Highlights

2021

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FOREWORD

Social links are being restored, despite the lasting pandemic. All members of the lab are fully back onsite, enjoying direct networking again. The lab weekly meetings, general assemblies and the team meetings are all taking place face-to-face. Yet, we are all dearly missing the all kinds of daily parties, currently still not possible, which we all know are key to the warm social atmosphere and creativity of a research laboratory. These are crucial especially for the young scientists working for a finite duration in the lab as students, PhD candidates and post-docs, for a quick and efficient building of a social network. Thus, while we all do our best to cope with the current constraints, we hope to be back to normal social life as soon as the public health situation allows. A first step was achieved with the General Assembly organized face-to-face end of September in *Château de la Baume* in Seyssins.

New strategic and game-changing partnerships started, which allow to strengthen our actions and expand our network. We are involved in two successful national initiatives of Excellence EquipEx, the 2D-MAG and NanoFutur projects, providing almost 3 M€ in total. These will allow to setup platforms for the synthesis of spintronic stacks, from the emerging 2D epitaxial materials to an industry-ready pilot line. We are also leading two new bilateral projects with the US and Germany on artificial intelligence topics, and benefit from the final renewal of a DARPA project on skyrmions. Several innovation-oriented grants will also contribute to support the rise of new memory and logic actions, making use of spin-orbit torques and ferroelectric/magnetic architectures.

We keep welcoming new collaborators, to achieve our missions. CEA research scientist Philippe TALATCHIAN and CEA technician Nicolas MOLLARD, who joined end of 2020, already contributed to key actions in their fields, artificial intelligence and scientific instrumentation. CEA research engineer Jérôme FAURE-VINCENT has joined the lab at the beginning of 2021, with the mission to setup the growth cluster for the magnetic tunnel junction pilot line. CNRS engineer Florian DISDIER joined this autumn, with mission to bridge all our activities in clean-room nanofabrication, a cornerstone in our studies. Finally, CEA engineer Isabelle de MORAES joined in December, supporting the platform for epitaxy of 2D spintronics materials and stacks.

2021 was a very successful year for our teaching scientists. Jean-Philippe ATTANÉ and Hélène BÉA, associated professors at the University Grenoble Alpes, were appointed Senior and Junior Members of the Institut Universitaire de France (IUF), beginning from October 1, 2021 for a period of five years. Moreover, Liliana BUDA-PREJBEANU obtained a full professor position at Grenoble INP.

We are now turning with confidence towards 2022, coming with specific challenges. On the side of science, we shall implement the first steps of our two national EquipEx projects, involving acquisition of new equipment, their hookup and benchmarking. On the side of organization and following the detailed evaluation of our carbon footprint in 2021, we will for the first time implement incentive actions to decrease it, and monitor it on the long run.

We hope that you will enjoy browsing the following pages, gathering a selection of scientific highlights and cornerstones of SPINTEC over the year 2021.

Lucian PREJBEANU, Executive Director / Olivier FRUCHART, Deputy Director

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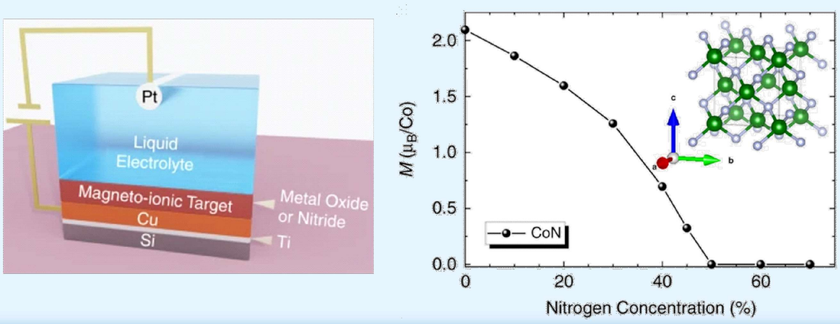
SPINTEC Highlights – December 2021 – Editor: Gregory Di Pendina

Directors of publication: Lucian Prejbeanu, Executive Director – Olivier Fruchart, Deputy Director

Voltage-driven motion of nitrogen ions: a new paradigm for magneto-ionics

Voltage-driven ionic transport in magnetic materials has traditionally relied on controlled migration of oxygen ions. In this work, led by researchers at UAB (Barcelona) in collaboration with colleagues at Georgetown University (D.C.), HZDR (Dresden), SPINTEC (Grenoble), ICN2 and CNM-CSIC (Madrid and Barcelona), room-temperature voltage-driven nitrogen transport was demonstrated using electrolyte-gating of a CoN film. The latter shows reversible voltage-driven ON-OFF ferromagnetism with low threshold voltages and exhibits enhanced rates and cyclability.

Electric-field control of magnetic properties is of major interest for future generations of energy-efficient applications. One of the promising routes towards efficient control of magnetism may be provided by voltage-driven ionic motion (called magneto-ionics) either in magnetic layered structures comprising transition metals (Co, Fe...) and oxides (GdO_x, HfO_x, MgO…), or structural oxygen motion in already oxidized materials (e.g. CoO_x etc.) However, there are still major drawbacks limiting their potential use in practical devices due to an inherent voltage trade-off between induced magnetization, speed and cyclability.



Schematic representation (left) and calculated variation of magnetic moment per Co atom as a function of increasing the N percentage in the CoN unit cell (right).

In this work, nitrogen magneto-ionics is demonstrated as an improved alternative to oxygen magneto-ionics. Namely, CoN and Co_3O_4 single-layer films grown by sputtering were voltage-actuated to compare nitrogen vs. oxygen magneto-ionic performances. These materials were selected since they both exhibit voltage-induced ON-OFF ferromagnetic transitions. Neither Co_3O_4 nor CoN are ferromagnetic at room-temperature. The magnetic properties of these systems are strongly correlated to the amount of either oxygen or nitrogen in the films. According to the virtual crystal approximation, for CoN, beyond 50 at. % of nitrogen in the unit cell, the magnetic moment becomes negligible [see Figure].

Remarkably, voltage-driven transport of structural nitrogen is found both experimentally and theoretically to be energetically more favorable than oxygen, resulting in lower operating voltages and enhanced cyclability. This together with the lower electronegativity (i.e., weaker bonds with Co) of nitrogen with respect to oxygen leads to overall enhanced magneto-ionic effects. Moreover, the magneto-ionic rates are faster than for oxygen magneto-ionics. This is due to the lower activation energy for ion diffusion and the lower electronegativity of nitrogen compared to oxygen.

Controlled motion of nitrogen ions with voltage may enable the use of magneto-ionics in new technological areas that require endurance and moderate operation speeds (e.g., neuromorphic computing or micro-electro-mechanical systems). These results may open new avenues in applications such as brain-inspired computing or iontronics in general.

Team: Theory/Simulation

Collaboration: UAB (Spain), ICN2 (Spain), CNM-CSIC (Spain), Georgetown Univ. (USA), HZDR (Germany)

Funding: ANR FEOrgSpin, ANR ELECSPIN

Further reading: *Voltage-driven motion of nitrogen ions: a new paradigm for magneto-ionics*, J. de Rojas et al., Nat. Comm. 11, 5871 (2020). *Open access: hal-03139703*

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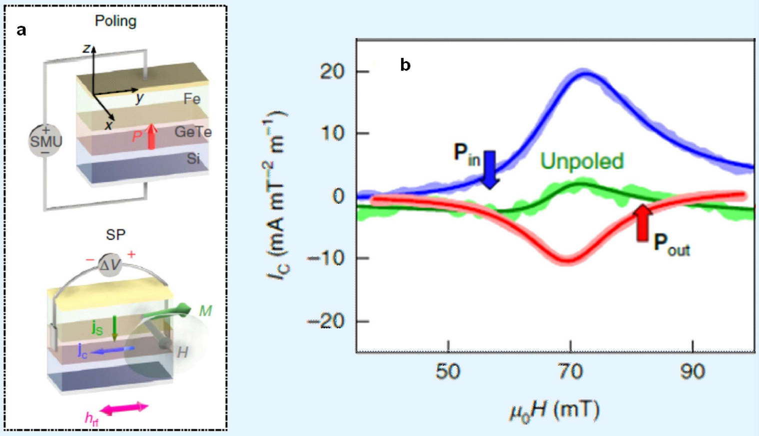
Room-temperature ferroelectric switching of spin-to-charge conversion in GeTe

The broken inversion symmetry of some semiconductors may allow for spin–charge interconversion, but its control by electric fields is volatile. This has led to interest in ferroelectric Rashba semiconductors, which combine semiconductivity, large spin–orbit coupling and non-volatility. Here we report room-temperature, non-volatile ferroelectric control of spin-to-charge conversion in epitaxial germanium telluride films.

Spintronics could potentially be used to create low-power solutions for beyond-complementary-metal–oxide-semiconductor (CMOS) technology. Ideally, spin would be added as an extra degree of freedom into semiconductor-based electronics operating on charge. However, combining ferromagnets (as spin generators and detectors) with semiconductors has proved challenging due to issues with material compatibility and impedance mismatch. Ferroelectric Rashba semiconductors (FERSCs) have been identified as alternative materials for operating on spin and integrating logic and memory functionalities. FERSCs have a broken inversion symmetry, like several other semiconductors; however, because they are ferroelectric, they also display giant Rashba spin splitting of the bulk bands, with the additional effect that the spin direction in each Rashba sub-band can be reversed by switching the ferroelectric polarization.

We show that ferroelectric switching by electrical gating is possible in germanium telluride, despite its high carrier density, leading to a large resistance change across GeTe/metal (300%) and GeTe/Si (4000%) interfaces and possibility for a non-destructive readout of the ferroelectric sate. We also show that spin-to-charge conversion has a similar magnitude to what is observed with platinum, but the charge current sign is controlled by the orientation of ferroelectric polarization. Comparison between theoretical and experimental data suggests that the inverse spin Hall effect plays a major role in switchable conversion.



