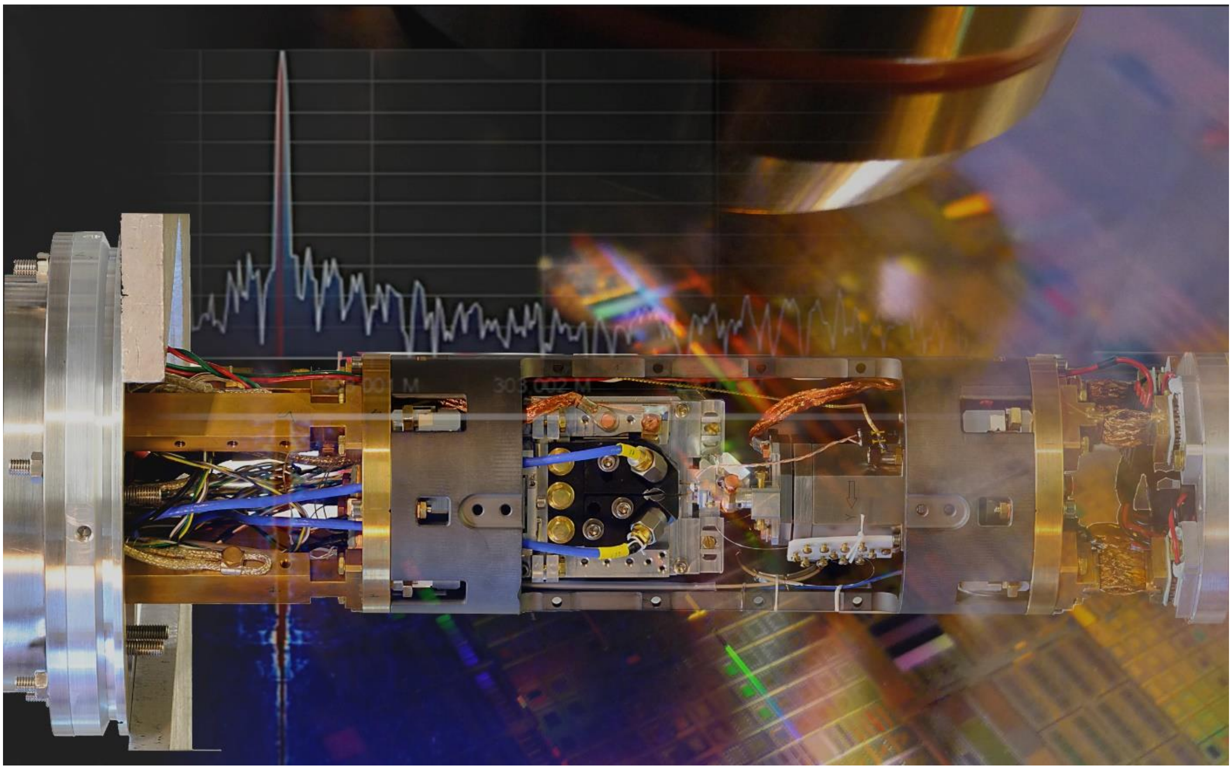
Highlights

2020



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FOREWORD

This year has been very special and a challenge to all, imposed by the pandemic. All members of the lab did their best to keep projects running, maintaining means to perform experiments and simulations, to turn their university lecturing remote and keep welcoming master students in the lab, and most importantly, to sustain social exchange and the feeling of a working community. The academic world showed its resilience against our much-reduced possibilities to travel, by quickly developing means for distant participation at conferences and schools. We are confident in our collective ability to turn this imposed constraint into experience for a better future, making a leap in the use of digital networking means, and thereby contributing to lowering the carbon footprint of our professional activities.

On the side of partnership, we are happy to be involved in seven new ANR projects, five European projects including two training networks and two ERC PoC, and the renewal of several key programs such as with DARPA, Samsung and INTEL. As regards innovation, the Spintronics Factory consortium in which Spintec is highly active released its roadmap for spintronics in Europe, through a review in Nature Electronics. Finally, our startups are still expanding, Antaios has raised 11M$ and HProbe more than €2 million in equity funding.

We have been actively preparing the future through gathering new collaborators. The year 2020 has been quite successful on this matter with Kevin Garello joining as an MRAM CEA research scientist, Lorena ANGHEL as Professor at the Grenoble Institute of Technology and Philippe TALATCHIAN as CEA research scientist to contribute to artificial intelligence. Adriana STOENESCU joined as CNRS assistant strengthening the financial and administrative team, and Nicolas MOLLARD as CEA technician joining the instrumentation team.

The year 2021 comes with its load of challenges and opportunities. Following our successful scientific evaluation for the period 2016-2020, we are looking forward to shaping our strategy for the long-term future of SPINTEC, being confirmed as directors for the five years to come. We intend to keep the mission of SPINTEC at the crossroads of research and innovation, covering the most modern aspects of spintronics.

We hope that you will enjoy browsing the following pages, gathering a selection of scientific highlights and cornerstones of SPINTEC over the year 2020.

Lucian Prejbeanu, Executive Director / Olivier Fruchart, Deputy Director

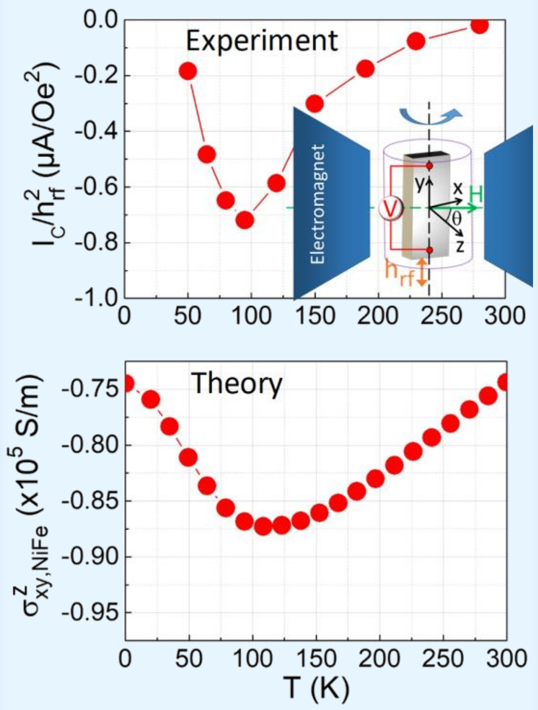
SPINTEC Highlights – December 2020 – Editor: Gregory Di Pendina

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

CONTENTS

Self-induced spin-charge conversion in ferromagnetic thin films

The generation of a spin current and its further conversion to a charge current have attracted considerable attention, facilitating advances in basic physics along with the emergence of closely related applications in the field of spintronics. In this study, we experimentally and theoretically demonstrated the self-induced inverse spin Hall effect for spin-charge conversion, triggered by spin-orbit interactions in ferromagnets. The results presented open a new pathway for the investigation of spin-orbit-related effects in materials for spintronics, while also advancing progress toward efficient spin-charge converters.



Self-induced charge current generated by spin-charge conversion in a permalloy layer at resonance (Experiment), and related spin Hall conductivity (Theory).

An electrical current can be converted to a spin current and vice versa as a result of the spin-orbit interaction (SOI), which links the spin and the orbital angular momentum of an electron. One of the related effects of this phenomenon, known as the inverse spin Hall effect (ISHE), is commonly used to study SOI in non-magnetic materials (NM) inserted into archetypal F/NM bilayers. In some of these studies, a spin current is pumped from the ferromagnetic (F) spin-injector at resonance, and the ISHE ensures spin-charge conversion in the NM. The contribution of the F to spin-charge conversion can be difficult to distinguish from that of the NM, and spin-charge conversion arising from the F is frequently neglected in experiments.

The main contribution of our work is that it presents systematic evidence of a self-induced ISHE. The findings were supported by distinct sets of temperature-, thickness, angular, and stack-dependent experimental data encompassing the main features of the self-induced ISHE. The experimental findings were corroborated by first-principle calculations. Most importantly, similar amplitudes but opposite signs for the bulk skew scattering and the side-jump plus intrinsic contributions to the temperature-dependent spin Hall conductivity in permalloy could explain why the SOI-related transverse signal was observed to display non-monotonous temperature-dependence. Interestingly, similar sets of experimental data were obtained whatever the material in contact with the permalloy layer: SiO$_2$, MgO, AlOx oxides, Cu, and Pt metals. This observation further confirmed the bulk origin of the effect. Insights on the direction of the self-induced current were obtained by addition of a reference layer of Pt to the stack, either as a buffer or as a capping layer.

The findings from this study contribute to our understanding of a previously overlooked and incompletely understood effect. The results further indicate that self-induced conversion within the F can be as efficient as that recorded with noble metals such as Pt, and thus needs to be carefully considered when investigating SO-related effects in materials destined for use in spintronics.

Teams: Antiferromagnetic spintronics, Spin-orbitronics, Theory and simulation

Collaborations: SYMMES Grenoble, University of Munich

Funding: ANR-15-CE24-0015-01, OSR-2015-CRG4-2626

Further reading: *Self-induced inverse spin Hall effect in ferromagnets: demonstration through non-monotonic temperature-dependence in permalloy*, O. Gladii, L. Frangou, A. Hallal, R. L. Seeger, P. Noël, G. Forestier, S. Auffret, M. Rubio-Roy, P. Warin, L. Vila, S. Wimmer, H. Ebert, S. Gambarelli, M. Chshiev, and V. Baltz, Phys. Rev. B 100, 174409 (2019). DOI: *10.1103/PhysRevB.100.174409*

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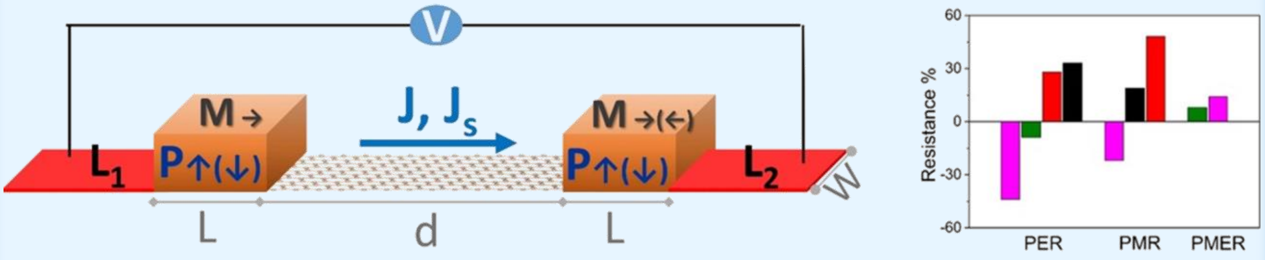
Multiferroic Proximity Effect in Graphene

A possibility of controlling electronic and magnetic properties of graphene via proximity of multiferroic substrate is demonstrated. Coupling graphene to a multiferroic oxide (bismuth ferrite) gives rise to a novel class of spin-dependent transport phenomena based on multiferroic-induced proximity effects in graphene. Based on these findings, a concept of multi-resistive device in lateral geometry is proposed.

