20 years of research at SPINTEC

Highlights

2002 - 2022

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2005


2008


2010


2013

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SPINTEC Highlights 20 years – January 2022 – Editor: Gregory Di Pendina

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FOREWORD

Dear colleagues and friends,

It is with great pleasure that we are writing the foreword of SPINTEC 20th anniversary booklet, compiling some of the main achievements of the laboratory during this period.

SPINTEC (SPINtronique et TEchnologie des Composants) was founded 20 years ago by Jean-Pierre Nozières and Bernard Diény, researchers from CNRS and CEA, through the merger of three teams from CEA Grenoble, the Louis Néel laboratory in Grenoble and the Institute of Physics and Chemistry of Materials in Strasbourg (IPCMS).

The objective of SPINTEC was, from its creation, to form a welded entity around the fast-growing field of spintronics, bridging the gap between fundamental research and innovative devices technology**.** This is key to enable upstream-downstream transfer, which until that moment had only been poorly covered within the French perimeter. This aim of a unique positioning brought together top-level scientists and applicative engineers, who have been working in close collaboration in order to ensure that new paradigms can be swiftly translated into technology proof of concepts and functional devices. As such, the outcome of the laboratory has been not only scientific publications and communications at international conferences, but also a coherent patent portfolio and the implementation of relevant functional demonstrators and device nanofabrication. The lab has launched four start-up companies from its creation, with three others being at different stages of development.

SPINTEC is housed on CEA Grenoble grounds. Initially created as an associated research unit between CEA and CNRS, SPINTEC transformed at the beginning of 2009 into a joint UJF-CEA-CNRS research unit (The UJF University has since then merged into the UGA), also associated with the Grenoble Institute of Technology (G-INP). In the CEA framework, SPINTEC has been part of DRFMC (later INAC), belonging with the Directorate of Matter Sciences (DSM, later integrated into the Directorate of Fundamental Research, DRF). On January 1st 2016, an internal reorganisation at INAC led the Nanostructures and Magnetism team join SPINTEC with about 15 researchers. Since 2019, SPINTEC is part of the new IRIG institute (Grenoble Interdisciplinary Research Institute), within its nanophysics department (DEPHY). Several management teams have successively led the laboratory from its creation:

- 2002 –2005: Jean-Pierre Nozières (CNRS, Director) - Bernard Dieny (CEA, Deputy Director)
- 2006: Bernard Dieny (CEA, Director) - Ahmad Bsiesy (UGA, Deputy Director)
- 2007 – 2010: Alain Schuhl (UGA, Director) - Bernard Dieny (CEA, Deputy Director)
- 2011 – 2015 : Jean-Pierre Nozières (CNRS, Director) - Bernard Dieny (CEA, deputy Director 2011 –2012) / Ursula Ebels (CEA, Deputy Director, 2012) / Lucian Prejbeanu (CEA, Deputy Director 2013 → 2015)
- 2016 –2020 : Lucian Prejbeanu (CEA, Director) - Olivier Fruchart (CNRS, Deputy Director)
- 2021 –Now: Lucian Prejbeanu (CEA, Director) - Olivier Fruchart (CNRS, Deputy Director)

20 years after its creation, with its 47 permanent staff and about 100 members in total, ideally located on the MINATEC campus in Grenoble, SPINTEC is now one of the leading spintronics research laboratories worldwide, pursuing missions of knowledge production, knowledge transfer for innovation, higher education and education through research, and community structuring. While SPINTEC was initially pretty much focused on spintronic memories called MRAM, for which emergence in the industry the lab actively contributed, holding a series of key patents, SPINTEC covers now a wide spectrum of topics, from upstream to downstream: emerging materials, spin textures (walls, vortices and skyrmions), magnetic tunnelling, spin transfer torques and charge-spin interconversion, spin-torque oscillators and magnonics, magnetic sensors, artificial intelligence, design of spintronic integrated circuits, technological integration and functional tests. To achieve this, SPINTEC boasts a complete chain of expertise: materials synthesis, clean room nanofabrication, structural, magnetic and electrical characterisation, instrumental development, use of large-scale instruments, theory, analytical and numerical modelling, CAD tools. The combination of this broad coverage and complementary skills are key assets for its positioning at the forefront of spintronics research.

In this special SPINTEC 20 years highlights edition, you can get a glimpse of key breakthroughs of the lab during this period, ranging from fundamental discoveries to technologically-oriented demonstrations: the thermally assisted MRAM concept and the creation of Crocus Technology, the design of hybrid CMOS/magnetic integrated circuits, the perpendicular magnetic anisotropy at magnetic transition metal/oxide interfaces, solutions for sub-10 nm MRAM with perpendicular shape anisotropy, the ultrafast all-optical switchable magnetic tunnel junctions, magnetic sensors with enhanced performances, the discovery of spin-orbit-torque phenomena and the Antaios creation, the development of spin-torque nano-oscillators, new concepts of skyrmions controlled by gate voltage and light, the domain wall dynamics in the 3D tubular geometry, the ferroelectric control of the spin-charge conversion for ultralow power spintronics, the epitaxial growth of 2D materials, proximity effects Induced in graphene, the physics of antiferromagnetic spintronics, the coherent coupling of distant macrospins by chiral phonons, innovative solutions for magnetism-based therapies, the development of the Hprobe instrumental start-up, the strengthening of the relationships between magnetism and microelectronics communities through InMRAM and IEDM events, and two higher-education events chaired by SPINTEC: ESM and ESONN.