(a) Schematics of the poling of GeTe and spin pumping experiments. (b) Normalized current produced by spin-pumping, for three different ferroelectric polarization states. The blue and red curves correspond to opposite polarization states. They are leading to opposite spin pumping signals, which means that opposite polarization states corresponds to opposite spin-to-charge conversion signs. The green curve refers to the pristine (unpoled) states. The relatively small amplitude of the spin-pumping signal in this unpoled state is due to a multidomain ferroelectric.

Like for ferromagnetics, this process is reconfigurable and non-volatile, operated by electric fields and thus offering reduced power consumption. FERSCs could thus potentially be used to develop all-in-one devices that integrate spin generation, manipulation and detection. Notably, these findings merge in one the reading and writing elements of the recently proposed Magneto-Electric Spin Orbit device proposed by Intel for attojoule logic, in memory computing or artificial intelligence. Respect to our previous findings in SrTiO3 interfaces, the ferroelectric control of spin-charge conversion can be achieved here at room temperature.

Team: Topological spintronics

Collaboration: CEA, PoliMi, CNR, Paul-Drude-Institut, CNRS

Funding: ANR TOPRISE, OISO, CONTRABASS

Further reading: *Room-temperature ferroelectric switching of spin-to-charge conversion in germanium telluride*, S. Varotto et al., Nat. Electron. 4, 740 (2021). *Open access: hal-03188292*

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Spin information transported over long-distances at room temperature in the ultra-low damping hematite antiferromagnet

A consortium led by physicists at JGU Mainz, in collaboration with CNRS/Thales Palaiseau, SPINTEC and LNCMI Grenoble, and NTNU Trondheim, demonstrated that transporting spin-information at room temperature and over long distances is within reach. They established and took advantage of two remarkable features of the insulating hematite antiferromagnet. Firstly, it can carry spin-information via current-induced pairs of linearly polarized magnons in its high-temperature easy-plane phase. Secondly, information is sustained as it moves through the material due to its record ultra-low magnetic damping.

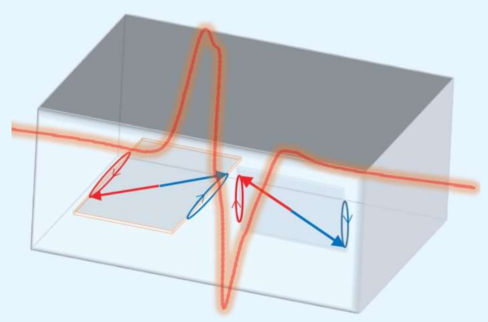

Illustration of the two linearly polarized modes in an easy-plane antiferromagnet, superimposed with a resonance absorption spectrum.

Because antiferromagnetic materials possess two magnetic sublattices, they can host pairs of spin waves, and eventually carry spin-information suitable for data encoding. These spin waves range from circular to linear polarizations, depending on the magnetic anisotropies in the material. Until now, only low-temperature easy-axis anisotropy antiferromagnets with circularly-polarized spin waves were reported to carry spin information over distances of micrometers-long. Here, long-distance spin transport was reported in the room-temperature easy-plane canted antiferromagnetic phase of hematite.

For an easy-plane anisotropy antiferromagnet, the linearly-polarized spin waves are not intuitively expected to carry spin. The mechanism at stake involves current-induced pairs of linearly-polarized spin waves with dephasing lengths in the micrometer range. Basically, a pair is initially induced electrically, by spin torque. It carries an effective circular polarization and thus a spin information. Because the two linearly-polarized spin waves constituting the pair follow two distinct dispersion laws, they 'unpair' (dephase) after some length. In optics, this is similar to light propagating in a birefringent material. The dephasing length is set by the relative dispersion laws. Over this length, the two spin waves propagate separately. They do not carry spin anymore because of their independent linear polarizations.

In addition to the ability of the high-temperature easy-plane phase of hematite to carry spin, the long transport distance was explained as a result of its record low magnetic damping. In this context, SPINTEC contributed to series of experiments of antiferromagnetic resonance. Damping was measured to be smaller than 10^{-5}, as in the best ferromagnets. This result was made possible thanks to the remarkable capabilities of a quasi-optical bench at LNCMI-CNRS, Grenoble. This bench is suitable for antiferromagnetic resonance as it combines high magnetic fields, high frequencies and low temperatures.

The findings from this study contribute to the understanding of a previously-overlooked and incompletely understood effect, associated to magnonic birefringence. The results further highlight the promising potential of insulating antiferromagnets for magnon-based devices.

Teams: Antiferromagnetic spintronics, Microwave devices

Collaboration: UMR CNRS/Thales Palaiseau, JGU Mainz, LNCMI Grenoble, NTNU Trondheim

Funding: ANR-15-CE24-0015-01, PE-18P31-ELSA, FET-Open-863155

Further reading: *Long-distance spin-transport across the Morin phase transition up to room temperature in ultra-low damping single crystals of the antiferromagnet α-Fe2O3,* R. Lebrun, A. Ross, O. Gomonay, V. Baltz, U. Ebels, A.-L. Barra, A. Qaiumzadeh, A. Brataas, J. Sinova & M. Kläui, Nat. Comm. 11, 6332 (2020). *Open access: hal-03298714*

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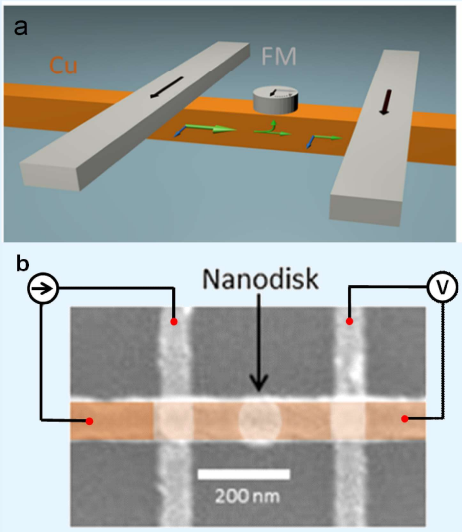
Measurement of the spin absorption anisotropy in lateral spin valves

The spin absorption process in a ferromagnetic material depends on the spin orientation relatively to the magnetization. Using a ferromagnet to absorb the pure spin current created within a lateral spin valve, we evidence and quantify a sizable orientation dependence of the spin absorption in Co, CoFe, and NiFe. These experiments allow us to determine the spin-mixing conductance, an elusive but fundamental parameter of the spin-dependent transport.

Spin-orbitronics considers the spin-to charge interconversion. Most of the techniques used in this field rely on non-collinear spin transport into ferromagnetic materials in order to detect or generate a spin current. The interaction of the spin current with a ferromagnet that possesses a magnetization transverse to the spin current's polarization is governed by the spin mixing conductance. This quantity is therefore of fundamental interest in order to evaluate the efficiency of the spin-to-charge interconversion.

However, the evaluation of such a quantity has proven difficult in available measurement techniques like FMR and Spin-Hall Magnetoresistance, because of the presence of parasitic effects such as the two-magnon scattering at GHz frequencies, and the presence of a charge current in the system. These spurious contributions can be avoided by using pure spin currents in a d.c. electrical measurement. Using lateral spin valves, we generated a pure spin current flowing between two ferromagnetic electrodes. A nanodisk is placed between the two electrodes and absorbs a part of the spin current, thus reducing the measured signal with respect to a lateral spin valve without absorber. Thanks to its shape anisotropy, the magnetization of the absorber could be rotated in a direction transverse or parallel to the polarization of the spin current. We then measured the difference in absorption efficiency between these transverse and parallel configurations. Using discrete numerical simulations, we extracted the spin mixing conductance at the interface between copper and 3d materials. Our results confirm that the relaxation efficiency of the spin current into a ferromagnet is higher when its magnetization is transverse to the polarization of the spin current. Furthermore, our results are in line with *ab initio* calculation, showing a very strong spin relaxation efficiency in 3d ferromagnets, only limited by the finite number of conductions channel in copper, giving a finite Sharvin conductance at the interface between copper and 3d ferromagnets.



(a) Design and (b) SEM view of the nanodevices with an absorbing nanodisk

Our results confirm the possibility to design nanodevices with a non-collinear geometry, allowing us to move toward the study of magnetization-dependent Spin Hall Effect in ferromagnetic materials.

Teams: Topological spintronics, 2D spintronics

Collaboration: Unité Mixte de Physique CNRS/Thales, Irig/Pheliqs

Funding: ANR OISO

Further reading: *Measurement of the Spin Absorption Anisotropy in Lateral Spin Valves*, M. Cosset-Chéneau, L. Vila, G. Zahnd, D. Gusakova, V.T. Pham, C. Grèzes, X. Waintal, A. Marty, H. Jaffrès, and J.P. Attané, Phys. Rev. Lett. 126, 027201 (2021). *Open access: hal-03119506*

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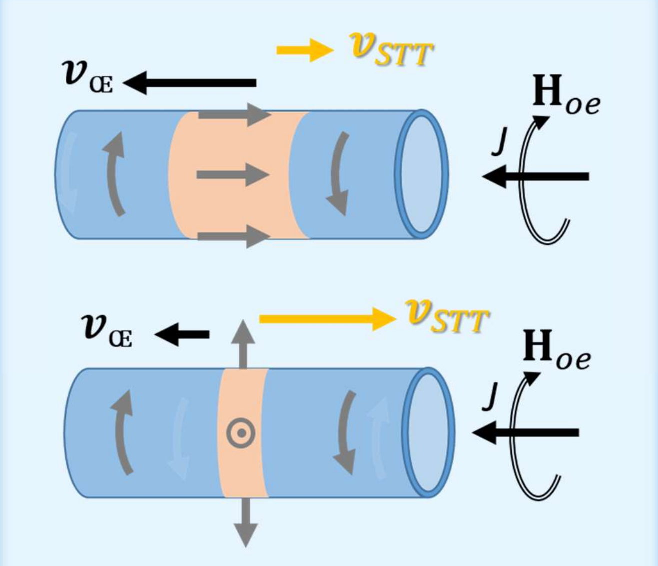
Theoretical study of current-induced domain wall motion in magnetic nanotubes with azimuthal magnetization

We report a theoretical overview of the magnetic domain wall behavior under an electric current in infinitely-long nanotubes with azimuthal magnetization. We highlight effects that, besides spin-transfer torques already largely understood in flat strips, arise specifically in the tubular geometry: the Œrsted field and curvature-induced magnetic anisotropy resulting both from the exchange interaction and material growth.