Graphene spintronics has become a promising direction of innovation that attracts a growing attention of scientists and engineers. Numerous efforts have been devoted to inducing magnetism in graphene via different means, one of which is the exchange-proximity interaction with magnetic insulators. Both experimental and theoretical developments on tailoring the proximity induced magnetic phenomena in graphene have been focused so far on using different magnetic insulators. Multiferroics co-exhibiting a magnetic (M) and ferroelectric (P) order constitute an interesting class of magnetic insulators that bring about an additional parameter in play that is the electric polarization P. However, the influence of both M and P orders on the proximity effect in graphene remained unaddressed.



Lateral spintronic device comprising two multiferroic regions on top of a graphene sheet. The relative orientation of magnetization M and electric polarization P in the multiferroic regions, give rise to proximity electro (PER)-, magneto-(PMR), and multiferroic (PMER) resistances.

Using first-principles calculations, SPINTEC theory group in collaboration with colleagues in France and USA have reported multiferroic-induced proximity effects in graphene that can be used to propose a six-resistance-states device. The calculations clearly show that by contacting graphene with bismuth ferrite BiFeO3 (BFO) film, the magnetic order and the ferroelectric polarization in the BFO substrate strongly affect spin-dependent electronic structure of graphene. Based on the extracted Hamiltonian parameters obtained from the graphene band structure, the group employed the tight-binding approach in the framework of scattering matrix formalism to calculate conductance and proximity resistance effects in a lateral device comprising two multiferroic regions on top of a graphene sheet. Exploring dependence of conductance on all possible relative magnetic and ferroelectric configurations of two BFO regions, six distinct resistance states were unveiled leading to a concept of multi-resistive lateral device. Furthermore, conductance states in the system give rise to three types of proximity resistance effects: proximity electroresistance (PER), proximity magnetoresistance (PMR), and proximity multiferroic resistance (PMER).

This finding paves a way towards multiferroic control of magnetic properties in two-dimensional materials and engineering of graphene spin gating by proximity effects.

Team: Theory and simulation

Collaborations: IRIG-PHELIQS, Grenoble (France); Dept. of Physics and Astronomy & Nebraska Cent for Materials and Nanoscience, Univ. of Nebraska, Lincoln, NE (USA)

Funding: H2020: Grant agreements No. 696656 & 785219 (Graphene Flagship). French ANR Project FEOrgSPIN (ANR-18-CE24-0017)

Further reading: *Unveiling Multiferroic Proximity Effect in Graphene*, F. Ibrahim, A. Hallal, D. Solis, X. Waintal, E. Y. Tsymbal, M. Chshiev, 2D Mater. 7, 015020 (2020). DOI: *10.1088/2053-1583/ab5319*

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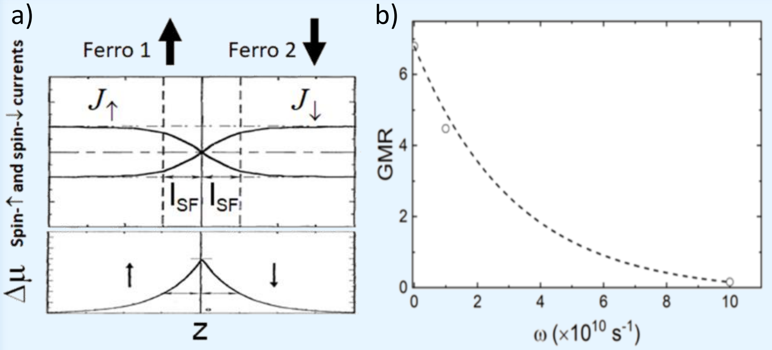
Spin accumulation dynamics in spintronic devices in the terahertz regime

Spin accumulation phenomena frequently occur in spintronic devices due to the difference of electrical resistivities of spin-up and spin-down electrons in magnetic materials. They are balanced by spin relaxation phenomena taking place in a diffusive regime and involving numerous individual scattering events. Consequently, although the time scale of elastic electron scattering in metals is in the femtosecond range, the dynamics of spin accumulation/relaxation phenomena in spintronic devices can be of the order of picosecond. This can have important impact on the performances of spintronic devices operating in the THz range.

In transition magnetic metals (Fe, Co, Ni and their alloys), conduction electrons carry the current differently depending whether their spin is aligned parallel (spin-up) or antiparallel (spin-down) to the local magnetization (spin-dependent scattering). For instance in Co, spin-up electrons carry ten times more current than spin-down electrons. If a current traverses a structure comprising two such magnetic layers, the current flow will strongly depend on the relative orientation of the magnetization in the two layers. When the magnetization of the two layers is antiparallel (Fig.a), one species of electrons carry most of the current in one magnetic layer while the opposite species carry most of the current in the other layer. This results in spin accumulation around their interface, balanced by spin relaxation effects. The spin-dependent scattering and associated spin accumulation/relaxation is at the origin of the current-perpendicular-to-plane giant magnetoresistance observed in magnetic metallic multilayers (stacks of alternating magnetic and non-magnetic layers) as well as in lateral spin-valves (devices consisting of magnetic patterns interconnected by non-magnetic conducting channels). These phenomena take place in the diffusive regime and results from numerous individual elastic scattering events. In the present theoretical studies, it was shown that although elastic scattering times in metals are in the range of femtoseconds, the time scale of spin accumulation variation can be significantly larger, especially in lateral spin-valves in which the spin conducting channels can be micron long. In such case, spin accumulation can build up on time scale of the order of picosecond. Nowadays, spintronic devices are proposed which operate in the THz range. They are often based on antiferromagnetic or ferromagnetic materials. According to the present study, their electrical response and in particular their magnetoresistance can strongly depend on the frequency at which they are operated as illustrated in Fig.b. These dynamics effects are important to take into account in the understanding of the properties of THz devices and in their optimization.



a) Representation of the spin current and spin accumulation ($\Delta\mu$) at the interface between two ferromagnetic layers in antiparallel magnetic configuration.

b) Evolution of the giant magnetoresistance amplitude (GMR) in a model structure of the form Ferro1 50nm/NM 500nm/Ferro2 50nm/NM 500nm as a function of the frequency ω at which the relative orientation of the magnetization of two magnetic layers is changed

Teams: MRAM, Theory and simulation

Funding: ERC MAGICAL n°669204

Further reading: *Spin accumulation dynamics in spin valves in the terahertz regime*, A. Vedyaev, N. Ryzhanova, N. Strelkov, A. Lobachev and B. Dieny, Phys. Rev. B, **101**, 014401 (2020). DOI: *10.1103/PhysRevB.101.014401*

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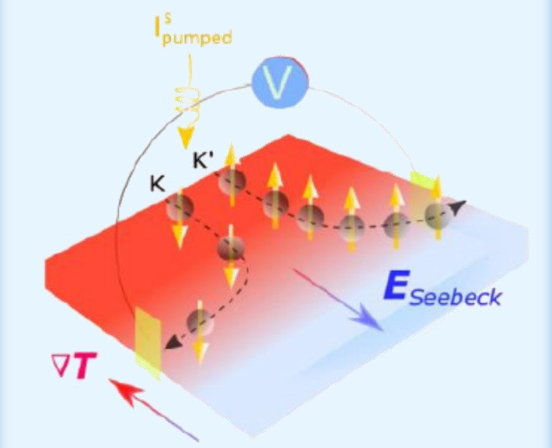
Experimental evidence of the valley Nernst effect in WSe$_2$

The Hall effect can be extended by inducing a temperature gradient in lieu of electric field, which is known as the Nernst effect. After the discovery of the spin Nernst effect, the collection would not be complete without mentioning the valley degree of freedom benchmarked by the observation of the valley Hall effect in transition metal dichalcogenides. Here we show the experimental evidence of its missing counterpart, the valley Nernst effect in WSe$_2$ which was predicted theoretically in 2015.



Sketch of the experimental observation of the valley Nernst effect. The combination of a temperature gradient (∇T) and spin pumping (I^S_{pumped}) to address a single valley (here K') leads to a transverse voltage due to the valley Nernst effect.

The valley Nernst effect comes from the interplay between thermoelectricity and the valley degree of freedom in monolayers of WSe2. In the monolayer form, WSe2 exhibits two inequivalent K-valleys (K and K') at the corners of the surface Brillouin zone due to inversion symmetry breaking and strong spin-orbit coupling. The spin splitting in K and K' valleys being opposite, it is possible to address the K valley with spin down and K' valley with spin up (see figure). By using van der Waals epitaxy, high-quality WSe2 mono and multilayers are grown on epitaxial graphene on SiC over large areas. Using such millimeter-sized sample, we are able to apply well-defined temperature gradients and demonstrate the very strong Seebeck response of this material. In a second step, we use the ferromagnetic resonance-spin pumping technique to (i) apply the temperature gradient by off centering the sample in the radio-frequency (RF) cavity and (ii) address a single valley using the spin pumping through spin-valley coupling (see figure). The combination of a temperature gradient and the valley polarization leads to the valley Nernst effect in WSe2 that we detect electrically in the RF cavity. The valley Nernst coefficient we measure is in very good agreement with the predicted value. This effect can be exploited to generate large transverse valley currents for valleytronics applications.