We would like to warmly thank all present and former colleagues and collaborators, who made possible these wonderful achievements, ground for this nice anniversary. Thank you all for your enthusiasm and hard work and for making the laboratory such a collegial and friendly environment.

Lucian Prejbeanu, Executive Director / Olivier Fruchart, Deputy Director

This booklet is dedicated to our beloved colleagues that passed away in the last years: Marta Kerekes, Bernard Rodmacq, Sebastien Bandiera, Gerard Casali

The Thermally Assisted MRAM concept – Creation of Crocus Technology

Activity on thermally-assisted MRAM started at the very creation of SPINTEC, with the first patents and a first demonstration of the proof of concept based on in-plane magnetic tunnel junctions with an exchange-biased storage layer. The originality of this concept stems from the specific writing process that combines a few-nanoseconds-short heating current pulse sent through the memory cell, with a pulse of magnetic field or spin-polarized current. Since this first demonstration in 2004, which enabled the launch of Crocus-Technology, several breakthrough concepts were developed, namely the thermally-induced reorientation of magnetization in perpendicularly-magnetized magnetic tunnel junctions, or the self-referenced architecture.

MRAM technologies gained in maturity from the beginning of 2000 onwards, benefiting from the progress in spintronics science, namely the tunnel magnetoresistance of MgO magnetic tunnel junctions, the spin transfer torque and the spin-orbit torque phenomena. Until 2004, most of the research and development activities were focused on the first MRAM architecture, in which the writing is done by two orthogonal coincident magnetic fields. This approaches resulted in the commercialization of the first MRAM products by Freescale Semiconductor and its spin-off Everspin Technologies in 2006. Field-written technology was robust and already used in a variety of applications where reliability, endurance, and resistance to radiation are important features, such as in automotive and space applications. However, the downsize scalability of field-writing in this conventional technology is limited by the large increase of the current densities needed to produce the writing magnetic fields. In addition, the write field extends all along the conducting line where it is produced and decreases relatively gradually in space, inversely proportional to the distance to this line. As a result, bits adjacent to selected bits may sense a significant fraction of the write field, which may yield accidental switching of these unselected bits. In order to overcome these difficulties, a new solution called Thermally Assisted MRAM (TAS-MRAM), was patented and developed by SPINTEC.

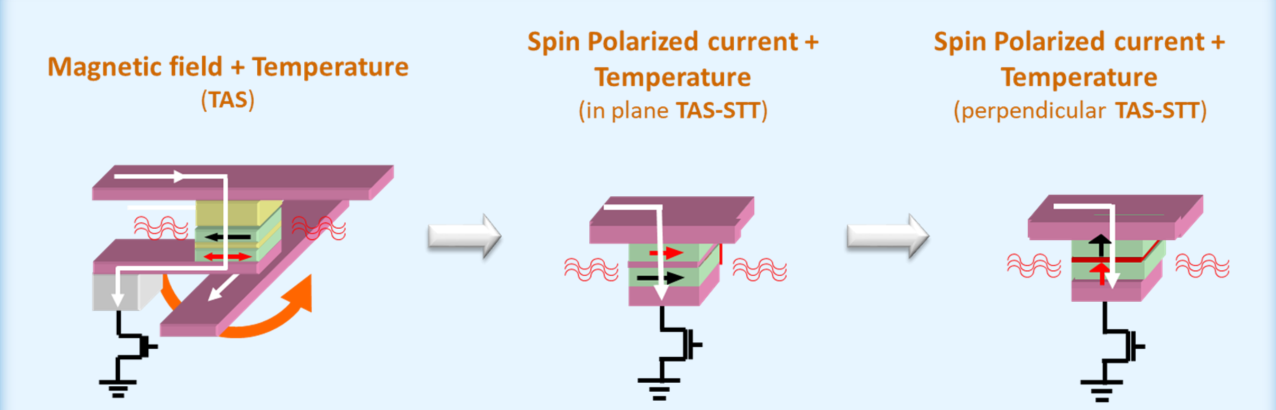

Fig. 1: Schematics showing different implementations of the TAS-MRAM concept.

The thermally-assisted approach offered a promising solution for a next generation of MRAM, as it solved several issues of the first generation: write selectivity, power consumption and thermal stability, whilst offering scalability to the 65 nm node: (i) as the selection at write is temperature-driven, the addressing errors are strongly reduced; (ii) only one magnetic field is required to write, leading to reduced power consumption. Furthermore, the write power can be further reduced, by using circular elements with no shape anisotropy; (iii) the exchange-bias anisotropy of the storage layer ensures a good thermal stability of information; (iv) since the system is not anymore bistable at zero field due to the exchange bias, TAS provides good reliability under field disturbance. Indeed, even if the resistance state of a bit is modified by external parasitic fields under standby conditions, the resistance state goes back to its initial state after the field perturbation ends. (v) TAS-MRAM presents a good scalability, since the heating power density P required to heat the junction is proportional to the square of the current density.