While magnetic nanowires and nanotubes have been synthesized and investigated for three decades, it is only recently that their properties are being monitored at the scale of single objects, such as for instance domain-wall motion. Recently, a very peculiar class of domains was observed in CoNiB nanotubes – domains with azimuthal (flux-closure) magnetization. Two possible sources of magnetic anisotropy have been mentioned to explain this peculiar magnetization orientation in long tubes: intergranular interface anisotropy and magneto-elastic coupling (inverse magnetostriction). Interestingly, such domains open the possibility of moving domain walls at very high field with only electric currents, via the Œrsted field.



Sketch of the domain wall in a nanotube subjected to the electron current. According to intrinsic tube properties, favoring a particular domain wall type, the domain wall dynamics is dominated either by the Oersted filed or by the spin-transfer torque.

In this context, we perform a theoretical and numerical study on the current-induced domain-wall dynamics in magnetic tubes with azimuthal domains, focusing particularly on the effect of the Œrsted field and spin-torque-induced effects. We combine theory based on an analytical 1D model to draw trends and highlight the physics at play, with micromagnetic simulations for an accurate description. We establish a phase diagram where stable azimuthal domains are predicted as a function of the anisotropy strength K and the tube geometry. In addition, stable Néel and Bloch wall structures (see figure) are predicted, resulting from the competition between the curvature-induced exchange energy, the demagnetization energy and the anisotropy energy. We show the existence of spin-transfer torque and/or Œrsted-dominated regime for both domain wall structures, and we report large domain-wall speeds reaching potentially 800 m/s and the presence of a so-called Walker breakdown. We pay particular attention to features that are analogous to flat strips, and those that are specific to tubes. For example, we show how the domain-wall speed and the Walker field depend on the anisotropy and the geometrical parameter of the magnetic tubes. Our study may guide the experimental realization of magnetic tubes for finding the optimal parameters to get the desired properties.

Teams: Theory/Simulation, Spin textures

Collaboration: Brno University of Technology, Institut Néel

Funding: ANR MATEMAC-3D

Further reading: *Theoretical Study of current-induced domain wall motion in magnetic nanotubes with azimuthal domains*, J. Hurst, A. De Riz, M. Stano, J-C. Toussaint, O. Fruchart, and D. Gusakova, Phys. Rev. B 103, 024434 (2021). *Open access: hal-02958749*

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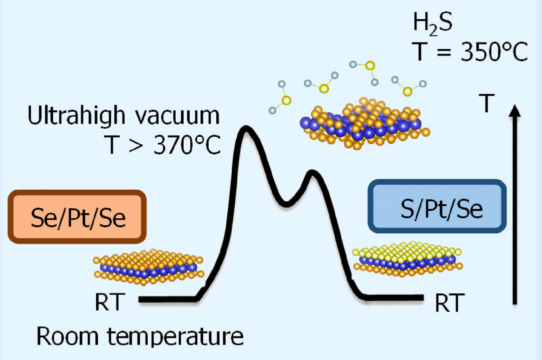
Synthesis of epitaxial monolayer Janus SPtSe

Two-dimensional materials like graphene or transition metal dichalcogenides (TMDs) have attracted a lot of attention during the last decade for their original electronic properties intimately related to their 2D character and symmetries. At Spintec, the "2D spintronics" team develops the molecular beam epitaxy of TMDs for spintronics and has recently succeeded in growing a new Janus monolayer of SPtSe. This new material associating high spin-orbit coupling and low symmetry might contribute to improve the writing-reading efficiency of magnetic memories.

The goal of this study is to exploit the Rashba spin-orbit coupling in two-dimensional materials for the development of a new generation of SOT-MRAM made of van der Waals materials. Considering TMDs, we selected PtSe2 for the large spin-orbit interaction induced by platinum atoms. However, the main obstacle to reach high Rashba spin-orbit coupling comes from the mirror symmetry of PtSe2 with respect to the Pt atomic plane leading to the absence of vertical electric dipole and field. In collaboration with IRIG-MEM, we have broken this mirror symmetry by substituting only the top layer of Se atoms by S atoms to form a so-called Janus SPtSe monolayer after the biface Roman God. This selective substitution generates a vertical electric dipole and potentially a very strong Rashba spin-orbit coupling.

The parent compound was one monolayer of $PtSe_2$ epitaxially grown on a platinum single crystal by self-limited selenization of the Pt. The final compound SPtSe was then synthesized by substituting the Se atoms in the top layer by S atoms using a well-controlled sulphurization process under H_2S atmosphere. It proceeded in two steps observed *in situ* and *operando* by grazing incidence x-ray diffraction at the European Synchrotron Radiation Facility (ESRF, beamline BM32). First, the $PtSe_2$ layer was annealed in ultrahigh vacuum up to 370°C. At this temperature, the $PtSe_2$ monolayer started degrading and some Pt-Se bonds were broken mostly in the top layer. However Se atoms stayed at the sample surface probably forming a "liquid" phase. In the second step, H_2S was introduced in the chamber and the presence of Pt catalyzed the H_2S molecules dissociation allowing S atoms to substitute Se ones. The whole process is schematically shown in the figure. The final atomic composition of the biface Janus monolayer was then checked *ex situ* by angle resolved x-ray photoemission spectroscopy.



Schematics of the process by which the top Se layer was selectively substituted by S atoms to form the Janus compound.

This is the first time this type of Janus compound could be synthesized and SPtSe, with large Rashba spin-orbit coupling, has great potential in the fields of magnetic and ferroelectric memories.

Team: 2D spintronics

Collaboration: IRIG-MEM, ESRF

Funding: ANR MAGICVALLEY

Further reading: *Synthesis of epitaxial monolayer Janus SPtSe*, R. Sant, M. Gay, A. Marty, S. Lisi, R. Harrabi, C. Vergnaud, M.-T. Dau, X. Weng, J. Coraux, N. Gauthier, O. Renault, G. Renaud and M. Jamet, npj 2D Mater. Appl. **4**, 41 (2020). *Open access: hal-03103750*

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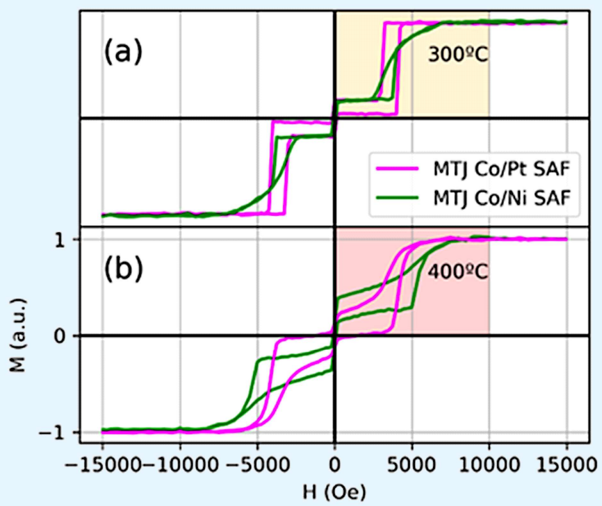
Sustainability analysis of perpendicular-anisotropy magnetic memory and platinum substitution

Perpendicular-anisotropy Magnetic Random Access Memory (MRAM) can contribute to reduce power consumption in electronic circuits. These spintronic devices also rely on materials like Co, Pt and Ru, having associated supply risk or environmental impact. A sustainability analysis of these devices shows, that the impact of the wafer substrate is much larger than that of the device materials themselves. This is due to the small material quantity used in the spintronic stacks, and target recycling measures. A substitution of Pt/Co by Ni/Co multilayers can also contribute to a 3x reduction of the global warming potential (GWP).

The use of MRAM in the fields of IoT (Internet of Things) and generally in information and communication technology (ICT) is expected to significantly increase, providing non-volatility and low power consumption to these applications. Supply risk, was evaluated considering recycling, substitution and supply concentration. Our analysis concludes that platinum is the element that poses the most significant risk, taking into account the amount of material that is used in the stack. Our investigation also confirms that due to the tiny amounts of material (only 3.4 milligrams of Pt is used), economic and environmental costs are dominated by the production of the substrate wafer itself, corresponding to 127 grams of Si.



Substitution of Co/Pt by Co/Ni multilayers in the reference layer of MRAM confirms similar annealing and thermal stability.

The highest motivation to consider Pt substitution is disruption supply risk, with 80% of world production concentrated in two countries, South Africa and Russia. An alternative to Pt is the replacement of the Co/Pt multilayer in the reference layer by a Co/Ni multilayer. Ni having no scarcity or supply disruption risks. Results show that the thermal stability reference electrode base on a multilayer of [Co 0.5 nm/Pt 0.25 nm] can be replaced by a [Co 0.18 nm/Ni 0.55 nm] multilayer, achieving the same magnetic and annealing stability, as shown in the figure. Copper was used as seed layer with Ni, without requiring other critical materials. The global warming potential of the Ni reference layer is reduced by a factor of 3, compared to the Pt alternative.

Finally, other possible material concerns were evaluated as not significant because of the small quantities used, as is the case for Mg in the MgO tunnel barrier, or for W used as 0.2 nm thin insertion layers acting as a boron getter in typical MRAM stacks. In conclusion, wider adoption of MRAM technology by the electronics industry can be envisioned in a sustainable way, with credible substitutions available to prevent risks in critical materials.