Team: 2D and semiconductor spintronics

Funding: ANR MAGICVALLEY

Further reading: *The valley Nernst effect in WSe2*, M. T. Dau, C. Vergnaud, A. Marty, C. Beigné, S. Gambarelli, V. Maurel, T. Journot, B. Hyot, T. Guillet, B. Grévin, H. Okuno, & M. Jamet, Nat. Comm. 10, 5796 (2019). DOI: *10.1038/s41467-019-13590-8*

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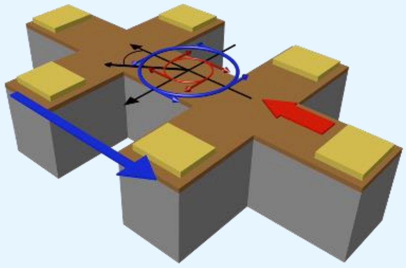
Observation of Large Unidirectional Rashba Magnetoresistance in Ge(111)

Relating magnetotransport properties to specific spin textures at surfaces or interfaces is an intense field of research nowadays. Here, we investigate the variation of the electrical resistance of Ge(111) under the application of an external magnetic field. We find a magnetoresistance term that is linear in current density *j* and magnetic field *B*, reaching 0.5 %, 100 times larger than in previous reports. We attribute this MR to the Rashba spin texture in the subsurface Ge(111) hole gas.

Magnetoresistance—a resistance induced by a magnetic field—is often associated with magnetic materials. Recent studies have identified a new effect called unidirectional magnetoresistance (UMR), which appears in nonmagnetic materials. The effect is characterized by an increase or decrease in the resistance, depending on the direction in which the current flows. Here, we discovered UMR in a surprising place—within the common semiconductor germanium. The size of the effect is 100 times larger than in previous cases. We propose a new theory of UMR to explain the results. UMR was first seen in 2017 in a topological insulator, and a detection of the effect in a two-dimensional electron gas quickly followed. As these systems are not intrinsically magnetic, it was inferred that UMR is the result of spin-momentum locking, which is the lining up of electron spins in a direction perpendicular to their momentum. Because of this spin-current connection, UMR could be useful in spintronic devices.



Schematics of the double Hall cross used to measure experimentally the unidirectional magnetoresistance in Ge(111). The UMR is related to the Rashba spin texture in the Ge(111) subsurface hole gas represented by the blue and red circles with opposite spin helicities.

To measure UMR in germanium, we grew a layer of germanium along its (111) crystal orientation on a silicon substrate. We ran a current through the layer, while applying an external magnetic field. The measured resistance depended on the current and the field, with the strongest UMR effect occurring when the current was perpendicular to the magnetic field. As an example, a current of 10 µA and a field of 1 T produced a 0.5% change in the resistance, compared to a 0.002% change in previously observed UMR materials. To explain this relatively large response, we propose that the Rashba effect—a well-known splitting in the bands associated with up and down spins—generates spin-momentum locking in the subsurface states of germanium.

Team: 2D and semiconductor spintronics

Collaboration: Unité Mixte de Physique CNRS-Thales

Funding: ANR TOP RISE

Further reading: *Observation of large unidirectional Rashba magnetoresistance in Ge(111)*, T. Guillet, C. Zucchetti, Q. Barbedienne, A. Marty, G. Isella, L. Cagnon, C. Vergnaud, H. Jaffrès, N. Reyren, J.-M. George, A. Fert, & M. Jamet, Phys. Rev. Lett. 124, 027201 (2020). DOI: *10.1103/PhysRevLett.124.027201*

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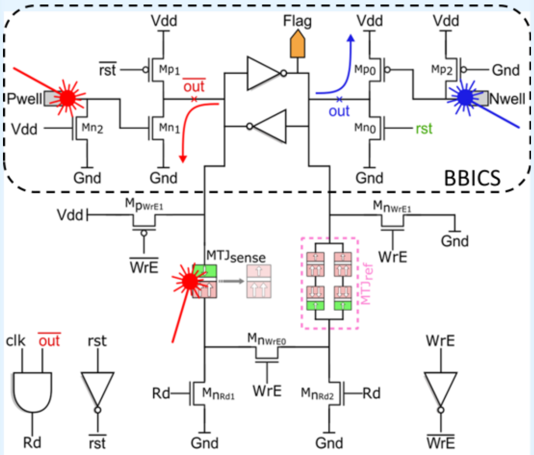
Detection of Heating and Photocurrent attacks using Hybrid CMOS/STT-MRAM.

Integrated Circuits (ICs) have to be protected against threatening environmental radiations and malicious perturbations. A large panel of countermeasures have been developed to answer the needs of this challenging field. This work proposes an innovative sensor to detect both photoelectrical injections and thermal perturbations aiming a circuit. This architecture is designated by "Dual Detection of Heating and Photocurrent attacks (DDHP)".

During the computation of a cryptographic algorithm, when faults are injected in specific locations of the IC and at the right time, it makes possible the retrieval of secret data. CMOS circuitry and Back-End of Line (BEoL) memories can both be sensitive to physical perturbations, by inducing a photocurrent in the structure or by heating it for instance. The Bulk Built-In Current Sensor (BBICS) is a widely studied detector enabling to sense any photocurrent induced in the bulk of a circuit. Such a sensor is efficient for integrated circuit back-side attacks.



Structure of the proposed DDHP sensor combining the BBICS sensor to STT-MRAM circuitry.

This work highlights the hybridization of this BBICS solution with the STT-MRAM technology in order to also sense front side thermal attacks. The proposed sensor is designated by "Dual Detection of Heating and Photocurrent attacks (DDHP)". This countermeasure is illustrated in the figure.

The implementation of this sensor was realized using the 28 nm FD-SOI Process Design Kit combined to STT-MRAM junctions with a diameter of 40 nm. Electrical and Monte Carlo simulations have demonstrated the excellent efficiency of this detector while facing different attacks aiming the P-substrate, the N-well or the STT-MRAM junctions. The DDHP sensor detects all these attacks from both sides of the integrated circuit, to then communicate failures to the system. After each detection and depending on the application, the system has then to decide the operation to be achieved as for instance erasing all the data in the circuit or restarting from the last known and secured functional state.

The same structure was also developed in the 180 nm Bulk CMOS and 200 nm junction diameter technologies as part of the GREAT project and was taped out. Thus, an experimental work testing the scope of action in terms of area of detection of a DDHP sensor must be led and depending on the observations, an advanced DDHP structure could be proposed.

Team: Spintronics IC design

Collaborations: CEA tech (Gardanne), IM2NP – Aix Marseille University (Marseille), EMSE (Ecole des Mines de Saint-Etienne).

Funding: GREAT European project, MASTA ANR project.

Further reading: *Dual Detection of Heating and Photocurrent attacks (DDHP) Sensor using Hybrid CMOS/STT-MRAM*, M. Kharbouche-Harrari, R. Wacquez, G. Di Pendina, J.–M. Dutertre, J. Postel-Pellerin, D. Aboulkassimi and J-M. Portal, In 2019 IEEE 25th International Symposium on On-Line Testing And Robust System Design (IOLTS). DOI: *10.1109/IOLTS.2019.8854374*

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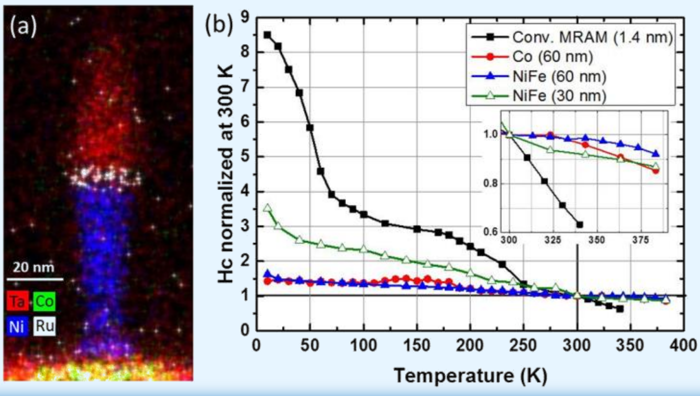
Reducing the impact of operating temperature in magnetic memory thanks to perpendicular shape anisotropy

MRAM is a type of nonvolatile memory that stores the binary information through the magnetic configuration of its main building block: the Magnetic Tunnel Junction (MTJ). In the last decade, the use of perpendicular anisotropy existing at the tunnel barrier interface, allowed to improve MRAM manufacturability. However, the thermal sensitivity of the interfacial anisotropy is a limitation for MRAM applications having to operate over a wide range of temperatures such as automotive application. How can the operating temperature range of MTJs be enlarged ?

The conventional stack used in perpendicular MRAM uses CoFeB electrodes and MgO tunnel barrier. The thickness of the magnetic storage layer is typically between 1.4 and 2.5 nm. In such a stack, the magnetization remains perpendicular to the layers thanks to an interfacial Perpendicular Magnetic Anisotropy (iPMA) which exists at the MgO/CoFeB interface and stabilizes the storage layer magnetization. The magnitude of the iPMA is important since it is directly related to the memory retention time (*i.e.*, how much time the memory can keep the stored information). However, the temperature sensitivity of the interfacial anisotropy is a limitation when trying to use this type of memory in applications requiring a wide range of operating temperatures. This is the case in automotive applications, which may operate from -40°C up to +150°C, as well as during chip soldering in system on chip fabrication (260°C for 1 minute). To solve this problem, SPINTEC researchers proposed a new concept of MTJ based on Perpendicular Shape Anisotropy (PSA). In this concept, the thickness of the storage layer is increased, so that its shape becomes a cylinder instead of a disk. This results in MRAM cells with a 20 to 30nm-thick storage layers and diameters ranging from 10 to 20nm. This geometry results in a natural perpendicular anisotropy arising from the shape, which adds to the iPMA and reinforces the effective perpendicular anisotropy of the cell. Researchers at SPINTEC studied the evolution of the storage layer coercive field (measure of its magnetic stability) over a wide range of temperature from 10 K to 380 K, and compared it with conventional MRAM based on iPMA. As PSA arises from the bulk material magnetic properties of the storage layer, its temperature dependence is much weaker than that of the iPMA in conventional MRAM which comprise very thin storage layer. In addition, the team demonstrated that despite the large thickness of the storage layer, PSA MRAM can still be written by electrical current pulse as conventional MRAM. The low or high resistance state is set by the current polarity through an effect called spin transfer torque. The weak temperature dependence of the magnetic and transport properties of PSA MRAM opens the route towards a variety of applications requiring a wide range of operating temperature (automotive, industrial, spatial…).