The breaktrougth results obtained by SPINTEC and LETI in the framework of the NEXT European project between 2001 and 2005, enabled the launch of a start-up, Crocus-Technology, which managed to raise 13.5 Million Euros from venture capitals in 2006. These results were awarded by the general prize of the ANVAR innovation in 2005, and allowed to the NEXT consortium to be finalist of the EU Descartes Prize in 2006. Since the first demonstration of the TAS-MRAM concept in 2004, several improvements and variations of this technology have been proposed and awarded for the technological transfer in 2012 by the SEE-IEEE Brillouin prize. The concept of heat assistance can be advantageously coupled to writing by spin-polarized current to significantly improve the thermal stability in STT-based systems. The use of spin transfer as writing means offers much better prospects for decreasing sizes than using magnetic field. Indeed with the spin transfer, the write current decreases as the cell size, while for field writing, the source current rather tends to increase as the size decreases. However, the STT-RAM suffers from the same problem as the field-based MRAM in terms of thermal stability for small sizes. The Thermally Assisted Spin Transfer Torque RAM concept allowed to ensure higher MRAM densities while minimizing the write current.

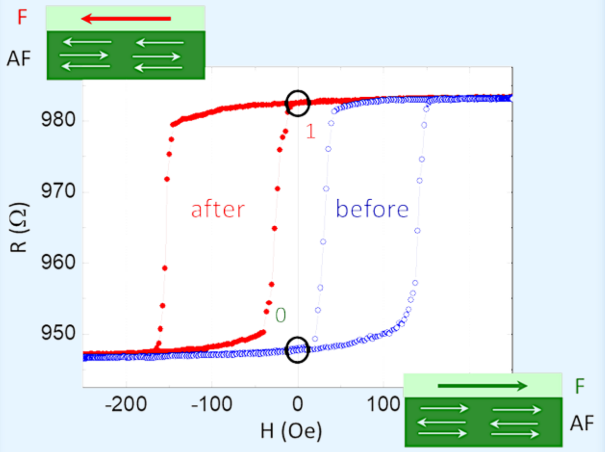

Fig. 2: Demonstration of the TAS-MRAM proof concept for in-plane exchange-biased magnetic tunnel junctions.

The joint R&D teams from Crocus and SPINTEC developed later a self-referenced reading concept, which now serves as a building block for the company's products in the smart-sensing market. This new concept makes the memory much more tolerant to process variations and is very promising for security applications (smart cards, routers, biometrics). These technological advances have enabled Crocus to grow dramatically, as evidenced by the fund-raising of 300M€ in 2011, enabling the company to go live with one of the first full magnetic back-end fab worldwide. Finally, the joint SPINTEC and Crocus teams demonstrated an ultra-low power memory concept extending the TAS-STT to perpendicular MRAM**.** SPINTEC laboratory / Crocus Technology collaboration is a good example of the fertile coexistence of fundamental research and technological application based on magnetic materials. The connection was kept alive through a joint lab, which funded a large number of "CIFRE thesis" and through hirings of more than ten former SPINTEC PhD students by Crocus.

Teams: MRAM, Theory / Simulation, Spintronics IC Design, Materials and Nanofabrication

Collaboration: LETI, Crocus Technology, Singulus, Tower Jazz, INESC, INL, LIRMM

Funding: FP6 NEXT, ANR SPIN, RAMAC, PATHOS, CILOMAG, bilateral industrial joint lab with Crocus Technology, ERC Hymagine

Further reading: *Thermally assisted switching in exchange-biased storage layer magnetic tunnel junctions*, I.L. Prejbeanu et al, IEEE Transactions on Magnetics, vol. 40, no.4, 2625 (2004), *DOI: 10.1109/TMAG.2004.830395*. *Thermally assisted MRAM,* I.L. Prejbeanu et al, J. Phys.: Cond. Mat. 19 (2007) 165218. *Spin transfer torque switching assisted by thermally induced anisotropy reorientation in perpendicular magnetic tunnel junctions,* S. Bandiera et al., Appl. Phys. Lett. 99, 202507 (2011), *DOI:10.1063/1.3662971*. *Thermally assisted MRAMs: ultimate scalability and logic functionalities*, I.L. Prejbeanu et al, J. Phys. D – Appl. Phys. 46(7) 074002 (2013).

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Magnetic tunnel junction process flow in the cleanrooms of the Upstream Technology Platform (PTA)

The field of spintronics largely relies on magnetic tunnel junctions to allow the electric detection of changes in the magnetization state of a magnetic electrode. Magnetic tunnel junctions are devices with two stacked magnetic electrodes separated by a tunnel barrier. To be measured electrically, junctions need to be shaped into a pillar for current to flow vertically. Bringing spintronic devices to fruition required a new process flow to pattern nanometer size junctions at the PTA. Overall, SPINTEC's access and active involvement in the PTA allowed it to become a reference laboratory for magnetic tunnel junction (MTJ) pillar fabrication, matching international state of the art single cell realizations.