Teams: MRAM, materials, instrumentation

Collaboration: Laboratoire CERAG Université Grenoble Alpes

Funding: French National Research Agency "Investissements d'avenir" program (ANR-15-IDEX-02) and project NEED for IoT by the University of Grenoble Alpes (UGA)

Further reading: *Evaluating critical metals contained in spintronic memory with a particular focus on Pt substitution for improved sustainability,* A. Palomino, J. Marty, S. Auffret, I. Joumard, R. C. Sousa, I.L. Prejbeanu, B. Ageron and B. Dieny, Sustain. Mater. Technol. 28, e00270 (2021). *Open access: hal-03170821*

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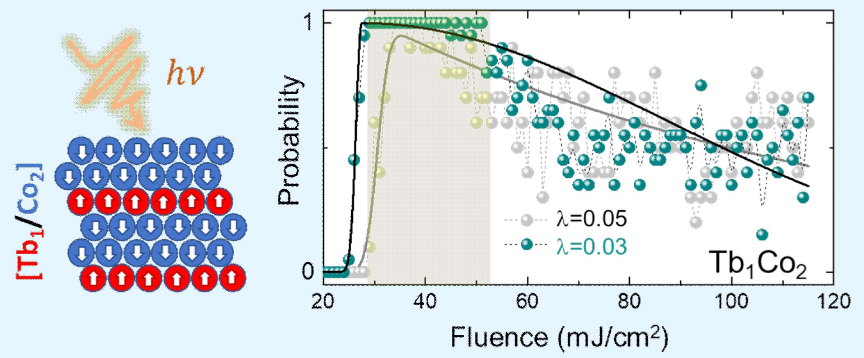
Single-shot all-optical switching of magnetization in Tb/Co multilayer-based MTJ

Atomistic spin simulations have been carried out to study the probability of all-optical switching of [Tb/Co] multilayered thin films. Playing with the composition of the sample, the material parameters and the fluence of the laser pulse, we have shown the possibility to get single-shot all-optical switching.

Since the first experimental observation of all-optical switching phenomena, intensive research has been devoted to finding suitable magnetic systems that can be integrated as storage elements within spintronic devices, and whose magnetization can be controlled through ultra-short single laser pulses. We have developed an atomistic spin solver coupled with a two-temperature model to be able to simulate the magnetization dynamics driven by ultra-short laser pulses. The multilayered structures are based on alternating *n* monolayers of Tb and *m* monolayers of Co. The model allowed to describe the thermal variation of the magnetization of each sublattice as well as the magnetization dynamics of [Tb_n/Co_m] multilayers upon incidence of a single 50 fs laser pulse. In particular, the conditions to observe thermally-induced magnetization switching were investigated upon varying systematically both the composition of the sample (*n*,*m*) and the laser fluence. The samples with one monolayer of Tb as [Tb_1/Co_2] and [Tb_1/Co_3] are showing thermally induced magnetization switching above a fluence threshold.



Switching probability of [Tb_1/Co_2] multilayer driven by 50fs laser pulse depending on the laser fluence. A large range with deterministic switching is found by adjusting material damping parameter λ.

The reversal mechanism is mediated by the residual magnetization of the Tb lattice, while Co is fully demagnetized in agreement with the models developed for ferrimagnetic alloys. The switching is however not fully deterministic, but the error rate can be tuned by playing with the damping parameter. Increasing the number of monolayers, the switching become completely stochastic. The intermixing at the Tb/Co interfaces appears to be also a promising solution to reduce the stochasticity.

These results predict for the first time the possibility of thermally-induced magnetization switching in [Tb/Co] multilayers, and suggest the occurrence of sub-picosecond magnetization reversal using single laser pulses. Preliminary experimental results performed by our collaborators from the SPICE project are in line with the simulations.

Teams: Theory/Simulation, MRAM

Collaboration: Radboud University (Nijmengen)

Funding: H2020 FET-Open Grant Agreement No. 713481 (Project SPICE)

Further reading: *All-optical spin switching probability in [Tb/Co] multilayers*, L. Avilés-Félix, L. Farcis, Z. Jin, L. Alvaro-Gomez, G. Li, A. Kirilyuk, A. V. Kimel, Th. Rasing, B. Dieny, R. C. Sousa, I. L. Prejbeanu, and L. D. Buda-Prejbeanu, Sci. Rep. 11 (1) (2021). *Open access: hal-03186985*

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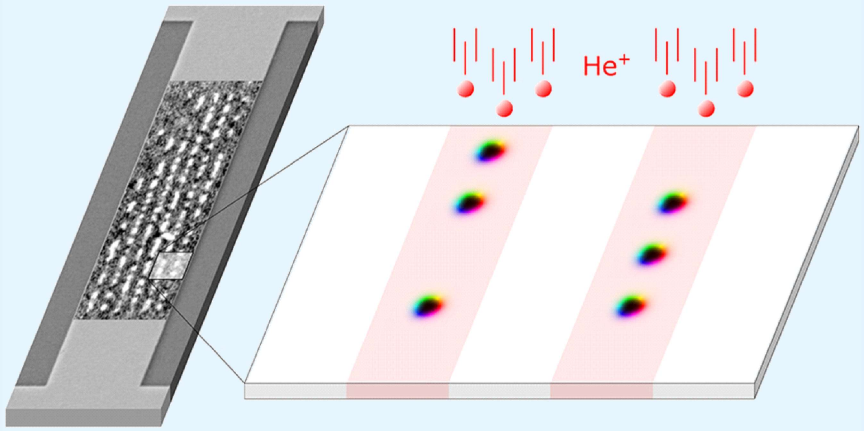
Helium ions put skyrmions on the track

Magnetic skyrmions are local twists of the magnetization, which hold promise as nm scale information carrier. Here we demonstrate that focused He+-ion irradiation can be used to create and guide skyrmions in magnetic tracks. This work opens up a new path to manipulate magnetic skyrmions in magnetic memory and logic devices

Magnetic skyrmions are currently fascinating many research groups in the world, as they could offer a new way to store and process information in our computers. These nanoscale magnetic textures are composed of elementary nanomagnets that wind up to form a stable spiral structure, like a well tighten node. Skyrmions can be manipulated by very low electrical currents, which opens a path for their use as information carriers in computing devices. Several groundbreaking memory and logic devices have thus been proposed, that promise very large information density and low power consumption.

These devices are based on the manipulation of trains of skyrmions in magnetic tracks, by electrical current. However, these applications still remained distant as skyrmions intrinsically move toward the edge of the track, where they can annihilate. In this work, we have shown that light He+ ion irradiation can be used to create and guide skyrmions in racetracks. Light He+ Ion irradiation is a well-known tool to modify the magnetic properties of magnetic ultrathin films. By using a focused ion beam, these magnetic properties can be changed at the nm scale in order to pattern magnetic tracks where skyrmion naturally nucleate (see figure). When driving them by current, skyrmions can be moved along the irradiated tracks, leading to the suppression of the transverse motion. This possibility to create skyrmion racetracks and guide their trajectory in magnetic ultrathin films open some novel perspectives to manipulate skyrmion in memory and logic applications.



Local ion irradiation leads to a change of the magnetic properties, which allows to stabilize magnetic skyrmions in tracks. Left: magnetic microscopy image of skyrmions in a 3 µm Pt/Co/MgO wide track. Skyrmions nucleate on the part irradiated with the focused He+ ion beam. Right: simulation of skyrmions in irradiated tracks.

Team: Spin orbitronics, Theory/Simulation, Materials

Collaboration: Laboratoire C2N (Orsay, France)

Funding: DARPA, ANR Skylogics

Further reading: *Helium ions put magnetic skyrmions on the track*, Roméo Juge, Kaushik Bairagi, Kumari Gaurav Rana, Jan Vogel, Mamour Sall, Dominique Mailly, Van Tuong Pham, Qiang Zhang, Naveen Sisodia, Michael Foerster, Lucia Aballe, Mohamed Belmeguenai, Yves Roussigné, Stéphane Auffret, Liliana D. Buda-Prejbeanu, Gilles Gaudin, Dafiné Ravelosona, and Olivier Boulle, Nano Lett. 21, 2989 (2021). *Open access: hal-03176468*

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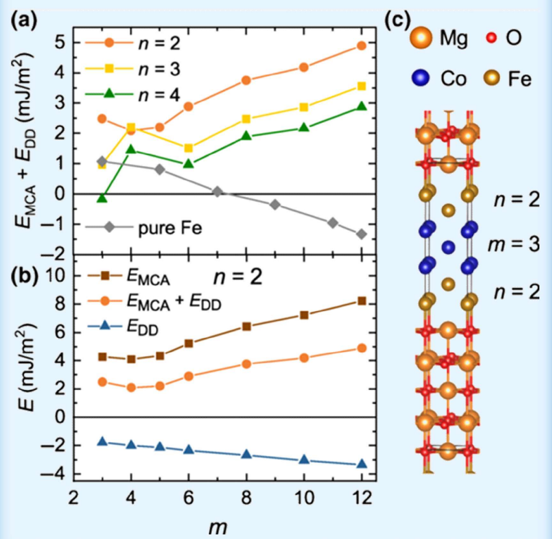
Giant perpendicular magnetic anisotropy enhancement in MgO-based magnetic tunnel junction by using Co/Fe composite layer

Magnetic tunnel junctions with perpendicular anisotropy form the basis of the spin-transfer-torque magnetic random-access memory (STT-MRAM), which is nonvolatile, fast, dense, and has quasi-infinite write endurance and low power consumption. Here, an alternative design of tunnel junctions comprising FeCoFe|MgO storage layers with greatly enhanced perpendicular magnetic anisotropy (PMA) is proposed, leveraging the interfacial PMA of Fe|MgO interfaces along with a strain-induced bulk PMA discovered within bcc Co.

MgO-based magnetic tunnel junctions (MTJs) are used in today's hard-disk-drive read heads and a variety of magnetic-field sensors, for their supremely-high tunneling magnetoresistance (TMR) effect. Furthermore, spin-transfer-torque magnetic random-access memory (STT-MRAM) based on MTJs comprising an MgO tunnel barrier has a potential to become a leading storage technology. The building block of STT-MRAM is a cell with high TMR for good readability, high spin-transfer-torque efficiency for good writability, and high magnetic anisotropy for good thermal stability and therefore memory retention. All of these requirements must be satisfied together using MTJs with perpendicular magnetic anisotropy (PMA) comprising widely employed CoFeB|MgO interfaces. However, with further downscaling of memory cell diameters the PMA provided by these interfaces becomes too weak in regards to thermal fluctuations, and excessively reduces the memory retention time.