(a*): Element mapping of a 60 nm thick NiFe storage layer based PSA MTJ using energy dispersive X-Ray spectroscopy (EDS). (b): Evolution of the coercive field normalized at 300 K as a function of temperature in the range 10-380 K for conventional MTJ (square symbols) and for three different stacks of PSA MTJ based on: 60 nm thick Co storage layer (circle symbols), 60nm thick NiFe storage layer (fill triangle symbols) and 30 nm thick NiFe storage layer (open triangle symbols). Inset: Zoom in the temperature range 300-400 K.*

Teams: MRAM, Spin-orbitronics, Theory and simulation

Collaboration: CEA Leti (E. Di Russo for TEM images)

Funding: ERC Advanced Grant MAGICAL N°669204.

Further reading: *Thermal robustness of magnetic tunnel junctions with perpendicular shape anisotropy*, S. Lequeux, N. Perrissin et. al. Nanoscale 12, 6378-6384 (2020). DOI: *10.1039/C9NR10366J*

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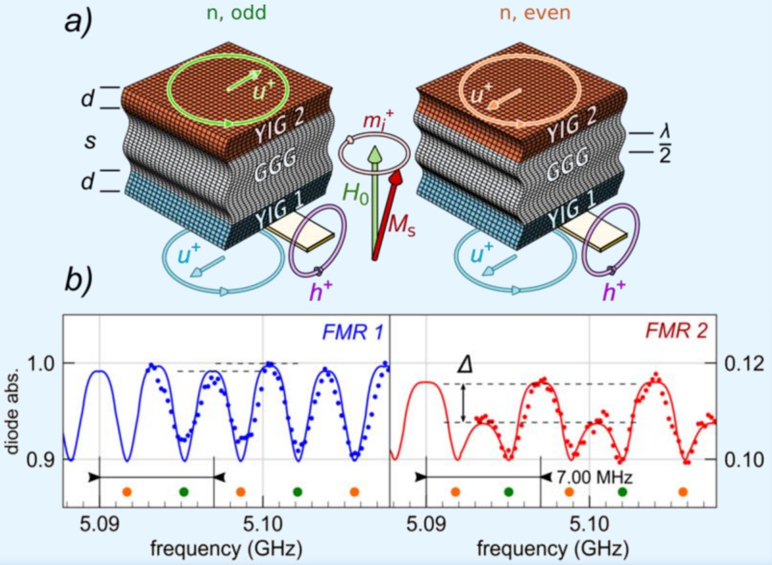
Coherent long-range coupling between spins by chiral phonons

We present experimental evidence for coherent long-distance transport of angular momentum inside a non-magnetic dielectric via the coupling to circularly polarized sound waves that exceeds previous benchmarks set by magnon diffusion by orders of magnitude.

a) Schematic diagram of the dynamic coupling between two magnetic YIG layers: the magnetic precession m^+ generates a circular shear deformation u^+ of the crystal lattice that can be tuned into a coherent motion of all fields causing constructive or destructive interference patterns. b) The signature is a contrast Δ in the ferromagnetic resonance signal between tones separated by half a phonon wavelength. The orange/green dots indicate the spectral position of the even/odd acoustic resonances.



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 nevertheless rely on the delocalized electrons present in metallic materials to carry the spin information, which induces losses by Joule heating. 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. In principle, the induced angular momentum can also pass through a non-magnetic insulator by coupling to circular vibrations of the crystal lattice called chiral phonons. However, the extent to which these phonons may mediate spin currents in a circuit remains to be demonstrated. In a recent experiment, a collaboration lead by researchers at SPINTEC used a microwave field to excite a current of chiral phonons through a half-millimeter thick layer of non-magnetic gadolinium gallium garnet sandwiched between two YIG films. By showing interference effects between the two magnetic layers, they demonstrated that circularly polarized acoustic phonons allow coherent transmission of spin information over millimeter distances.

This work has since inspired theoretical work showing the interest of using this discovery with an electric current, which is more practical for powering spintronic devices.

Team: Microwave devices

Collaborations: CEA-Saclay, UBO Brest, Dassault Aviation, Univ. of Tohoku and Univ. of Oakland

Funding: ANR MAESTRO

Further reading: *Coherent long-range transfer of angular momentum between magnon Kittel modes by phonons* K. An, A. N. Litvinenko, R. Kohno, et al. Phys. Rev. B 101, 060407(R) (2020). DOI: *10.1103/PhysRevB.101.060407*

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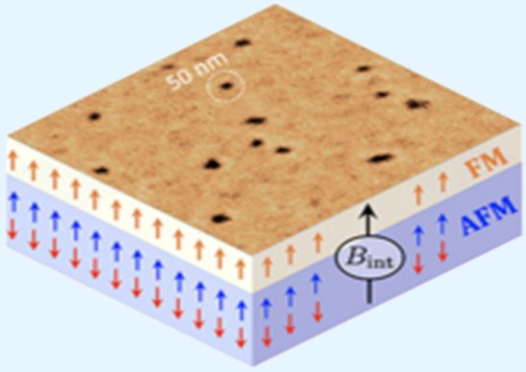
Room-Temperature Skyrmions at Zero Field in Exchange-Biased Ultrathin Films

Magnetic skyrmions are topologically protected spin textures of great interest for nanoscale information storage and processing. However, stabilizing small skyrmions without applying an external magnetic field remains challenging. This study employs a thin ferromagnetic layer exchange-biased by an antiferromagnetic film to stabilize ferromagnetic skyrmions down to 30 nm in diameter, at zero magnetic field. In such a magnetic structure, exchange bias enhances skyrmion stability against external magnetic field perturbations, making this a promising platform for spintronic 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 quasiparticles are composed of elementary nanomagnets that wind to form a stable spiral structure, like a well tighten node. Although predicted in the 80's, it has only been observed for the first time in 2009. Three years later, two research teams demonstrated that 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 based on the manipulation of skyrmion in nanotracks have thus been proposed, that promise very large information density and low power consumption. However, these applications still remained distant as skyrmions had been observed only at low temperature or in the presence of large magnetic fields and in exotic materials far from any applications. In 2016, we made an important discovery by demonstrating magnetic skyrmions at room temperature in ultrathin Pt/Co(1nm)/MgO multilayer nanostructures, a system also developed at SPINTEC for MRAM magnetic memory.

In this study, we did a step further toward application by demonstrating ultras-mall skyrmions, down to 30 m in diameter, stable at room temperature and without magnetic field in an exchange-biased Pt/Co/Ni80Fe20/Ir20Mn80 multilayer stack. This is achieved through an advanced optimization of the multilayer-stack composition in order to balance the different magnetic energies controlling the skyrmion size and stability. Magnetic imaging is performed both with magnetic force microscopy and scanning nitrogen-vacancy magnetometry, the latter providing unambiguous measurements at zero external magnetic field. In such samples, we show that exchange bias provides an immunity of the skyrmion spin texture to moderate external-magnetic-field perturbations, which is an important feature for applications such as memory devices. These results establish exchange-biased multilayer stacks as a promising platform toward the effective realization of memory and logic devices based on magnetic skyrmions.



A NV center magnetic microscopy image of magnetic skyrmion stabilized at zero external magnetic field on top of a sketch of the ultrathin film stack. The stack is composed of a Pt/Co/NiFe magnetic layer (FM) exchange coupled to an IrMn antiferromagnet (AFM). The exchange coupling with the IrMn layer leads to an effective Bint on the FM which allows the stabilization of the small skyrmions at zero field.

Teams: Spin-orbitronics, Theory and simulation, Spin textures

Collaborations: Laboratoire Charles Coulomb (Montpellier, France), FZ Jülich (Jülich, Germany), Institut Néel (Grenoble)

Funding: DARPA, ANR Skylogic

Further reading: *Room-Temperature Skyrmions at Zero Field in Exchange-Biased Ultrathin Films*, K. Gaurav Rana, A. Finco, F. Fabre, S. Chouaieb, A. Haykal, L. D. Buda-Prejbeanu, O. Fruchart, S. Le Denmat, P. David, M. Belmeguenai, T. Denneulin, R. E. Dunin-Borkowski, G. Gaudin, V. Jacques, and O. Boulle, Phys. Rev. Applied 13, 044079 (2020). DOI: *10.1103/PhysRevApplied.13.044079*

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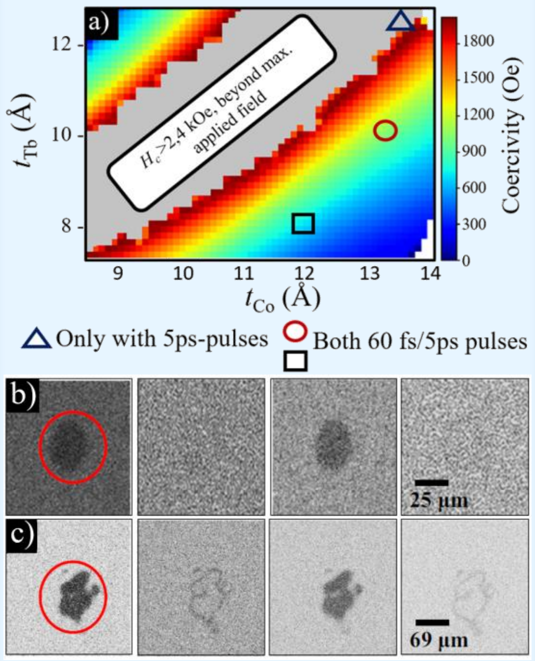
All-optical switching of magnetization in Tb/Co-multilayer based electrodes

This work reports the development of perpendicular magnetic tunnel junctions incorporating a stack of Tb/Co nanolayers whose magnetization can be all-optically controlled via helicity-independent single-shot switchingAbstract here. Toggling of the magnetization of the Tb/Co electrode was achieved using either 60 femtosecond-long or 5 picosecond-long laser pulses, with incident fluences down to 3.5 mJ/cm^2.