As part of the RENATECH cleanroom network and in operation since 2008, the Upstream Technological Platform (PTA) is a 1000-class clean room resulting from the pooling of technical and human resources of IRIG/CEA and CNRS (with a large involvement of SPINTEC and LTM laboratories). The clean room extends over 700 m² on two different locations, one at CEA, another one at Grenoble INP within the CIME clean room, a university cleanroom dedicated to higher education, 200 m away. The PTA offers all technical capabilities needed to cover a wide range of projects in nanoscience and micro-nanotechnology: equipment facilities for lithography with sub 10 nm resolution, deposition and etching to fabricate objects from thin-film materials down to nanometer-lateral-size patterns. The PTA can accommodate all types of substrates, with size from 5x5 mm² up to 100 mm-diameters wafers. A large diversity of materials can be processed in a flexible approach including contamination management, very suitable to serve the exploratory mission of SPINTEC. More generally, it serves research fields such as nano-electronics, MEMS & NEMS, magnetism and spintronics, integration of nano-materials and nano-objects and photonics. The purpose of the facility is to provide the tools and training to researchers, as well as to welcome industrial companies looking for a place to develop their project. Flexibility, ease of access and use, are the cornerstones of the PTA management. The pooling of facilities across fundamental research institutes in Grenoble allows users to benefit from the combination of a state of the art facility with an optimal flexibility.

Figure 1: UV lithography and physical etch process tool areas inside the 10-05 cleanroom site.

MTJs need to be shaped into nanostructure of small size, for several reasons, depending on the application: get magnetic electrodes closer to single domain states, improving the TMR signal, reducing the current consumption, design cells compatible with high-density memories. The specific MTJ flow has three critical steps, illustrated in Figure 2. The first step is the initial hard mask definition that will set the pillar diameter. In most cases, tantalum is used as the hard mask material, that will be patterned with an anisotropic reactive ion etch step using a fluorine-based chemistry. The second critical step is the ion beam etch (IBE), with aim to use the hard mask to define the MTJ, and also provide a self-aligned electrical top contact to the tunnel

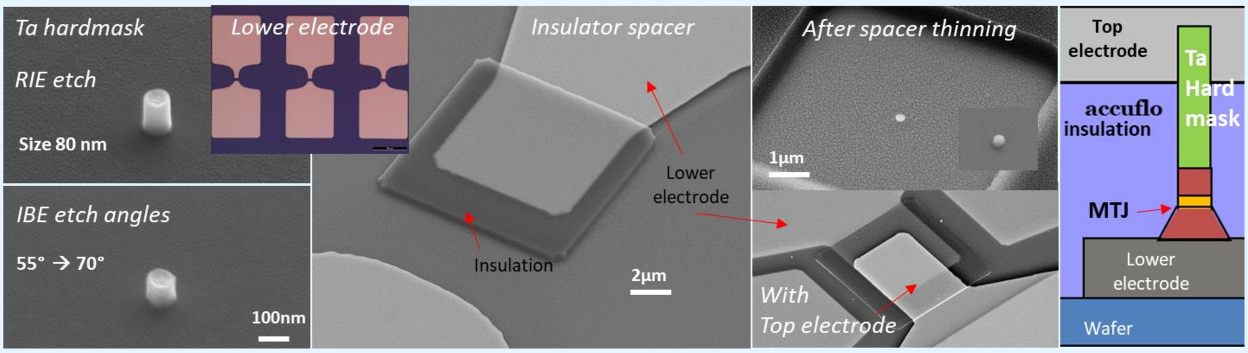

Figure 2: From the left, fabrication steps of magnetic tunnel junction pillars and illustration cross section right.

junction. The challenge lies in etching the full stack without creating side electrical short-circuit paths around the MgO tunnel barrier. The third critical step is to create an electrically-insulating spacer, to prevent a direct electrical contact between the top and bottom electrode leads. A specific constraint is that the spacer must be thinned down to release the top of the Ta hard mask, so as to gain electrical contact to the junction top electrode. The impact of the last two steps on device yield is reflected in the dispersion of resistance and TMR signal values, while the first two affect the junction size and therefore also the magnetization reversal behavior in fabricated devices. The whole magnetic tunnel junction (MTJ) pillar process flow comprises about 16 process steps, which can be completed in typically 2-3 weeks or in a record time of 3 days for rocket priority runs. This expertise is now made available for national and international project partners. Over time, this process has contributed to tens of projects, including various industrial partnerships related to MRAM (Samsung, AMAT, Crocus Technology, Hprobe, Antaios, Spin transfer). These projects address technology readiness levels up to the proof of concept (TRL 1-3), providing first demonstrations or key improvements to existing technologies.