(a) Effective PMA (E_{MCA}+ E_{DD}) in Fe(n)Co(m)Fe(n) storage layer interfaced with MgO as a function of number of monolayers n, m. The PMA in this composite layer is always maintained unlike in pure MgO|Fe|MgO (gray diamonds; its thickness is m+4 ML, the same as the overall thickness for n = 2). (b) E_{MCA}, E_{DD}, and the effective PMA (E_{MCA}+ E_{DD}) for n = 2. The effective PMA increases with the Co thickness. (c) Supercell of the MgO|Fe(2)Co(3)Fe(2)|MgO with periodic boundary conditions applied in all directions.

In this work, we provide an alternative solution that allows boosting the PMA by introducing a bulk Co interlayer into the bulk of conventional Fe|MgO-based MTJ, therefore allowing improved downsize scalability of out-of-plane magnetized MRAM. Namely, based on density-functional-theory (DFT) calculations, we propose an alternative design of MTJs comprising storage layers of the form Fe(n)Co(m)Fe(n), where n and m denote the number of monolayers. This approach allows greatly enhancing the PMA up to several mJ/m^2 thanks to the combination of interfacial perpendicular anisotropy of Fe|MgO interfaces along with a strain-induced bulk PMA discovered within bcc Co. This giant enhancement dominates the demagnetizing energy when increasing the film thickness, and it is required to have at least two Fe atoms at the MgO interface and three successive Co atoms in the bulk to obtain the PMA enhancement [see Figure]. Together with estimated TMR values similar to the pure Fe|MgO case and robustness against interfacial roughness, the proposed design is a promising candidate as a storage layer for STT-MRAM cells with highly improved thermal stability compared to conventional STT MRAM.

Teams: Theory/Simulation, MRAM

Collaboration: CEITEC BUT (Czech Republic)

Funding: ERC Adv. Grant MAGICAL, Erasmus+ Program of the European Union

Further reading: *Giant perpendicular magnetic anisotropy enhancement in MgO-Based magnetic tunnel junction by using Co/Fe composite layer*, L. Vojáček et al., Phys. Rev. Appl. 15, 024017 (2021). *Open access: hal-03156056*

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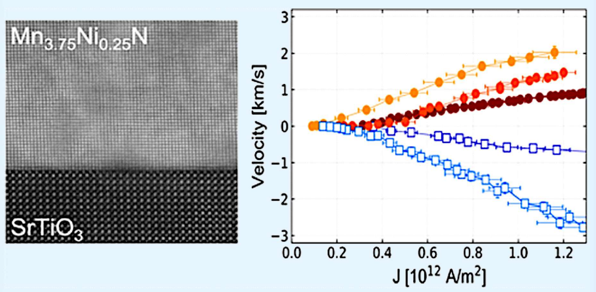
Current-driven domain wall dynamics in Ferrimagnetic $Mn_{4-x}Ni_xN$ thin films

We report very large spin-transfer-torque-driven domain wall velocities, approaching 3000m/s, in rare-earth-free ferrimagnetic $Mn_{4-x}Ni_xN$ thin films close to the angular momentum compensation point. We also observe a reversal of the domain wall motion direction across the angular momentum compensation point.

The interest towards ferrimagnets has recently grown because of their ability to reach the vicinity of the angular momentum compensation point, by varying the temperature or the composition. The smaller magnetization allows obtaining faster domain wall motions than in ferromagnets. This has also propelled studies on ferrimagnets for domain-wall-based logic devices and more generally for spintronics memory applications. Among the ferrimagnets, an interesting rare-earth and critical-element-free compound is Mn_4N, which can be doped with Ni to reach the compensation point.



Left: TEM image of Mn3.75Ni0.25N on SrTiO3 substrate showing epitaxial growth.
Right: Current density vs velocity curves for Mn4-xNixN, positive velocities shown for before and negative velocities after the angular momentum compensation point.

$Mn_{4-x}Ni_xN$ is grown epitaxially with Mn and Ni target source with an RF-nitrogen plasma on $SrTiO_3$ substrates, on which good-quality films with large mm-scale and smooth domain have already been demonstrated. From the TEM characterization, it is shown that Ni is well distributed in the whole system with a very nice epitaxial growth. As the Ni concentration is increased, the velocity increases as the system gets closer to the angular momentum compensation point, approaching 3000 m/s. As the angular momentum compensation point is crossed, the direction of the domain wall motion is reversed: the domain walls propagate along the direction opposite to that of the electron flow. This phenomenon is explained by DFT calculations, which show that the spin polarization is carried out by the Mn II sub-lattice, which always remains positive in this system while magnetization is reversed.

These results gives us an insight on the effect of spin transfer torques on the domain walls before and after the compensation points. They are of great interest from a technological point of view, as the velocities obtained here are comparable to domain-wall velocities obtained in spin-orbit torque driven systems, whereas there is no additional heavy metal layers here, nor external in-plane fields or Dzyaloshinskii Moriya interaction.

Teams: Topological spintronics, Theory/Simulation

Collaboration: University of Tsukuba (Japan), Institut Néel

Funding: IDEX-DOMINO, JSPS KAKENHI (No. 19KK0104 and 19K21954), Marie Sklodowska-Curie Grant Agreement No. 754303, Laboratoire d'excellence LANEF in Grenoble (ANR-10-LABX-0051)

Further reading: *Current-Driven Domain Wall Dynamics in Ferrimagnetic Nickel-Doped Mn4N Films: Very Large Domain Wall Velocities and Reversal of Motion Direction across the Magnetic Compensation Point*, S. Ghosh *et al.*, Nano Lett. 21, 6, 2580–2587(2021). *Open access: hal-03188294*

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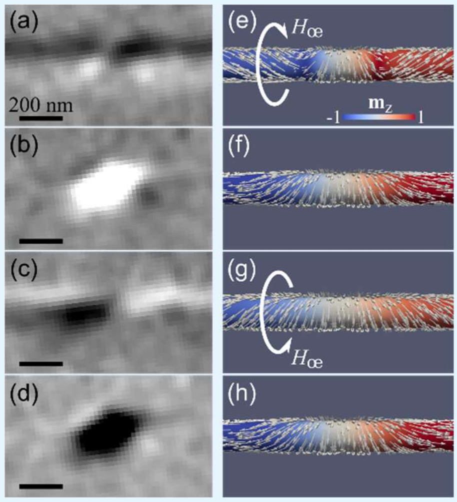
Time-resolved magnetic imaging of Œrsted-field effects in cylindrical nanowires

We have conducted time-resolved stroboscopic imaging of the magnetization dynamics in cylindrical nanowires subject to nanosecond pulses of electric current. These confirm the dramatic impact of the Œrsted field in the cylindrical geometry. Through a thorough quantitative analysis, we extract features during the pulse of current, such as the azimuthal component of magnetization in magnetic domains and the breathing of magnetic domain walls, with an impact expected on their mobility.

Three-dimensional nanomagnetism and spintronics is a fast-rising topic, driven by the prediction of novel physical phenomena. These include curvature-induced effective magnetic anisotropy and Dzyaloshinskii-Moriya interactions, the non-reciprocal dispersion of spin waves, and specific topologies of domain walls preventing their instability compared with counterpart domain walls in thin flat strips. In recent years, we confirmed experimentally the existence of these specific domain walls in cylindrical nanowires, called Bloch-point walls, demonstrated their unusual high mobility under spin-polarized current, and hinted at the crucial role of the large Œrsted field in these three-dimensional conduits, in the stabilization of the domain walls.

Here, we conducted time-resolved imaging of magnetization dynamics to provide a microscopic support to our observations, inferred previously from static magnetic imaging following domain-wall motion. For that purpose, we used Scanning Transmission X-ray Microscopy (STXM) combined with X-ray Magnetic Circular Dichroism (XMCD), implemented at the Pollux beamline from the Swiss Light Source (SLS) synchrotron. We fed a periodic sequence of spin-polarized current in the wire, combining two nanosecond pulses of positive and then negative current with density >10^{12} A/m^2, each separated by several tens of ns of waiting time. All photon bunches are collected and sorted versus their time delay by a dedicated FPGA developed at SLS, which in a few tens of minutes delivers hundreds of averaged snapshots, each separated by only a few hundreds of picoseconds. We then developed a quantitative analysis of the images, taking into account the calibration of absorption through matter, the image broadening due to the beam size, and a background intensity resulting from incoherent illumination. Applying this to a domain wall between two tail-to-tail domains, this allowed us to put figures on the azimuthal tilt of magnetization in the otherwise axial domains, up to 30°, and the periodic breathing of the domain walls (see Figure).



Experiments (left) and simulations (right) of the impact of the OErsted field on magnetization dynamics in a 100 nm-diameter wire during nanosecond positive (a,e) and negative (c,g) current pulse, and in-between pulses (b,f and d,h).

These results are in excellent agreement with micromagnetic simulations, providing a firm ground for our understanding of the specific dynamics of magnetization textures in the cylindrical geometry. On this basis we are currently performing further experiments to control domain-wall motion in such wires, and also seek to evidence the non-reciprocity of spin waves in cylindrical magnetic nanotubes.