Ever since the first observation of all-optical switching of magnetization in the ferrimagnetic alloy GdFeCo using femtosecond laser pulses, there has been significant interest in exploiting this process for data-recording applications. In particular, the ultrafast speed of the magnetic reversal can enable the writing speeds associated with magnetic memory devices to be potentially pushed towards THz frequencies.

Our results highlight a first evidence of helicity-independent all-optical switching in a [Co/Tb]5 multilayered-based system coupled to CoFeB layers with both ps- and fs-long single laser pulses. We also explored the magneto-optical properties of the multilayers and its thermal stability upon different annealing temperatures. The magneto optical response and the perpendicular magnetic anisotropy of our system was achieved even after annealing at 250 °C. The laser pulse duration and fluence dependence for the CoFeB/[Tb/Co]$_5$ electrodes was also explored using single 60 fs and 5 ps laser pulses with fluences below 4.0 mJ/cm^2. Images obtained for a laser pulse duration D = 5 ps and 60 fs, shows a clear reverse of the magnetization is observed for F = 3.5 mJ/cm^2. Our all-optical switching electrode FeCoB/Ta/[Tb/Co]$_5$ was integrated into a perpendicularly magnetized tunnel junction. Electrical evaluation of nanopatterned AOS-MTJ showed TMR ratios up to 36 % depending on the diameter of the junctions and on the number of repetitions of the [Tb/Co] bilayers. The full structure of the junctions consist of: Ta(30Å)/FeCoB(11Å)/MgO(23Å)/FeCoB(13Å)/Ta(2Å)/[Tb(9.5Å)/Co(12.5Å)]$_5$. The TMR distribution of hundreds of MTJ with different diameters have a minimum resistance of 6 kΩ. As far as we know, we are presenting the first study that reports the helicity-independent all-optical switching in a Co/Tb multilayered-based system.



a) Coercive field mapping of the [Tb/Co]$_5$ multilayers indicating the combinations of thicknesses which present all-optical switching. b) and c) Background substracted Kerr microscopy images showing the reversal of the oop magnetization of the FeCoB/Ta/[Tb/Co]$_5$ after a series of laser pulses of b) ps and c) fs-long duration.

These results are highly promising for the development of p-MTJs in which the storage layer is all-optically addressed using single-shot laser pulses, thus facilitating writing frequencies that could be advanced towards the THz scale.

Teams: MRAM, Theory and simulation

Collaboration: Radboud University (Nijmegen)

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

Further reading: *Single-shot all-optical switching of magnetization in Tb/Co multilayer based electrodes*, L. Avilés-Félix, A. Olivier, G. Li, C. Davies, L. Álvaro-Gómez, M. Rubio-Roy, S. Auffret, A. Kirilyuk, A. Kimel, Th. Rasing, L. D. Buda-Prejbeanu, R. C . Sousa, B. Dieny & I. L. Prejbeanu, Sci. Rep. **10**, 5211 (2022). DOI: *10.1038/s41598-020-62104-w*

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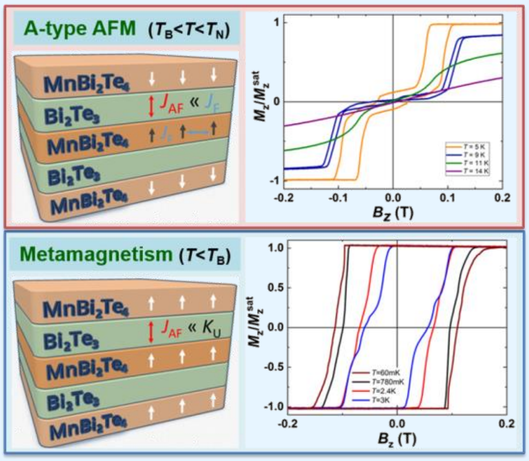
Metamagnetism of Weakly Coupled Antiferromagnetic Topological Insulators

Layered magnetic topological insulators are candidate to unveil novel electronic phases controlled by the magnetization. In $MnBi_4Te_7$, we evidenced a transition from an antiferromagnetic to a ferromagnetic-like metamagnetic state, possibly realizing the quantum anomalous Hall regime in ultra-thin films above 1K.



Transition from antiferro- to meta-magnetism in a van-der-Waals layered magnetic topological insulator $MnBi_4Te_7$, a candidate to realize novel topological states (QAH, Axion insulator) at liquid-Helium temperatures. In the fully-saturated magnetization state, charge transport is ideally only due to spin-polarized ballistic edge states.

3D topological insulators ideally have an insulating bulk and 2D gapless topological surface states (TSS). In magnetic materials, time-reversal symmetry is broken by the internal exchange field, so that an energy gap opens for TSS, resulting in novel topological states. For a homogenous magnetization, it realizes a Chern insulator or the quantum anomalous Hall state (QAH), with dissipation-less spin-polarized transport at edges, or a Weyl semimetal phase. For complex magnetic structures, additional symmetries can generate other topological states. Antiferromagnets are thus candidates to realize the axion insulator phase. In general, the magnetization becomes an easily tunable parameter with some potential to modify topological electronic phases by applying small external magnetic fields.

Recently, van der Waals multilayers of 2D ferromagnets have raised specific interest, with the possibility of tailoring exchange-coupled magnets having a nontrivial band structure. A unique example is the so-called MBT family, $[MnBi_2Te_4][Bi_2Te_3]_n$ with the integer $n \geq 0$, realizing stoichiometric magnetic topological insulators. The magnetic base unit, a $MnBi_2Te_4$ septuple layer, is a 2D ferromagnet with a perpendicular anisotropy K_U that stabilizes an out-of-plane ferromagnetic order and generates the QAH state. Stacks of septuple layers form the $MnBi_2Te_4$ compound, with an antiferromagnetic interlayer coupling leading to 3D antiferromagnetic order. Other compounds have *n* units of the nonmagnetic Bi_2Te_3 spacer in between 2D ferromagnetic layers, and therefore a reduced interlayer exchange coupling.

We studied the magnetic properties of the $MnBi_4Te_7$ compound (n=1) by magnetotransport measurements. We evidenced that the relative strength of the interlayer exchange coupling to the uniaxial anisotropy K_U controls a transition from an A-type antiferromagnetic order to a ferromagnetic-like metamagnetic state. A bilayer Stoner-Wohlfarth model describes this evolution, as well as the typical angular dependence of specific signatures, such as the spin-flop transition of the uniaxial antiferromagnet and the switching field of the metamagnet. This result is important to search for new classes of topological materials, in particular to observe the QAH phase above 1K, which requires to control the micromagnetic configuration of thin films. Thanks to its versatile magnetic and electronic properties, the MBT family is a unique material platform for the realization of tunable topological quantum phenomena with spin-textured quasiparticles.

Team: Spin-orbitronics

Collaboration: IFW Dresden; PTA

Funding: FET PRO-active "TOCHA"

Further reading: *Metamagnetism of Weakly Coupled Antiferromagnetic Topological Insulators*, A. Tan, V. Labracherie, N. Kunchur, A.U. B. Wolter, J. Cornejo, J. Dufouleur, B. Büchner, A. Isaeva, R. Giraud, Phys. Rev. Lett. 124, 197201 (2020). DOI:*10.1103/PhysRevLett.124.197201*

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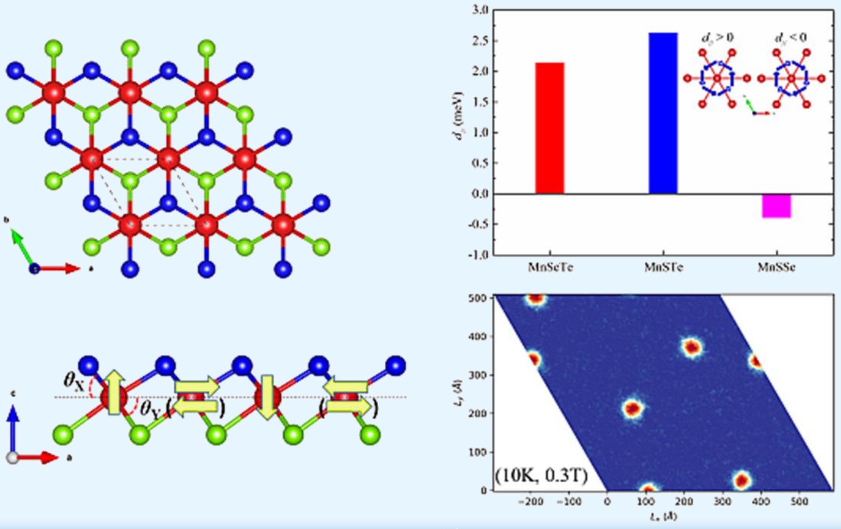
New materials for skyrmions: van der Waals 2D magnets

The intense recent research on skyrmions has focused on multilayers of classical magnetic materials (Co, CoFeB, Fe…). In this work, the authors explore skyrmions in van der Waals bi-dimensional magnets, a new type of magnetic material in the broad family of 2D materials. Using *ab initio* and Monte Carlo calculations, they demonstrate that skyrmions should exist in the so-called Janus transition metal dichalcogenides.

The magnetic skyrmions are topological quasiparticles that can be created, displaced and detected with electrical currents. They are promising for many types of applications such as memory and logic devices. Significant research efforts on skyrmions has so far focused on multilayers comprising interfaces of heavy metals (or oxides) with classical magnetic materials such as Co, CoFeB or Fe. However, skyrmions in such metallic multilayers have still important drawbacks for their use in practical devices. This collaborative work between SPINTEC (UGA, CNRS, CEA), Unité Mixte de Physique (CNRS, Thales) and colleagues at NIMTE & CAS in China demonstrates that skyrmions may exist in transition metal dichalcogenides (TMD) of the Janus type (i.e. MnSeTe and MnSTe), a new class of 2D magnets in the large family of bi-dimensional materials such as graphene. Furthermore, the temperature and magnetic field range for observation of skyrmions are also predicted as a guide for experimental exploration.