Throughout the years, the process flow was used to demonstrate numerous device working principles. Initially focusing on MRAM, thermally-assisted field writing was demonstrated. The discovery of spin-orbit torque was followed by demonstrations of energy-efficient sub-ns switching, made possible by a variation of the pillar process flow, to accommodate for the required three terminal device magnetic tunnel junction geometry. At the same time, spin torque oscillators combining in-plane magnetization and perpendicular polarizers, proved to be effective in RF frequency generation and detection, based on the fabrication of nanopillars. In 2017 a solution for MRAM downscaling below 10nm was demonstrated by using perpendicular shape anisotropy. More recently the flow evolved to provide an optical access to the tunnel junction top electrode using an ITO hard mask and top contact, providing a platform for photonics-spintronics integration with pico/femtosecond reversal times. The future will probably bring us skyrmion detection, stochastic tunnel junctions for neuromorphic computing and cryogenic operation to interface quantum dots. Such a wide range of effects and applications is a real testimony to the wealth of physics, their technological interest and the fundamental role of the magnetic tunnel junction pillar flow in making it all happen. The evolution since the start is clearly visible in the different lateral size milestones that were achieved throughout the years (Fig.3), reaching state of the art realizations at sub-30 and sub-10nm lateral sizes.

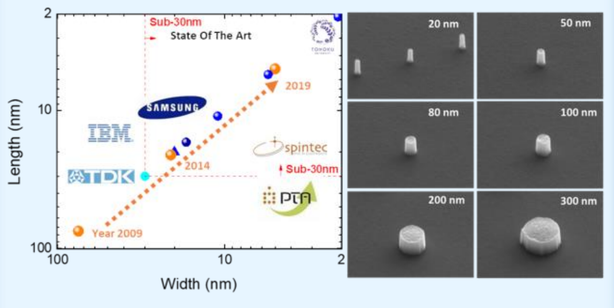

Figure 3: Evolution of magnetic tunnel junction lateral size since the first MTJ outputs in 2008.

While the core mission of SPINTEC is at TRL 1-3, transforming our discoveries into innovation requires our know-how to be implemented at higher TRL together with R&D and industrial partners, typically at TRL levels 4-6 (system integration). This requires a hybrid integration of CMOS circuits with the magnetic elements, placing higher requirements in terms of fabrication yield and tight distributions of critical device parameters, such as resistance values, TMR signals or switching voltage distributions, in the case of memory elements. Towards this goal, compatibility with 200mm foundry wafers will be the next step towards a complete magnetic pilot line at SPINTEC. Approved national funding projects will provide upgrades to existing critical steps, in the deposition and ion-beam etching tools, making way for a full 200mm process flow in an expanding collaboration with LETI as the local technology partner.

Teams: MRAM, 2D spintronics, Materials-Nanofabrication-Instrumentation, RF, Sensors, IC design

Collaboration: LTM, LETI

Funding: EU projects (ERC, FET-Open, ICT, MSCA-ITN), ANR, industry

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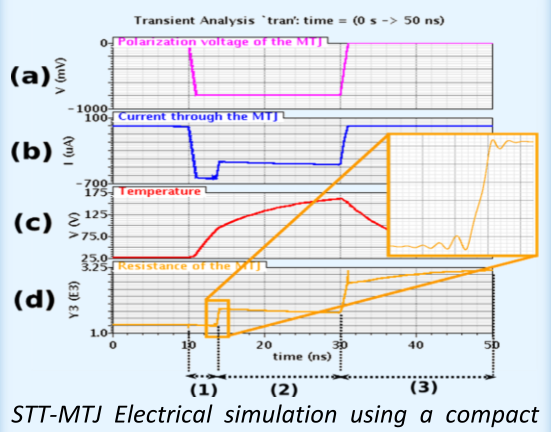
Hybrid CMOS/Magnetic Integrated Circuits design

The Spintronics Integrated Circuit design team of SPINTEC aims at evaluating the benefits that can be expected from using spintronic devices to improve Integrated Circuits (IC) performance. This requires adapting the microelectronics standard design tools and flows to integrate the magnetic devices. This enables to imagine innovative architectures of circuits to take advantage of non-volatile devices at all abstraction levels and for various applications like low-power, space or security for instance. SPINTEC was pioneer in the development of design methodology and tools for spintronics ICs and has acquired a renowned expertise.

Over the last decade, the interest for integrating MRAM within CMOS electronics has amazingly increased, among both academic and industrial actors. Therefore, an essential point is to be able to design complete circuits using standard methodology and tools. This starts by so-called compact models that describe the electrical response at the level of an individual device. At SPINTEC, this work started at the very beginning in 2003 with the first flavors of Magnetic Tunnel Junctions (MTJs), developed experimentally in the lab. These MTJs were switched by magnetic field, possibly assisted with local heating (Thermally Assisted Switching: TAS) and then by the so-called Spin Transfer Torque (STT) effect. We have developed further models, following the progress of the technology and the discovery of new devices or phenomena, such has Spin-Orbit Torques (SOT), superparamagnetic MTJs exhibiting a stochastic behavior, multilevel MTJs and so on. Many patents and publications have been produced on these aspects. The key interest of these models is their compatibility with the main industrial electrical simulators. The methodology for their development is similar as the one of the standard BSIM model used for transistors, meaning the use of a generic model whose parameters and standard deviations due to process variations are provided by a corner file. SPINTEC was thus pioneer and is now expert in the development of such models. These models have been used many times in different research projects to investigate hybrid circuit's architecture embedding MTJs with CMOS transistors. It includes in particular non-volatile latches and flip-flops, for which several patents have been filled, widely used for registers in microprocessors for instance. This set of models also served to design innovative memory architectures like hybrid Content Addressable Memories (CAM), logic–in-memory circuits such as programmable Arithmetic and Logic Units (ALU) for instance and reprogrammable circuits. In particular, we proposed an innovative hybrid Field Programmable Gate Array (FPGA) for space application resulting in the first functional demonstrator of spintronic logic circuit functional in Europe.

