, while STT becomes more and more mature and close to industrialization, new generations are studied in laboratories and in particular at Spintec, like electric field assisted writing scheme of spin/charge current interconversion by spin orbit effect. These new technologies promise still better performance but are actually at the stage of theoretical studies, from fundamental understanding to materials developments.
The aim of the internship is a preliminary evaluation of the advantages that can be expected from memory and logic circuits using these new concepts. It will be necessary to develop compact models of the devices and integrate them in the standard tools of microelectronics for electrical simulations. These models will then be used to design elementary circuits which will allow in the long term an evaluation of the gains for more complex circuits. The internship could address the following tasks :

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

Requested skills

The candidate should have a master degree or equivalent, from university or engineer school. His skills should cover microelectronics full-custom/circuit level design preferably using Cadence. VerlilogA language programing notions would be an asset. The level of English should allow the candidate to read and write scientific articles, as well as attending technical discussions which could be made in English. An attraction for research and multidisciplinary are very important for this internship.

Possibility to follow with a PhD Yes

Proposal N° : 16

Contact

DUHEM François, francois.duhem@cea.fr, Tel:+33 (0)4 38 78 52 98

Title

System-level simulation and design space exploration of non-volatile neuromorphic architectures

Keywords

Neuromorphic computing, system-level modeling, non-volatile memory

Summary

Hardware neural network implementation is a hot topic in research and is now considered as strategic for several international companies. Leading projects in neuromorphic engineering have led to powerful brain-inspired chips such as SyNAPSE, TrueNorth and SpiNNaker. Most of these technologies work well in centralized computing farms but will not fit embedded systems or Internet-of-Things (IoT) requirements, due to their energy consumption. Heterogeneous integration between CMOS and emergent technologies is seen as an opportunity to go past this limitation. In particular, Magnetoresistive Random-Access Memory (MRAM) is considered one of the most promising Non-Volatile Memory (NVM) technology expected to mitigate energy consumption when integrated in computing architectures. However, we still miss a high-level perspective on how NVM actually benefits energy efficiency and how it can be improved any further. In the frame of a collaboration between Spintec and the LEAT lab in Sophia Antipolis, a spiking neural network simulator has been developed in SystemC to estimate metrics such as energy consumption, silicon area and performance in various architectures, laying ground for system-level exploration of non-volatile neuromorphic architectures.

In this context, the aim of the internship is to carry on this work and add new features to the simulator. In particular, the intern will have to refine NVM modeling and compare with actual hardware implementations to assess the simulator accuracy. The intern will eventually demonstrate the simulator functionalities by defining the fittest architecture for a vision-based cognitive task, showcasing the benefits of this non-volatile architecture compared to its volatile counterpart.

Full description of the subject

Hardware neural network implementation is a hot topic in research and is now considered as strategic for several companies. Indeed, the recent interest around deep neural networks for pattern recognition has put a new spotlight on neuromorphic engineering and a few industrial giants now dominate the deep learning sector, mainly American (Nvidia, Google, IBM, Intel...). They usually rely on General-Purpose Graphics Processing Units (GPGPUs) for the learning process, and dedicated hardware for inference on embedded targets, which is known to be energy-efficient.

Leading projects in neuromorphic engineering have led to powerful brain-inspired chips able to simulate numerous spiking neurons to investigate a new kind of computer architecture (SyNAPSE, TrueNorth), or to help neuroscientists through international projects such as the

Human Brain Project in Europe (SpiNNaker). Most of these technologies work well in centralized computing farms but will not fit embedded systems or Internet-of-Things (IoT) requirements, due to their energy consumption. Heterogeneous integration between CMOS and emergent technologies is seen as an opportunity to go past this limitation.
Non-Volatile Memories (NVMs) have gained traction in the last few years as they are expected to help mitigating the ever growing energy consumption due to leakage in advanced technology nodes. Among emerging NVM technologies, Magnetoresistive Random-Access Memory (MRAM) is considered to be one of the most promising as it reaches performance levels close to those of Static RAM (SRAM) with very high endurance and good downsize scalability.
One promising use of MRAM is non-volatile processors, where non-volatile storage elements are integrated in the memory hierarchy in order to reduce energy consumption. Many studies showed magnetic and hybrid general-purpose processor architectures, with the resulting trade-off between performance, area and energy consumption. These studies do not consider domain-specific accelerators, even though they are usually necessary to achieve higher energy efficiency compatible with embedded systems requirements. In this context, a collaboration between Spintec and the LEAT lab (Laboratoire d'Electronique, Antennes et Télécommunications) in Sophia Antipolis led to the development of a SystemC simulator that is able to evaluate non-volatile spiking neural network implementations. It infers important metrics such as silicon area, energy consumption and performance while ensuring functional validation. The simulator is expected to lay the ground for wide adoption of such architectures in the growing market of embedded neuromorphic architectures, with potential applications in smart cities, wearables, IoT, mobile robotics, connected and autonomous vehicles, and so on.

The goal of the internship is to continue the development of the simulator and extend it with new features to provide finer-grained comparison between volatile and non-volatile architectures. The intern's missions will be the following:

- Bibliography on NVM and non-volatile architecture modeling
- Refinement of the NVM models
- Development of new features for the simulator
- Assessment of the simulator accuracy
- Demonstration on an application to be defined

Requested skills

Applicants should have background in embedded systems, system architecture, electronics and programming language such as C/C++ (SystemC appreciated). Knowledge in RTL development is a plus.

Possibility to follow with a PhD No