The left panel shows the top and side views of the crystal structure for MnXY (X,Y=S, Se, Te, X≠Y) Janus monolayers. The upper right panel presents the calculated in-plane DMI parameters $d_{//}$ in MnSeTe, MnSeTe and MnSSe structures. The bottom right panel shows a typical image of the disordered assembly of skyrmions in case of MnSeTe Janus monolyer.

Using first-principles calculations it was shown first that significant Dzyaloshinskii-Moriya interaction (DMI) can be obtained in a series of Janus monolayers of manganese dichalcogenides MnXY (X,Y= S, Se, Te, X≠Y) in which the difference between X and Y on the opposite sides of Mn breaks the inversion symmetry. In particular, the DMI amplitudes of MnSeTe and MnSTe are comparable to those of state-of-the-art ferromagnet/heavy metal heterostructures. Next, by performing Monte Carlo simulations, it is found that at low temperatures the ground states of the MnSeTe and MnSTe monolayers can transform from ferromagnetic states with wormlike magnetic domains into the skyrmion states by applying an external magnetic field. At increasing temperature, the skyrmion states start fluctuating above 50 K before an evolution to a completely disordered structure at higher temperature. The present results pave the way for new device concepts utilizing chiral magnetic structures in specially designed 2D ferromagnetic materials.

Team: Theory and simulation

Collaborations: Unité Mixte Phys. CNRS/Thalès (France), NIMTE (China), HMFL (China), DIPC (Spain)

Funding: EU Horizon 2020 (Graphene Flagship), NSFC & CAS (China), DARPA TEE (USA), DIPC (Spain)

Further reading: *Very large Dzyaloshinskii-Moriya interaction in two-dimensional Janus manganese dichalcogenides and its application to realize skyrmion states*, J. Liang, W. Wang, H. Du, A. Hallal, K. Garcia, M. Chshiev, A. Fert & H. X. Yang, Phys. Rev. B 101, 184401 (2020) (Editors' Suggestion). DOI: *10.1103/PhysRevB.101.184401*

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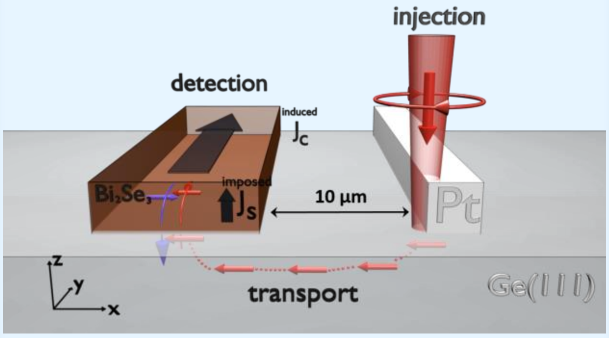
Spin-orbitronics at a topological insulator-semiconductor interface.

Topological insulators (TI) represent a new class of insulating materials hosting metallic surface states. Moreover, those surface states exhibit a Dirac cone energy dispersion where the strong spin-orbit coupling leads to a helical spin texture at the Fermi level. This property can be exploited to detect spin currents in conventional semiconductors like silicon or germanium. Here, we demonstrate the integration of the TI Bi2Se3 on a germanium platform and demonstrate the high spin current detection efficiency.

TIs hold great promises for new spin-related phenomena and applications thanks to the spin texture of their surface states. However, a versatile platform allowing for the exploitation of these assets is still lacking due to the difficult integration of these materials with the mainstream Si-based technology. Here, we exploit germanium as a substrate for the epitaxial growth of Bi2Se3, a prototypical TI. We probe the spin properties of the Bi2Se3/Ge pristine interface by investigating the spin-to-charge conversion taking place in the interface states by means of a nonlocal detection method. The spin population is generated by optical orientation in Ge, and diffuses towards the Bi2Se3 which acts as a spin detector (see figure). We compare the spin-to-charge conversion in Bi2Se3/Ge with the one taking place in Pt in the same experimental conditions. Notably, the sign of the spin-to-charge conversion given by the TI detector is reversed compared to the Pt one, while the efficiency is comparable. Due to the higher resistivity of Bi2Se3, the output voltage resulting from the spin-to-charge conversion is much higher than for platinum making Bi2Se3 an ideal spin detector on germanium. By exploiting first-principles calculations, we ascribe the sign reversal to the hybridization of the topological surface states of Bi2Se3 with the Ge bands. These results pave the way for the implementation of highly efficient spin detection in TI-based architectures compatible with semiconductor-based platforms.



Sketch of the nonlocal spin injection detection scheme used in this work. The spin current is generated optically using optical spin orientation in Ge and Bi_2Se_3 plays the role of the spin current detector by inverse the Rashba-Edelstein effect.

Teams: 2D and semiconductor spintronics, Theory and simulation, Spin textures

Collaborations: Politecnico di Milano (Italy), PFNC (Grenoble)

Funding: ANR TOP RISE

Further reading: *Spin orbitronics at a topological insulator-semiconductor interface*, T. Guillet, C. Zucchetti, A. Marchionni, A. Hallal, P. Biagioni, C. Vergnaud, A. Marty, H. Okuno, A. Masseboeuf, M. Finazzi, F. Ciccacci, M. Chshiev, F. Bottegoni, M. Jamet, Phys. Rev. B 101, 184406 (2020). DOI: *10.1103/PhysRevB.101.184406*

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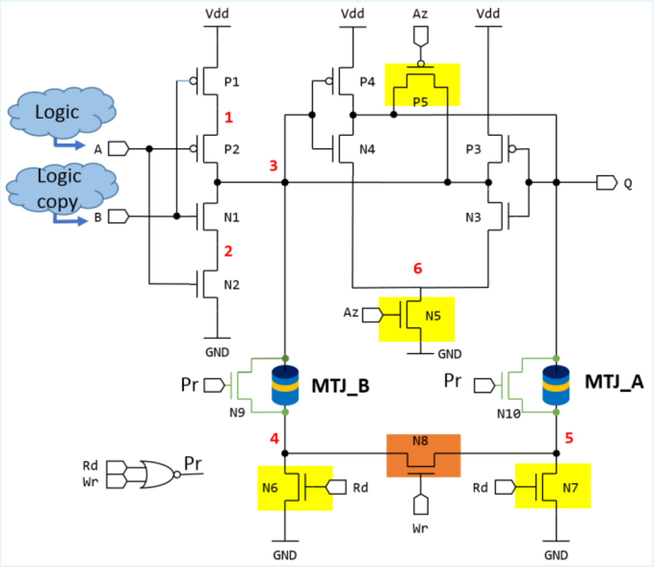
Spin Transfer Torque Magnetic Tunnel Junction for Single Event Effect mitigation in IC Design.

Due to its good radiation effects tolerance and its inherent non volatility, Spin-Transfer Torque Magnetic Tunnel Junction (STT-MTJ) is considered as a promising candidate for high-reliability electronics. A radiation tolerant circuit design suitable for space application is proposed in this study.

Radiation effects research on semiconductors has been pursued since the 1960s becoming an extremely vivid area of research and development. Nevertheless, for embedded systems in space environments, a radiation robust circuit design is still an open challenge.

The Spintronics Integrated Circuit Design team of SPINTEC investigated Radiation Hardening by Design Techniques combined with FD-SOI 28 nm process, attested to be six times more resilient than bulk technology to heavy-ion irradiation, with non-charge based memory: the Spin Transfer Torque Magnetic Tunnel Junction. The proposed logic-in memory circuit is a sequential block able to mitigate the impact of Single Event Effect due to heavy ions strikes. MTJs are used to store the output state and its complement, while the CMOS part takes charge of the combinational operations. In this context, the main problem still to be faced is the unwanted switching of magnetic devices due to the activation of surrounding peripheral circuits as a particle strike consequence.



Proposed radiation-tolerant sequential circuit. The numbers in the circuit represent the nodes most sensitive to radiation.

Two different strategies have been pursued in order to ensure robustness of the MTJ state against particle strikes. First, the impact of the different MTJ parameters on switching was evaluated by calibrating parameters within the compact model used in the electrical simulation environment. Next, reduction of the current flowing though the MTJs induced by a strike was achieved by inserting a transistor in parallel to each MTJ. The key idea is to obtain a less resistive shunt path for the current pulse induced by particle strikes. Experimental test campaigns are planned in the next future. If the robustness to high radiation rate is confirmed, a suitable strategy for space circuit design could be to replace as many transistors as possible with magnetic devices, using the logic-in-memory concepts based on purely magnetic logic gate.

Team: Spintronics IC Design

Collaborations: LIRMM (Montpellier); CNES (Toulouse)

Funding: CNRS-CNES

Further reading: *Spin- Transfer Torque Magnetic Tunnel Junction for Single- Event Effects mitigation in IC Design* O. Coi, G. Di Pendina,, G. Prenat, L. Torres, IEEE Transactions on Nuclear Science 0018-9499 (2020). DOI: *10.1109/TNS.2020.3002649*

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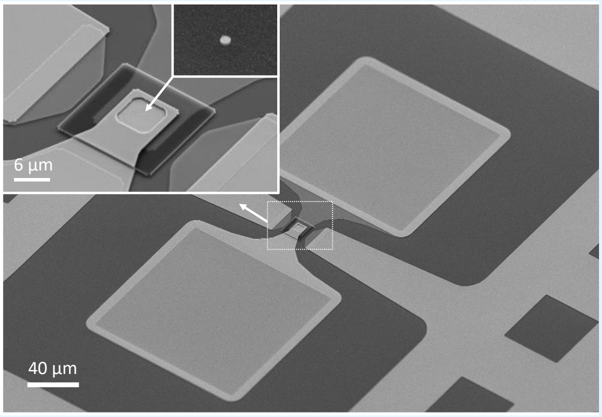
Optical access of magnetic tunnel junctions for future hybrid spintronic–photonic memory circuits

We demonstrate in this study a fabrication process that enables the realization of a top transparent conductive electrode of magnetic tunnel junctions (MTJs), building blocks of magnetic random access memories (MRAMs). This work opens up the realization of future and faster nonvolatile memories based on hybrid spintronic photonic circuits. This new process has been electrically validated by comparison with our standard process and we have been able to integrate materials in which their magnetization can be switched optically.