Teams: Spin textures, Theory/Simulation

Collaboration: Institut Néel, Friedrich-Alexander Universität Erlangen-Nürnberg, SLS light source

Funding: Labex LANEF, ANR Matecmac-3D, Renatech

Further reading: *Time-resolved imaging of Œrsted field induced magnetization dynamics in cylindrical magnetic nanowires*, M. Schöbitz, S. Finizio, A. De Riz, C. Thirion, D. Gusakova, J.C. Toussaint, J. Bachmann, J. Raabe, O. Fruchart, Appl. Phys. Lett. 118, 172411 (2021). *Open access: hal-03134319*

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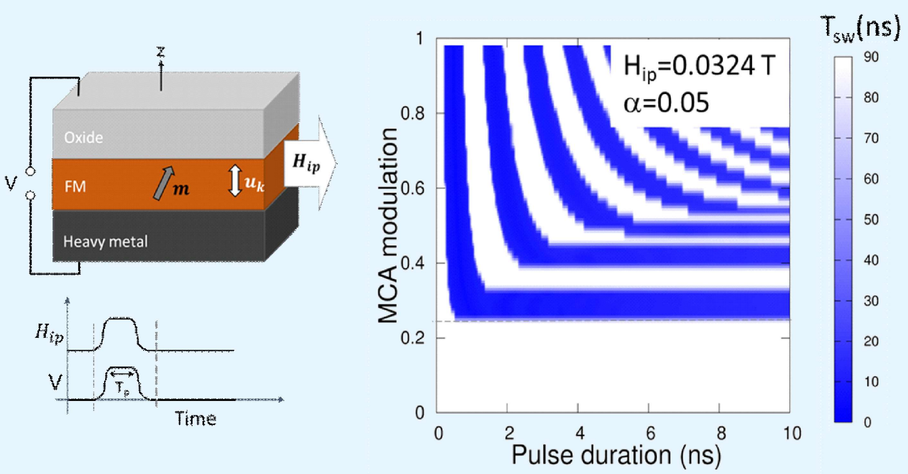
Route towards efficient magnetization reversal driven by the voltage control of magnetic anisotropy

Using a macrospin approach, we carried out a systematic analysis of the role of the voltage controlled magnetic anisotropy on the magnetization dynamics of nanostructures with out-of-plane magnetic anisotropy. Diagrams of magnetization switching have been computed depending on the material and experiment parameters, thus allowing predictive sets of parameters for optimum switching experiments.

Voltage-controlled magnetic anisotropy (VCMA) became in the last ten years a subject of tremendous interest in the field of spintronics due to its promising potential outcomes: fast and low power consumption magnetization manipulation in magnetoresistive random access memories with enhanced storage density. To understand the role of the VCMA and find how to take benefit of it, we performed macrospin simulations of the precessional magnetization switching assisted by a pulse of gate voltage, synchronized with a pulse of external in-plane magnetic field.

Trilayer structure with gate controlled magnetic perpendicular anisotropy. An in-plane field is simultaneously applied with the gate voltage. The associated magnetization switching diagram depending on the pulse duration and the anisotropy modulation for a sample with enhanced damping.



Our simulations show that both the switching probability and the switching time depend strongly on the material and experiment parameters such as the surface anisotropy, Gilbert damping, duration/amplitude of electric and magnetic field pulses. Two characteristic times of the trajectory of the magnetization were analyzed analytically and numerically, setting a lower limit for the duration of the pulses to achieve an optimal reversal. Following the conditions for the minimum electric field required to switch the magnetization, we demonstrate that a very interesting switching regime exits, where the fast precessional reversal does not anymore depend on the voltage pulse duration. This represents a promising path for the magnetization control by VCMA with enhanced versatility since it does not require the precise control of the pulse duration. Such regime can be tuned via specific magnetic material parameters such as the Gilbert damping.

Teams: Theory/Simulation, MRAM, Magnetic sensors

Collaboration: Babes-Bolyai University and Technical University (Cluj-Napoca, Romania)

Funding: ERC Adv grant 669204 MAGICAL

Further reading: *Route towards efficient magnetization reversal driven by voltage control of magnetic anisotropy*, R. A. One, H. Béa, S. Mican, M. Joldos, P. Bradao Veiga, B. Dieny, L. D. Buda-Prejbeanu and C. Tiusan, Sci. Rep. 11, 8801 (2021). *Open access: hal-03206091*

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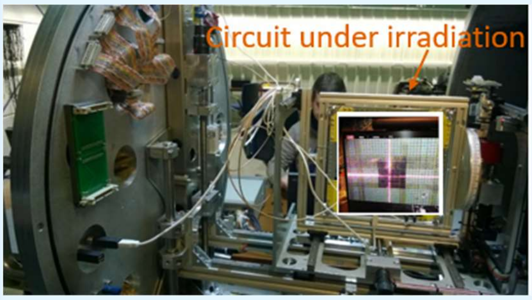
Heavy-ion irradiation effects on advanced perpendicular anisotropy spin-transfer torque magnetic tunnel junction

This study investigates heavy-ion irradiation effects on Perpendicular Magnetic Anisotropy Spin-Transfer Torque Magnetic Tunnel Junction devices (p-STT-MTJs). The radiative campaign took place at the Cyclotron Resource Centre of Université Catholique de Louvain (UCL).

Designers of space systems have to deal with ensuring complex data processing, while obtaining, at the same time, a proper level of radiation tolerance, a reduced payload size, weight, and power (SWaP) as well as a competitive price. Moreover, they are usually reluctant to use devices without significant space heritage that ensures predictable behavior. In trying to create a harsh environment performance database for emerging devices, a considerable amount of research has been carried out in the exploration of technologies that aim to ensure a radiation tolerance higher than transistors in integrated circuits. For these motivations, perpendicular magnetic anisotropy STT devices represent today the most advanced and promising technology to achieve high-density (over 1 Gb of memory capacity) application in harsh environment.



Vacuum chamber at UCL Cyclotron Facilities. The picture also shows the heavy ion centered beam (violet cross) on the circuit during the irradiation.

In order to test the effects of heavy ion, a test campaign was organized. This radiative campaign took place at the Cyclotron of Université Catholique de Louvain (UCL) facilities. The considered devices consist of p-STT-MTJs being purely magnetic memories. They were fabricated at SPINTEC using the most advanced CoFeB-MgO-CoFeB process. Single-event upset (SEU) tolerance and modification of magnetic properties have been investigated. The irradiation of the multilayer structure with 995-MeV $124Xe^{35+}$ ion indicates a negligible Single Event Effect (SEE) sensitivity nor detrimental effect of statistical significance on electrical properties. Instead, the TMR is slightly increased in the lowest half of the InterQuartile Range (IQR), suggesting an annealing-like effect on the MgO crystallinity. Concerning the magnetic properties, a general reduction in the coercive field involved in the AP to P switching, combined with an increase of the offset field have been detected. Depending on the intensity of these phenomena, write operations stability could be threatened by the observed hysteresis loop degradation due to the reduced stability of the AP state. This drift could likely be symptomatic of degradation mechanisms that take place in the device stack such as thermally activated diffusion of Ru and Ta, the formation of pinholes in the Ru Synthetic Anti Ferromagnetic (SAF) spacer and the miscibility of Co/Pl SAF multilayer. Indeed, the large quantity of affected MTJs could not be entirely related to direct ion strike occurrences. Since the fluence reached during the irradiation experiment was moderate, and the lack of high-density MTJ matrix in the irradiated circuits, another mechanism, most likely a thermal effect, could have induced the observed degradation. Hence, heavy-ion irradiation may affect MTJs also by thermally activated and thermal-induced effects rather than exclusively direct ion strike. Modifications to magnetic properties occur before degradation of electric properties.

Teams: Spintronics IC design, MRAM

Collaboration: Centre National d'Etudes Spatiales (CNES), Laboratoire d'Informatique, de Robotique et de Microélectronique de Montpellier (LIRMM), TRAD.

Further reading: Heavy-Ion Irradiation Effects on Advanced Perpendicular Anisotropy Spin-Transfer Torque Magnetic Tunnel Junction, O.Coi, G. Di Pendina, R. Sousa, N. Adrianjohany, D. Dangla, R. Ecoffet and L. Torres in *IEEE Trans. Nucl. Sci.* 68 (5), 588 (2021). *Open access: hal-03255402*

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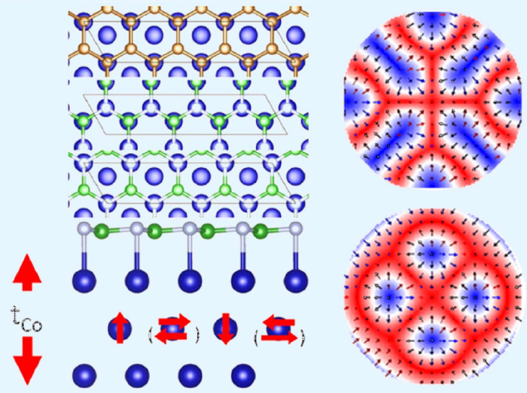
Dzyaloshinskii–Moriya interaction and skyrmion states at 2D materials/Co Interfaces

We report significant Dzyaloshinskii–Moriya interaction (DMI) and perpendicular magnetic anisotropy (PMA) at interfaces comprising hexagonal boron nitride (h-BN) and cobalt (Co), remaining stable over a large range of Co film thickness. Furthermore, it is demonstrated that that such significant DMI and PMA give rise to the formation of skyrmions under small applied external fields.

Interfacial Dzyaloshinskii–Moriya interaction (DMI) and perpendicular magnetic anisotropy (PMA) in magnetic nanostructures traditionally composed of metals and/or oxides have gained much attention in recent years. Indeed, they play a major role in the formation of chiral magnetic structures, such as spin spirals and skyrmions, which are promising for the next generation of data storage devices. On another hand, two-dimensional (2D) materials such as graphene (Gr) and hexagonal boron nitride (h-BN) are appealing as novel materials with exceptional properties that could replace conventional ones and open new prospects for information technology.



Investigated Gr/Co, h-BN(AB)/Co and h-BN(AC)/Co structures (left panel) and relaxed magnetization distributions of 100 nm wide h-BN(AC)/Co(3ML) with labyrinth domains transformed into skyrmion states at finite external magnetic field applied.

In this work, significant and robust DMI and PMA at 2D material/Co interfaces is demonstrated using first-principles calculations. By comparing the behavior of these phenomena at graphene/Co and h-BN/Co interfaces of different stacking, even though the PMA behavior shows similarities for both cases, the DMI at h-BN/Co interface shows significantly larger values remaining robust over a large Co thickness range unlike for Co/Gr interface [Figure below]. The physical mechanisms of such a behavior are attributed to existence of competing dipoles at the Co/Gr interface compared to only one dipole at the opposite h-BN/Co interface which gives rise to a larger DMI associated with stronger Rashba spin-orbit coupling in case of h-BN/Co compared to that of Co/Gr. Furthermore, the possibility of skyrmions formation at h-BN(AC)/Co interface with the application of small external magnetic field and stable up to hundred Kelvin is demonstrated.