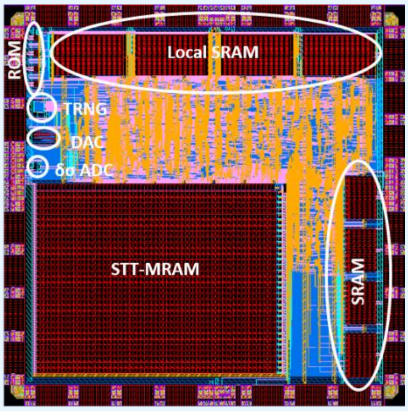


STT-MTJ Electrical simulation using a compact model developed at SPINTEC.

In order to evaluate the benefits of such circuits at application level, it is necessary to bring up these building elements in the digital design flow to allow designing and simulating the full circuit. This requires characterizing these blocks and generating a library for digital simulation, synthesis and place and route operations. It consists of a digital behavioral model as well as characterization files to describe their timing and power features. With this in mind, we proposed the first full hybrid digital design flow, which was used in particular to evaluate the gains in power consumption of a processor made non-volatile thanks to the use of MTJs. From these works, the Spintronics IC design team has developed one of the first analog and digital design flow for hybrid integrated circuits. This enabled the design of basic blocks as well as very complex circuits such as microprocessors, in collaboration with many French and European partners. Using this flow, several demonstrators have been conceived and fabricated in the framework of research projects. The ANR project DIPMEM was focused on design for validation of a hybrid CMOS/Magnetic process developed by SPINTEC in collaboration with CEA-LETI. In the European project SPOT, coordinated by SPINTEC, the purpose was to develop an hybrid CMOS/SOT process. A demonstrator embedding memory blocks was designed, fabricated and tested giving encouraging results. In the framework of the European project GREAT, also coordinated by SPINTEC, a non-volatile microcontroller embedding multi-purpose STT-MTJs in digital and memory parts, as well as magnetic field sensor and RF communication innovative structures. The purpose of this GREAT project was to illustrate the versatility of this technology, which can address digital and analog functionalities, resulting in the first demonstrator of a spintronic microcontroller.

This wide expertise acquired led to the creation of the eVaderis startup in 2014, aiming at designing and fabricating STT-based embedded microcontrolers. This work also opened the way to fruitful collaborations to address the use of spintronics for specific applications. For instance, SPINTEC and CEA-LETI were pioneers in the field of asynchronous spintronics circuits. On this topic, SPINTEC led the NOVELASIC project in 2015 for which several dissemination have been produced and awarded by a best paper award. SPINTEC is also presently coordinating the ANR project NV-APROC supported by four industrial partners (Tiempo IC, Antaios, Sigfox, IDEMIA StarChip). In addition, a tight collaboration with CNES (Centre National d'Etudes Spatiales / national center for space studies) for one decade so far, allowed studying the use of STT and SOT with standard techniques to harden circuits against radiations for space applications, in particular through a test campaign under heavy ions and protons. These studies, published in RADECS and NSREC conferences as well as in the prestigious TNS Journal (Transaction on Nuclear Science), showed for instance an intrinsic radiation robustness against proton irradiation. It also demonstrated a certain robustness in terms of electrical parameters and some magnetic properties variations against heavy ion irradiation. Additional studies need to be performed, on hybrid integrated circuits for instance. The Spintronics IC design team also addressed the field of security/cryptography in collaboration with EMSE, IM2NP and CEA-Tech through the ANR project MISTRAL presently on going. This project aims to experimentally develop secured schemes to protect objects and embedded systems at different levels of the IC: nanofabrication, design, countermeasures in Light Weight Cryptographic (LWC) algorithms. SPINTEC participates in the robustness study to external circuit attacks (Laser and Magnetic Field). We are also proposing different MRAM stacks to increase to global robustness of such circuits. Future studies will focus on several attack experiments.

In the future, the team will expand these studies in two directions. First, we will rely on the foundations built so far to investigate new computing schemes like neuromorphic computing, stochastic computing, In Memory Computing (IMC) or reversible logic, which is currently fast rising in the community. We will also integrate new generations of writing schemes such as Voltage Controlled Magnetic Anisotropy (VCMA) and optical switching or spintronics devices like skyrmions, oscillators to still improve the performance or open the door to new writing schemes thanks to new functionalities.



Layout of the non-volatile microcontroller demonstrator designed, fabricated and tested in the framework of the European GREAT project.

Team: Spintronics IC design

Collaborations: LIRMM, CEA-LETI, C2N, KIT, Crocus Technology, IM2NP, CMP, TowerJazz, CNES, TRAD, EMSE, CEA-Tech.