MRAMs have been moving up in the memory hierarchy in the last decades thanks to their non-volatility, low energy consumption, high endurance and its compatibility with silicon (Si) complementary metal-oxide semiconductor (CMOS) processing. To reach the processor and cache level, MRAM has to be written even faster, at pulse durations in the range of pico-and femto-seconds. This is the goal of the European FET project called SPICE, developing a spintronic-photonic IC platform to create world class ultra-fast and low power memory and sensor designs by combining spintronics (MRAMs) and photonics (crystal photonic) into hybrid circuits. To achieve this ambitious goal, we have developed an optical access to the spintronic element, i.e. a transparent and conductive electrode (TCO). In our work, we used a well-known material in the TCO family: the indium tin oxide (ITO) with the best transparency, low resistivity and easy to process

By optimizing the ITO deposition conditions to obtain low resistivity (as low as 4.8×10^{-4} Ω.cm) and optical transparency (>80%), we have shown that it can be used as hard mask to pattern the MTJ pillars down to a diameter of 50 nm. We integrated it in the process and compared with our standard process based on tantalum (Ta) hard-mask, using a well-known reference magnetic stack based on [Pt/Co]/FeCoB/MgO/FeCoB MTJ. Electrical performances based on the tunnel magnetoresistance (TMR), key figure of merit in MRAM, are similar between the ITO and Ta based processes validating thus this new process flow.



Scanning electron microscopy image of a MTJ device based on ITO top electrode process with FeCoB/MgO/FeCoB/[Tb/Co] magnetic stack with zooms on MTJ areas and the pillar prior the realization of the top electrode.

A further step was achieved by integrating materials with optically switchable magnetization. These materials are multilayers of terbium and cobalt (Tb/Co) coupled with FeCoB free layer in a MTJ. By optimizing the materials and the ion beam etch (IBE) patterning, the new process flow was validated electrically achieving 28% TMR, demonstrating a process suitable and robust for different magnetic stacks. This work is novel, bringing closer the realization of faster MRAM based on spintronic-photonic hybrid circuits.

Team: MRAM, Spin-orbitronics

Collaborations: Aarhus Universitet, IMEC, Radboud Universiteit, Quantum Wise

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

Further reading: *Indium Tin Oxide (ITO) optical access for magnetic tunnel junctions in hybrid spintronic–photonic circuits,* A. Olivier, L. Avilés Félix, A. Chavent, L. Álvaro-Gómez M.l Rubio Roy, S. Auffret, L. Vila, B. Dieny, R. C. Sousa and I. L. Prejbeanu, Nanotechnology (2020),

DOI: *10.1088/1361-6528/ab9c56*

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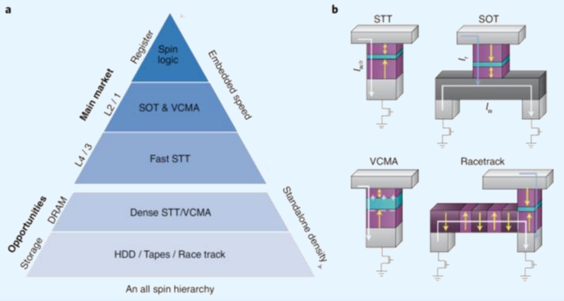
The European network SpintronicFactory publishes its roadmap on spintronics

The European network SpintronicFactory, led by SPINTEC and the Thales-CNRS joint research laboratory, published on August 19, 2020 in Nature Electronics an ambitious spintronics roadmap. This discipline, on the interface between magnetism and microelectronics, is reaching maturity, offering broad prospects for innovation.

Since its birth in Europe at the end of the 80s, spintronics has shown exceptional dynamism on a fundamental level and presents important prospects in information and communication technologies. Spintronics has a more and more important place in the microelectronics industry, namely after the launch in industrial production by the major industrial players in the field (Samsung, TSMC, INTEL, Global Foundries) of a new type of magnetic memories (MRAM), providing low power electronic circuits with new features and improved performances. The SpintronicFactory network, created in 2016, aims to promote excellent research in spintronics in Europe and all the potential for innovation that it carries. On August 19, 2020, the consortium published in Nature Electronics his vision of the application spintronics roadmap, which identifies the next challenges to be met: (1) for memories, production of very high density chips through the development of disruptive 3D inspired solutions; reduction in power consumption by implementing fundamental, less power-consuming interface effects using spin-orbit coupling or voltage control of magnetic properties. (2) for magnetic sensors, improved sensitivity and widening of the magnetic field measurement range. These challenges reflect the very diverse needs of this market, which concern smartphones (3D magnetometers / digital compasses), the automotive sector (linear or angular position sensors, speed), current and power sensors, scanners. New applications are emerging in the Internet of Things (IoT) and biomedical fields with the development of reliable low-power devices on silicon or flexible substrates. (3) In rf and THz technologies, spintronic oscillator and diode functions are of interest to telecom components. It is now necessary to allow their concrete integration into different application fields, in particular compact and low-consumption telecommunications, THz applications (imaging, security), micro-energy recovery and artificial intelligence. Milestones are proposed to demonstrate the applicative potential of spintronics, making possible to further reduce the consumption of electronic circuits or to introduce new features. The challenges identified relate in particular to the efficiency of conversions between spin current and charge current in the new concepts. Meeting these various challenges will require progress in mastering unconventional materials, their interfaces on which spintronic functionalities often depend, their nanofabrication and their use in production lines, including their specific metrology. Developments should also be carried out in numerical simulation, ranging from the integration of new effects into multiphysics codes, to multi-scale approaches ranging from atoms to systems.



Nonvolatile magnetic memories. (a) Modification of the memory hierarchy by spintronic solutions where main markets are embedded cache memories (L1–4) and possibly extending to in-memory computing and logic applications, and standalone memories opportunities markets for intermediate memory layers (DRAM, storage class) and storage applications requiring high density and low power. (b) MRAM architectures considered.

Teams: MRAM, Spintronic IC design, Microwave devices

Further reading: *Opportunities and challenges for spintronics in the microelectronics industry*, B. Dieny, I.L. Prejbeanu, K. Garello et al, Nature Electronics volume 3, pages 446–459(2020). DOI: *10.1038/s41928-020-0461-5*

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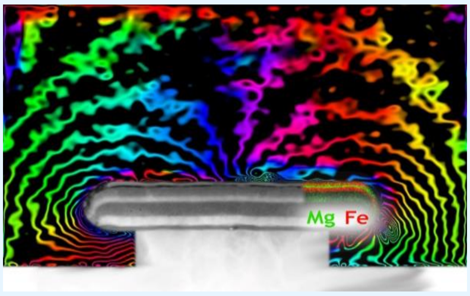
Unveiling the heart of magnetic memory cells thanks to electron holography

Magnetic spintronic memory called STT-MRAM have recently entered in volume production at major microelectronic foundries. The research in this area is now focused on preparing the future memory generations with higher capacity, higher speed, lower power consumption, wider range of operating temperature. To conduct this type of research, it is important to be able to accurately visualize the micromagnetic state of individual memory cell of dimensions down to 20nm. SPINTEC in collaboration with LETI and PFNC have demonstrated that this is possible by electron holography.

Electronic holography is an electron microscopy technique which allows to obtain information on the electric and magnetic fields seen by electrons as they pass through the sample. It is based on the interference between a beam passing through the sample and a reference beam. Team from SPINTEC and from LETI and the Nanocharacterization Platform (PFNC) have shown that this technique can be used to provide an image of the magnetic stray field around individual memory cells. The knowledge of this stray field allows, through modelling, to derive the micromagnetic state of the magnetic layers comprised in the memory cell, in particular of the storage layer. The study was performed on relatively large cells of diameter 230nm. However, from the obtained signal to noise ratio and thanks to contrast enhancement imaging technique, it was established that the technique could still be used for cells of diameters down to 20nm which are of industrial relevance for the development of MRAM of future generations. Besides, the influence of the memory temperature on the storage layer micromagnetic state could be investigated in-situ. It was observed that while in conventional MRAM, the storage layer magnetization points out-of-plane (up or down to represent logic “0” or “1”, above a certain temperature (in the range 150°C-250°C depending on sample composition), the storage layer magnetization tends to fall into the plane of the layers. This phenomenon is due to a thermal decrease of the perpendicular anisotropy existing at the interface between the magnetic storage layer and the tunnel barrier. This magnetization reorientation can lead to the formation of complex micromagnetic states (called C-state because the magnetization curls along the cell side as in a C-letter). These are valuable information which can be used to adjust the design of the memory cell. As a matter of fact, in MRAM cells, the storage layer magnetization has to remain out-of-plane and as uniform as possible.



An off axis electron holography phase image of the magnetic stray field produced by the storage layer of a magnetic random access memory cell (STT-MRAM). The color-code depicts the orientation of the magnetic field lines and the grey-level image shows the MRAM device of 230 nm top-diameter together with its chemical analysis by Energy-dispersive X-ray spectroscopy (EDX).
Electron holography is shown to be an excellent tool for characterizing the micromagnetic state of the storage layer in magnetic memory cells by imaging the magnetic stray field surrounding the cell. The investigation has been conducted on MRAM cells realised by an innovative patterning approach which consists in depositing a magnetic stack on top of a T-shaped non-magnetic pillar. This nano-patterning approach avoids the difficult etching of the magnetic stack during processing and enables the realization of high density memory chips.