Compared to the widely-studied skyrmion materials based on ferromagnet/metal interfaces, h-BN/Co and Gr/Co systems are simpler to synthesize, and free of heavy metals, thus being advantageous to lower Gilbert damping and lower critical driving current density and high-speed skyrmion motion. Furthermore, the realization of skyrmions in h-BN/Co is an interesting perspective toward exploring interfaces comprising other 2D materials. These findings demonstrate that 2D materials provide a viable alternative for heavy metals in the next-generation spintronic devices based on domain walls or skyrmions, and inspire further investigations on the exotic magnetic properties on the 2D material/magnetic metal interfaces.

Team: Theory/Simulation

Collaboration: Unité Mixte Phys. CNRS/Thales (France), NIMTE (China)

Funding: EU Horizon 2020 (Graphene Flagship), NSFC & CAS (China)

Further reading: *Rashba-Type Dzyaloshinskii–Moriya Interaction, Perpendicular Magnetic Anisotropy, and Skyrmion States at 2D Materials/Co Interfaces*, A. Hallal, J. Liang, F. Ibrahim, H. X. Yang, A. Fert and M. Chshiev, Nano Lett. 21, 7138 (2021). *Open access: hal-03342479*

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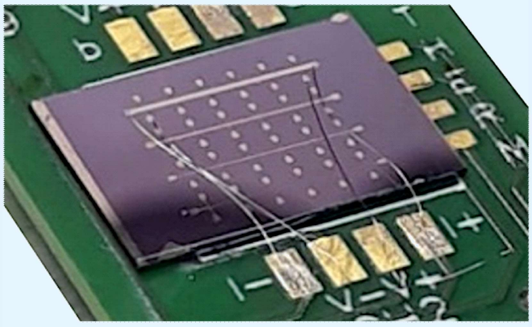
Penetration depth of Cooper pairs in antiferromagnets

Researchers at SPINTEC Grenoble, in collaboration with PHELIQS & CIME Grenoble and LOMA Bordeaux, demonstrated how the superconducting proximity effect can be used to evaluate the penetration of Cooper pairs in metallic antiferromagnets. These findings represent a stimulating example of how antiferromagnets and superconductors may envision a common future by showing how to infer essential information using Cooper pair transport through antiferromagnets.

The interplay between superconductivity and magnetism has attracted considerable attention in recent decades, due to its importance for studies in basic physics and related applications. As a consequence, a variety of phenomena have been described in ferromagnet / superconductor hybrids, such as the spin switch effect, the superconducting magnetoresistance effect, and domain-wall superconductivity. At the heart of domain wall superconductivity, Cooper pairs consisting of electrons of opposing spins experience the short-range exchange field averaged over the superconducting coherence length. This phenomenon reduces the critical temperature (T_C) of the superconducting layer. A magnetic domain wall flanked by opposite spins reduces the averaged exchange field and thus allows for a partial recovery of the superconducting temperature, ΔT_C. This recovery is achieved through the creation of an additional – and more efficient – superconducting pathway in the magnetic layer.



Picture of a typical device used to perform transport measurements.

The main contribution of this paper is that it presents a systematic investigation of the superconducting proximity effect in ferromagnet(Pt/Co)/spacer(IrMn and Pt)/superconductor(NbN) heterostructures. The findings presented indicate that by tuning the various parameters at play, the recovery of the superconducting critical temperature in the presence of ferromagnetic domains and domain walls can be maximized to a degree that makes it possible to carry out two types of studies that were previously impossible. We were therefore able to: i) probe how the recovery of the superconducting critical temperature gradually evolves with all the intermediate magnetic configurations of the ferromagnet; and, ii) determine that the recovery of the superconducting critical temperature gradually reduces with the thickness of the metallic spacer layer. Most importantly, these experiments allowed us to evaluate the penetration of Cooper pairs in the IrMn metallic antiferromagnet, an information thhat is crucial for electronic transport, and up to now has been difficult to access experimentally for antiferromagnets.

The results presented open a new pathway for the investigation of electronic transport in antiferromagnetic materials for spintronics.

Teams: Antiferromagnetic spintronics, Materials, Instrumentation

Collaboration: PHELIQS Grenoble, CIME Grenoble, LOMA Bordeaux

Funding: ANR-15-CE24-0015-01, PE-18P31-ELSA, OSR-2015-CRG4-2626

Further reading: *Penetration depth of Cooper pairs in the IrMn antiferromagnet, R. L. Seeger, G. Forestier, O. Gladii, M. Leiviskä, S. Auffret, I. Joumard, C. Gomez, M. Rubio-Roy, A. I. Buzdin, M. Houzet, V. Baltz,* Phys. Rev. B 104, 054413 (2021). *Open access: hal-03133353*

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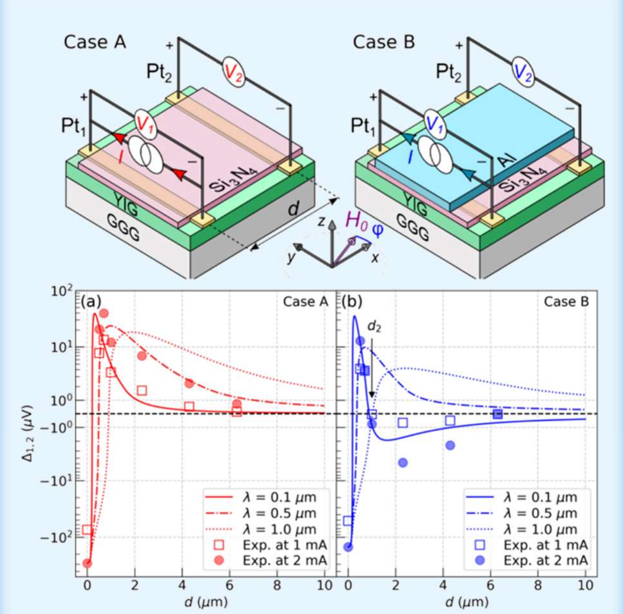
Spin diffusion length of thermal magnons

Using the spin Seebeck effect (SSE), we study the short-range propagation distance of thermally-induced spin currents inside insulator magnetic thin film. We find that the spin diffusion length of thermal magnons (magnons carrying quanta of energy, $k_B T$) is in the submicron range.

The vision of spintronics is to use the spin of an electron rather than its charge, to allow computers and other electronic devices to operate faster while reducing their energy consumption. Most of the devices rely on the delocalized electrons present in metallic materials to carry the spin information. It turns out that electrically-insulating magnetic materials, such as yttrium iron garnet (YIG), also allow the spin to propagate between localized magnetic moments via propagating spin-waves, which transmit information from an atomic site to the other without any Joule effect.

The spin transport properties are governed by λ, the characteristic decay length over which spin is conserved. Previous reports on measuring λ in YIG at room temperature by the spin Seebeck effect (SSE) indicates that in the long-range regime, the SSE signal follows an exponential decay with a characteristic length $\lambda_0 \simeq 10\mu m$. But, the distance range of the transport study is also a potent means to select a very specific part of the magnon spectrum, where one has in essence efficiently filtered out any short decay magnons.



Comparison of the measurements of the local (V_1) and nonlocal (V_2) Spin Seebeck voltages generated in YIG|Pt|Si_3N_4 (case A) and (case B) YIG|Pt|Si_3N_4|Al stacks. The Al capping allows to change the vertical thermal gradient without altering the YIG interface. Sole a short decay length λ≈0.1µm can reproduce the measured double crossing found experimentally in (b).

In a recent experiment, a collaboration led by SPINTEC has measured the spatial distribution of thermally-generated magnons in the short range. We altered the temperature profile across the YIG film with an aluminum capping layer. This allows to disambiguate spin currents driven by temperature and chemical potential gradients by comparing the SSE signal before and after adding the capping on the same device. We use a linear response magnon transport theory to obtain, λ≃0.1µm, (see Figure) which is about two orders of magnitude smaller than previous reports. Our proposed fit with a short λ captures well the short-range behavior in both cases A and B. This result does not contradict earlier works. The data observed for case A are similar to the one already observed in other YIG devices, where the fit of the long-range decay behavior has led to the larger λ_0. Our suggestion is that the long decay magnons are not thermal magnons, but instead magnetostatic magnons carrying much lower quanta of energy.

Behind this debate lies a fundamental issue, which suggests that magnon transport cannot be described by a diffusive model forming one gas with a single λ, whose value would govern SSE on all length scales.

Teams: Insulatronics, Topological spintronics

Collaboration: CEA, LabSTICC, UCLA

Funding: ANR Maestro

Further reading: *Short-range thermal magnon diffusion in magnetic garnet,* K. An, R. Kohno, N. Thiery, D. Reitz, L. Vila, V. V. Naletov, N. Beaulieu, J. B. Youssef, G. de Loubens, Y. Tserkovnyak, and O. Klein, Phys. Rev. B 103, 174432 (2021). *Open access: hal-02935127*

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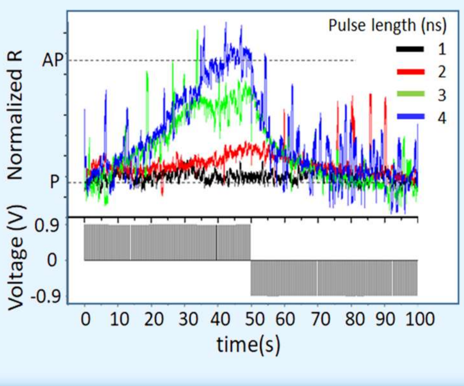
A new spintronic memristive component for neuromorphic circuits

Abstract : Neuromorphic computing is a bio-inspired technology which aims at mimicking the brain working principles. It can be used for fast and energy-efficient applications through the implementation of networks of artificial neurons and synapses. Artificial synapses are implemented as electronic components called memristors. These are non-volatile memory devices whose resistance can take several intermediate values between minimum and maximum, the resistance varying monotonously as a function of the polarity of the current pulses flowing through the device. In the present study, a novel concept of spintronic memristor was proposed which takes advantage of the know-how acquired at SPINTEC in the development of magnetic memory (MRAM) and radiofrequency nano-oscillators.