Funding: French ANR (DIPMEM, MARS, MASTA, NV-APROC), European Commission (SPOT, GREAT), CEA (NOVELASIC, MAD), CNRS.

Further reading: *Beyond STT-MRAM, Spin Orbit Torque RAM SOT-MRAM for High Speed and High Reliability Applications*, Spintronics-based Computing, Springer, Open access: hal-01976635. *Compact Modeling of a Magnetic Tunnel Junction Based on Spin Orbit Torque*, in IEEE Transactions on Magnetics, July 2014, Open access: hal-02010859. *Spin Orbit Torque Non-Volatile Flip-Flop for High Speed and Low Energy Applications*, in IEEE Electron Device Letters, March 2014, Open access: hal-03506992. *Ultra-Fast and High-Reliability SOT-MRAM: From Cache Replacement to Normally-Off Computing*, in IEEE Transactions on Multi-Scale Computing Systems, Jan.-March 2016, Open access: hal-01864485. *Heavy-Ion Irradiation Effects on Advanced Perpendicular Anisotropy Spin-Transfer Torque Magnetic Tunnel Junction*. IEEE Trans. Nucl. Science, 2021, Open access: hal-03255402.

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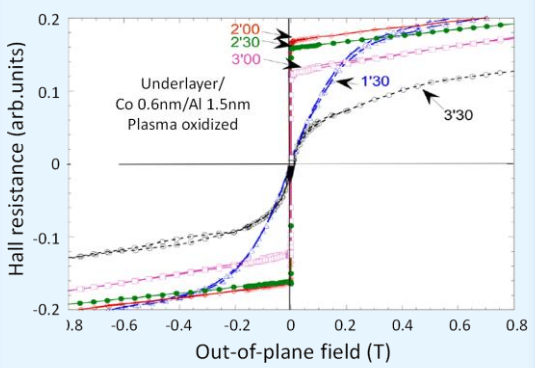
Perpendicular magnetic anisotropy at magnetic transition metal/oxide interfaces

SPINTEC discovered in 2002 that an interfacial perpendicular magnetic anisotropy spontaneously exists at the interface between a magnetic transition metal (e.g. Fe based alloys) and an oxide (AlOx, MgO, TaOx etc). It arises due to electronic hybridization between Fe and O orbitals across the interface. This phenomenon only studied at SPINTEC between 2002 and 2009, is nowadays used in all spintronic devices implementing out-of-plane magnetized magnetic tunnel junctions. It also plays important roles in new fields of research including spin-orbit torques, voltage control of magnetic properties, skyrmions etc.

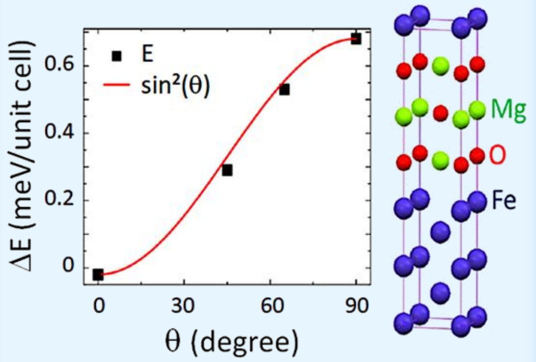
Spin electronics has dramatically expanded over the past 30 years thanks to a strong synergy between basic research and applications (recording, sensors, memory). This evolution has been possible thanks to outstanding progress in the growth and nanostructuration of magnetic multilayered films and particularly of magnetic tunnel junctions, which are crucial elements for applications in microelectronics. While we were optimizing the oxidation conditions for the formation of the tunnel barrier in magnetic tunnel junctions, we discovered in 2002 a phenomenon of particular interest: the existence of a perpendicular magnetic anisotropy (PMA) at magnetic metal/oxide interfaces (Figure 1). This is a very intriguing and fascinating phenomenon. Indeed, magnetic anisotropy was so far believed to occur mostly in materials having large spin-orbit interactions (for instance in Co/Pt multilayers or rare earth based alloys used in permanent magnets). Very surprisingly, the observed anisotropy at magnetic transition metal/oxide interface is arising in a system with quite weak spin-orbit interaction, while the amplitude of this PMA (~1.45mJ/m²) [2,3] is remarkably large, even larger than at Co/Pt interface (anisotropy ~1.4 mJ/m²). Several subsequent studies published by SPINTEC between 2002 and 2009 [3-5] clearly demonstrated that this PMA is associated with the hybridization between the transition metal and oxygen orbitals across the interface. This conclusion was based on detailed X-Ray absorption and photoemission studies. From those, it was established that the interfacial perpendicular anisotropy reaches a maximum amplitude when the growth conditions are such that Co(Fe)-O chemical bonding starts forming across the Co(Fe)/ oxide interface [2,3]. The phenomenon is very general since it was observed with a large variety of oxides (AlOx, MgO, TaOx, HfOx…), either amorphous (AlOx [1]) or crystalline (MgO [2]). The origin of this PMA in terms of electronic hybridization was later confirmed at SPINTEC by ab-initio calculations (Figure 2) [5].