Teams: MRAM, Spin textures, Spin orbitronics

Collaboration: CEA - LETI

Funding: ERC MAGICAL n°669204, ERC Holoview n°306535 and Carnot project MAGICMAPS

Further reading: *An electron holography study of perpendicular magnetic tunnel junctions nanostructured by deposition on pre-patterned conducting pillars*, V.Boureau et al, Nanoscale 12, 17312 (2020). DOI: *10.1039/D0NR03353G*

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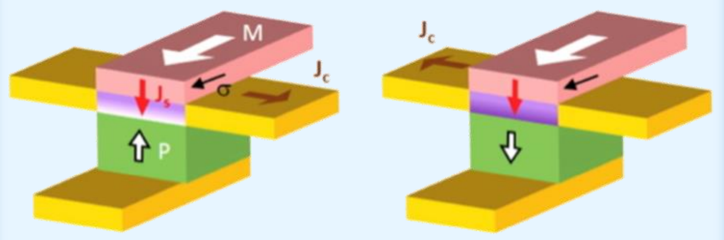
Controlling and detecting spin currents using ferroelectricity

In an article in Nature we are showing that the generation and detection of spin currents can now be done in a very energy-efficient way using non-magnetic interfaces controlled by electric fields. The result is a reduction in the power consumption of non-volatile spintronic devices by typically a factor of a thousand.

To generate and detect spin currents, spintronics traditionally uses ferromagnetic materials, in which the spins are all aligned along a given direction (spin up or spin down). Ferromagnetism has the advantage of giving spintronic devices a non-volatile character, which can reduce the overall energy cost of devices. However, the energy required to reverse the magnetization by application of a magnetic field or electric current remains significant.

Researchers in Spintec have developed, in collaboration with the CNRS/Thales Joint Physics Unit, a new approach to generate and detect spin currents by exploiting the particular electronic properties present at the interface between two non-magnetic materials. In these systems, the injection of a charge current in a given direction generates spins in a transverse direction; reciprocally, the injection of spins in one direction gives rise to a charge current along the transverse direction. The way in which spin and charge currents are thus interconverted (and in particular their sign) is determined by the nature of the interface.



Example of a device. A ferromagnetic material (red) is used to generate a vertical spin current J_S and inject it through an interface material (purple), in which it is converted into a lateral J_C charge current. The spins σ are represented by the small black arrow and their direction is fixed by the direction of magnetization of the ferromagnetic material M represented by the big white arrow. Traditionally, to change the sign of the charge current produced, the magnetization of the ferromagnetic must be reversed by applying a magnetic field or a strong current to it. Here, this is achieved by reversing the polarization P of the ferroelectric material (green) acting on the interface by means of an electric field.

While spintronics has traditionally relied on ferromagnetic metals as spin generators and detectors, spin-orbitronics exploits the efficient spin-charge interconversion enabled by spin-orbit coupling in non-magnetic systems. This is providing new opportunities for devices, such as the MESO transistor proposed recently by Intel, which relies on writing magnetic information through magnetoelectric coupling, and reading it by spin-charge conversion.

By giving these interfaces a ferroelectric character, the researchers were able to control the sign of interconversion via electrical polarization. To do this, they applied a strong electric field to induce a ferroelectric character to the oxide used, obtaining for the first time a non-volatile electrical control of the conversion between charge current and spin current. This opens up the possibility of encoding information through the polarization of the ferroelectric element, and using spin-charge conversion to read this polarization state.

This work paves the way for spintronic devices in which the non-volatility would be provided not by ferromagnetism but by ferroelectricity, and for which the electrical consumption would thus typically be reduced by a factor of 1000.

Team: Spino-rbitronics

Collaboration: Unité Mixte de Physique CNRS/Thalès

Funding: ANR TOPRISE, ANR OISO

Further reading: *Non-volatile electric control of spin-charge conversion using a SrTiO3 Rashba system*
P. Noël et al. Nature 580, 483 (2020). DOI: *10.1038/s41586-020-2197-9*

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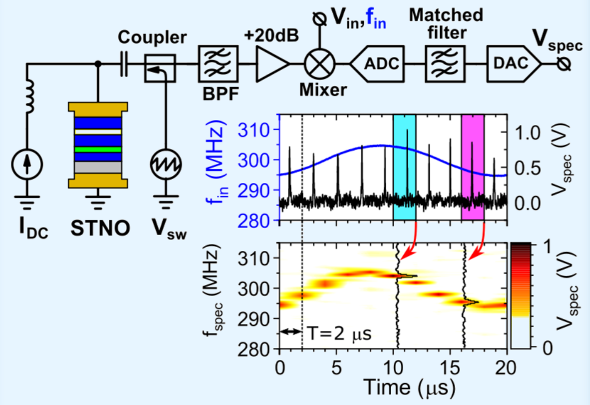
Pushing the limits of fast swept-tuned spectrum analysis using Spin-Torque Nano-Oscillators

Recent progress in nanotechnology has led to the development of spin-torque nano-oscillators (STNO), whose time constants, due to their nano-scale size, are naturally of the order of 1-100 nanoseconds. At SPINTEC we demonstrated experimentally for the first time that the use of such STNOs in swept-tuned microwave spectrum analyzers leads to a substantial reduction of the characteristic sweeping times, opening the path to develop spectrum analyzers (SA) with high temporal resolution.

In our digital world and with the rapid development of IoT and wearable electronics, the amount of wirelessly transmitted data is constantly growing. This dictates high data rates and complex transmission protocols. The research in the field of modern communication technologies thus requires measurement tools capable of fast spectral analysis, such as spectrum analyzers whose local oscillator frequency can be swept rapidly in the desired frequency interval. However, conventional voltage controlled oscillators (VCOs) have a low tuning bandwidth meaning that the corresponding sweep rates are limited to 1-10 MHz due to parasitic parameters arising from the macroscopic dimensions of the used components. In contrast to this, the frequency of spin-torque nano-oscillators (STNOs) can be swept on timescales of 1-100ns via a time varying input signal, as shown on the figure. This is possible due to their nanoscale dimensions. STNOs can thus be used as a reference frequency-swept oscillator in swept-tuned spectrum analyzers.



Principle of the ultra-fast spectrum analyzer (SA) based on STNOs. For the developed SA a matched filter is used to compress the chirp signal from the mixer into a single peak. Results are demonstrated for a vortex-state STNO tracking the sinusoidal variation of the frequency of an unknown signal.

At SPINTEC we developed such an STNO-SA system and demonstrated its operational principle using vortex-state STNOs that generate signals in a bandwidth of 40 MHz around a carrier frequency of 300MHz achieving sweeping rates of up to 1.5MHz. The ultimate demonstration of very high sweep rates of up to 50MHz was achieved using uniform-state STNOs that generate signals in a much wider band of 1GHz around 9GHz. In both cases, the obtained frequency resolution at highest sweep rates is very close to the resolution defined through the “bandwidth” theorem. We also demonstrated that it is possible to resolve several frequency components simultaneously and to track fast frequency changes (see figure). This makes STNO-based ultra-fast spectrum analyzers a very promising technology despite their relatively high intrinsic phase noise and opens a new field of applications for STNOs. We expect that these ultrafast STNO-based spectrum analyzers with nanosecond temporal resolution will become in the near future practical and highly competitive microwave signal processing devices that will considerably impact modern radar and communication technologies

The uniform-state STNOs were deposited and nanofabricated at the technological platform PTA and the vortex-state STNOs were provided via a collaboration with INL, Braga (Portugal).

Teams: Microwave devices, MRAM

Collaborations: Oakland University, Rochester, USA; INL, Braga, Portugal

Funding: ERC Magical

Further reading: *Ultrafast Sweep-Tuned Spectrum Analyzer with Temporal Resolution Based on a Spin-Torque Nano-Oscillator*, A. Litvinenko, V. Iurchuk, P. Sethi, S. Louis, V. Tyberkevych, J. Li, A. Jenkins, R. Ferreira, B. Dieny, A. Slavin, and U. Ebels, Nano Lett. 20, 8, 6104–6111 (2020). DOI: *10.1021/acs.nanolett.0c02195.*

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SPINTEC research topics

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 going up to in-memory computing or artificial intelligence. Electric field control of the magnetization, possibly in combination with spin-charge interconversion, as well as optical switching of the magnetization are studied as further extension of spintronic memories beyond-CMOS technologies.

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.

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.

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.

MICROWAVE DEVICES

The aim of this activity is to provide a fundamental understanding of the excitation, manipulation and detection of the linear and non-linear magnetization dynamics via spintronics phenomena for magnetic nanostructures based on metallic, insulating, ferro-, ferri or antiferromagnetic materials. Specific attention is given to the engineering of the spinwave dispersion, the coupling to phonons and photons as well as to identify potential microwave applications (oscillators, filters, detectors).

2D AND SEMICONDUCTOR SPINTRONICS

The « semiconductor and 2D spintronics » team deals with spin dependent phenomena in two important classes of materials: Si and Ge which are the materials of today’s microelectronics and transition metal dichalcogenides 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.

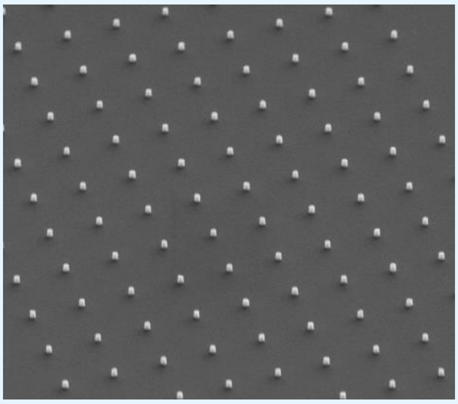
THEORY AND SIMULATION

The team covers all aspects of fundamental 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, SPINTEC gathers, in a flexible and project-oriented organization, physicists and engineers from the academic and the industrial world. The laboratory was created in 2002 and rapidly expanded to currently reach 100 persons of which 44 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 objective is to **bridge fundamental research and innovative device technology in the fast-growing field of spin electronics** (spintronics). The *international technology roadmap for semiconductors (ITRS)* now reckons that spintronics devices will play a major role in tomorrow's semiconductor chips, with the potential to totally displace the stand-alone (e.g. DRAM) and embedded memory market. Other fast-developing fields include magnetic field sensors, hardware components for artificial intelligence and bio-applications. In this context, it is our strategy is several-fold: to be at the forefront of research, to generate a strong IP position, and to establish the proper partnerships for technology transfer.



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

SPINTEC plays also a major role in higher education in the field of 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.

SPINTEC unique positioning brings together top-level scientists and applicative engineers that work in close collaboration in order to ensure that new paradigms can be swiftly translated into technological proof 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** and implementation of **relevant functional demonstrators**.

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

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