This novel memristor consists of a magnetic tunnel junction slightly modified from those used in MRAM cells. A magnetic tunnel junction is formed of two magnetic layers separated by a tunnel barrier. One of the layer called the reference layer has a fixed magnetization while the magnetization of the other (the storage layer) can be switched or rotated. When a current flows throughout this device, its resistance depends of the relative orientation of the magnetization in the two magnetic electrodes, a phenomenon named tunnel magnetoresistance. Two important modifications have been brought to the junction to change its functionality from MRAM cell to memristor. First, while MRAM encodes the information in a binary form ("0" and "1") corresponding to two magnetic configurations (minimum resistance-parallel magnetic configuration or maximum resistance-antiparallel configuration), this memristor is designed to reach a large number of intermediate values of resistance. To achieve this, we exploited the cosine variation of the tunnel conductance as a function of the angle between storage layer and reference layer magnetizations. A special storage layer based on ferromagnetic/antiferromagnetic coupled layers was developed exhibiting an isotropic coercivity thus allowing to stabilize the storage layer magnetization in any in-plane direction. For this, the thickness of the antiferromagnetic layer was adjusted so that this layer creates an effective solid friction on the magnetization of the storage layer. A second requirement is to be able to rotate the storage layer magnetization step by step, clockwise or anticlockwise depending on the voltage pulse polarities, while limiting the angular excursion between 0 and 180°. Based on our earlier work on spin transfer radiofrequency oscillators, we demonstrated that this can be achieved by adding to the in-plane magnetized junction an additional layer with out-of-plane magnetization and adjusting the spin-transfer influences from this additional layer and from the reference layer. The resulting device exhibits memristive functionality as illustrated in the Figure.



Electrical characterization of the device memristive behavior: Evolution of the device resistance when submitted to a train of positive voltage pulses followed by a train of negative ones. The average resistance drifts up with positive pulses and down for negative pulses. The superposed noise is due to thermal fluctuations of the storage layer magnetization.

Teams: MRAM, Theory / simulation, Material-Nanofabrication-Instrumentation, Topological spintronics

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Further reading: *Spintronic memristor for neuromorphic circuits based on the angular variation of tunnel magnetoresistance*, M. Mansueto, A. Chavent, S. Auffret, I. Joumard, L. Vila, R.C. Sousa, L. D. Buda-Prejbeanu, I. L. Prejbeanu and B. Dieny, Nanoscale 13, 11488 (2021).

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SPINTEC research topics

SPIN ORBITRONICS

The team covers new concepts to devices: exploring new concepts in spintronics based on spin dependent transport with various systems: structure inversion asymmetry (spin orbit torques, Rashba effect, Spin Hall Effect, Topological Insulators), and alternative geometries in order to develop innovative architectures of devices.

TOPOLOGICAL SPINTRONICS

The team aims at manipulating spins currents in nanostructures, in particular in quantum materials with Dirac fermions, such as topological insulators or Weyl semimetals, or at oxide interfaces. Some important aspects of future spintronics devices, such as the efficient spin-charge interconversion at interfaces or the ballistic transport of spin states for quantum interconnects, are studied by magneto-transport measurements.

2D SPINTRONICS

The team deals with spin-dependent phenomena in several important classes of materials: Si and Ge, which are the materials of today's microelectronics, and transition metal dichalcogenides and surfaces of topological insulators, which are emerging 2D materials with exceptional optical and spin-orbit properties. We are studying model systems grown by molecular beam epitaxy and their spin properties.

ANTIFERROMAGNETIC SPINTRONICS

Antiferromagnetic materials could represent the future of spintronics, thanks to the interesting features they combine: they are robust against perturbation due to magnetic fields, produce no stray fields, display ultrafast dynamics and generate large magneto-transport effects. In this team, research efforts are being invested in unraveling spin-dependent transport properties of antiferromagnets.

SPIN TEXTURES

The team is interested in novel spin textures, Bloch-point domain walls, tubular structures and magnetic skyrmions. This involves the three components of magnetization and their three-dimensional distributions, which may be topologically-protected. The team designs the systems, images the spin textures with advanced techniques, and addresses these with spin-polarized current. The applied background are concepts for 3D magnetic memories and sensors.

SPIN INSULATRONICS

The team aims at understanding and controlling microwave oscillations of magnetization around its equilibrium, which are the natural dynamical response to external perturbations (*e.g.*, thermal fluctuations, microwave fields). This offers the promise for a new class of microwave devices based on magnetic insulators, benefiting from their small foot-print, their ability to be controlled electrically, and their integrability with CMOS technology to design local oscillators, microwave filters, detectors, and non-reciprocal devices.

MICROWAVE DEVICES

The aim of this activity is to provide a fundamental understanding and control of the excitation, manipulation and detection of the linear and non-linear magnetization dynamics via spintronics phenomena occurring in magnetic nanostructures. Specific attention is given to identify potential microwave applications (oscillators, filters, detectors).

MAGNETIC SENSORS

The team activities cover up-stream research on the effect of gate voltage on interfacial magnetic properties, as well as sensor development (proof of concept) and expertise to support industrial R&D. This experimental research is essentially based on magnetic (VSM, MOKE) and electric (magnetotransport and noise) measurements.

MRAM MEMORIES

The MRAM team develops memory concepts with improved thermal stability, low power consumption and/or ultrafast writing. The targeted applications range from standalone to embedded memories, for various usages ranging from in-memory computing to artificial intelligence. Electric-field control of magnetization, possibly in combination with spin-charge interconversion, as well as optical switching of magnetization, are studied as further extension of spintronic memories beyond-CMOS technologies.

SPINTRONICS IC DESIGN

The team is dedicated to the evaluation of the benefits of using magnetic devices in Integrated Circuits (ICs). It is expected that integrating non-volatility in ICs could contribute to push forward the incoming limits in the microelectronics scaling. This work includes integrating the magnetic devices in standard design tools, design hybrid circuits and evaluate their performance for various applications, *i.e.*, low power, neuromorphic, security, radiation hardening.

HEALTH AND BIOLOGY

The team benefits from the know-how of the laboratory in magnetic materials, spin-electronics and nanofabrication. Its efforts are mainly focused towards the fabrication of engineered magnetic micro- nano- particles or devices, prepared by top-down approaches, specially designed for biomedical applications, such as cancer cells destruction triggering, tissue engineering.

ARTIFICIAL INTELLIGENCE

This team brings together various expertise of SPINTEC in spintronic devices: nanofabrication, characterization, circuit integration, architecture, and algorithm techniques, to implement hardware solutions for artificial intelligence (AI) and unconventional computing. Spintronic devices provide substantial opportunities to improve the energy efficiency of next-generation computing hardware. The team also takes advantage of brain-inspired computing models to deploy cutting-edge neuromorphic algorithms, closing the gap between current hardware AI implementations and exceptional brain computing ability.

THEORY AND SIMULATION

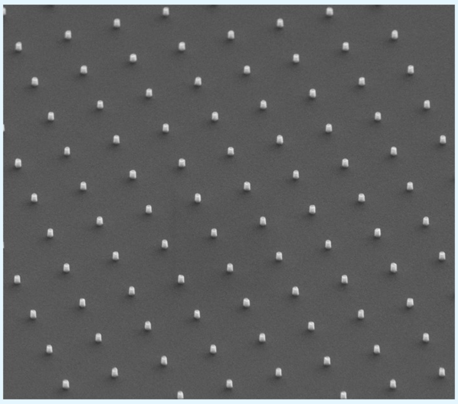
The team covers all aspects of fundamental and applied physics related to spin electronics by employing a wide range of theoretical approaches including ab initio, tight-binding, free electron and diffusive methods, combined with micromagnetic and atomistic simulation approaches. This allows explaining experimental observations, providing solutions for specific problems and predicting novel properties and phenomena guiding the experimental work to optimize spintronic nanostructures.

About SPINTEC

Positioned at the crossroad of science and technology, SPINTEC (SPINtronique et TEchnologie des Composants) is one of the leading spintronics research laboratories worldwide, ideally located on the *MINATEC* campus in Grenoble. The laboratory was created in 2002 and rapidly expanded to now exceed 100 persons of which 47 Permanent staff and about 50 Ph.D. students, post-docs and international visitors. **The scientific institutions taking part in the lab are**: *CEA*, *CNRS*, and the *University of Grenoble Alpes* including the *Grenoble Institut of Technology*.

SPINTEC's objective is to **bridge fundamental research and innovative devices in the fast-growing field of spin electronics** (spintronics). Indeed, the *international technology roadmap for semiconductors (ITRS)* now reckons that spintronics devices will play a major role in tomorrow's semiconductor chips, with high potential for stand-alone (e.g. DRAM) and embedded memories, magnetic field sensors, hardware components for artificial intelligence and bio-applications.

In this context, SPINTEC brings together top-level scientists and applicative engineers who work in close collaboration, to ensure that discoveries at the forefront of research can be swiftly translated into technological proofs of concepts and functional devices. As such, **the outcome of the laboratory is not only scientific publications and communications at international conferences**, but also a **coherent patents portfolio**, implementation of **relevant functional demonstrators**, and partnerships for technology transfer. Our large scale provides the critical mass to master all required steps ranging from materials, nanofabrication, electrical and magnetic characterization, condensed-matter theory, simulation and the design of dedicated integrated circuits.



Matrix of 30nm STT-MTJ processed within CEA-PTA clean room facilities by Spintec staff

Whereas our fundamental research is mostly operated through collaborative grants with other research laboratories, **applied research is often carried out in partnership with private actors**. These can be large corporations (Applied Materials, Samsung, Seagate, INTEL), SME's (SNR, Singulus) or **start-up companies spun-off from SPINTEC**: *Crocus Technology* in 2006, *eVaderis* in 2014, *HProbe* in 2016, *Antaïos* in 2017, while the process for the creation of a fifth one is ongoing.

SPINTEC plays also a major role in higher education in magnetism and nanotechnology, through chairing three highly-visible international schools: the European School on Nanosciences and Nanotechnology ESONN, the European School on Magnetism ESM and the school on applied spintronics InMRAM.

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