Out-of-plane hysteresis loops (Hall resistance proportional to Mz) measured for Pt 3 nm/Co0.6 nm/Al 1.5 nm after various durations of exposure to an oxygen plasma. The crossover from a slanted loop (1'30min) to square loops (2'00-3'00) indicates the onset of the PMA as the Co/Al interface turns into a Co/AlOx interface. At 3'30 oxidation time, the Co layer starts to get oxidized [1,2].

While between 2002 and 2009 this phenomenon of PMA at magnetic transition metal/oxide was only studied at SPINTEC, it became much more visible following a publication from Tohoku University reporting spin-transfer-torque switching in out-of-plane-magnetized magnetic tunnel junctions (MTJ) in which the out-of-plane anisotropy was precisely induced by the PMA at CoFeB/MgO interface [6]. This study attracted a considerable attention in the context of MRAM research and development. Indeed, for STT-MRAM, out-of-plane magnetized MTJs offer a much better downsize scalability compared to their in-plane counterparts. However, as explained above, perpendicular anisotropy is generally associated with large spin-orbit interaction, implying also large Gilbert damping since the Gilbert damping is also associated with spin-orbit interaction. For spin transfer torque switching, a large damping is detrimental since the current required to switch by STT is proportional to damping. This apparent incompatibility between large PMA and low STT switching current was a fundamental problem in the development of out-of-plane-magnetized STT-MRAM. Fortunately, the use of the CoFeB/MgO interfacial PMA allowed to efficiently circumvent this problem since these interfaces exhibit both high anisotropy and low Gilbert damping. MTJs based on FeCoB/MgO are nowadays commonly used in all STT-MRAM developed and commercialized by companies such as Samsung, TSMC, Global Foundries, Intel etc. These STT-MRAM are used as eFLASH replacement at nodes below 28nm, beyond which eFLASH technology is no longer scalable. The fact that SPINTEC was the only laboratory worldwide working on this interfacial PMA phenomenon between 2002 and 2009 allowed us to file several key patents related to this phenomenon and its use in spinelectronic devices.

Besides, this interfacial PMA phenomenon is also interesting for several other research areas that have emerged in the past ten years and have now become very active topics of spintronics research [7].



Ab-initio calculation of the angular dependence of the magnetic anisotropy energy in Fe/MgO, where ϑ is the angle between the magnetization direction and the normal to the interface plane. Unit cell used in the calculation [5].

-Comparatively to films based on Co/Pt multilayers, PMA films based on Co(Fe)/oxide happen to exhibit much weaker magnetic pinning, with coercive field of a fraction of mT instead of hundreds of mT in systems based on Co/Pt interfaces. This makes them very interesting for devices based on spin textures propagation. Record values of domain wall speeds were obtained in such systems.

-The interfacial magnetic metal/oxide PMA can be tuned by applying a voltage across the oxide layer. Indeed, the electric field penetrates sufficiently inside the magnetic layer to influence the electronic band filling around the interface. Since the PMA has an interfacial origin, this effect is large enough to yield a significant modulation of the PMA as a function of the bias voltage. This opens a unique way to manipulate the magnetic properties in thin films with voltage instead of current, with much reduced energy. This approach could lead to magnetic memories with much reduced power consumption than STT-MRAM.

-The electric field that spontaneously exists at a magnetic metal/oxide interface due to charge transfer between the metal and the oxygen atoms leads to an interfacial Rashba effect. This effect can be used to switch the magnetization of the magnetic metallic layer or to generate steady state magnetic excitations with an in-plane current in three terminal magnetic tunnel junctions. These devices may lead to fast and low power memories (spin-orbit torque memory, SOT-MRAM) and logic devices.

Teams: MRAM, Theory / Simulation, Materials-Nanofabrication-Instrumentation

Funding: ERC HYMAGINE, ERC MAGICAL

Further reading: (1) *Crossover for in-plane to perpendicular anisotropy in Pt/CoFe/AlOx as a function of the Al degree of oxidation: a very accurate control of the oxidation of tunnel barrier*, S.Monso, Appl.Phys.Lett.804157 (2002). (2) *Analysis of anisotropy crossover due to oxygen in Pt/Co/MOx trilayer*, A. Manchon et al, J. Appl. Phys. 104, 043914 (2008). (3) *Influence of thermal annealing on the magnetic properties of Pt/Co/AlOx trilayers*, B. Rodmacq et al, Phys. Rev. B 79, 024423 (2009). (4) *Pt/Co/oxide and oxide/Co/Pt electrodes for perpendicular magnetic tunnel junctions*, L. E. Nistor et al, Appl. Phys. Lett. 94, 012512 (2009). (5) *First-principles investigation of the very large perpendicular magnetic anisotropy at Fe|MgO and Co|MgO interfaces*, H. X. Yang et al, Phys. Rev. B 84, 054401 (2011). (6*) A perpendicular-anisotropy CoFeB–MgO magnetic tunnel junction*, S. Ikeda et al, Nat.Mat.9, 721 (2010). (7) *Perpendicular magnetic anisotropy at transition metal/oxide interfaces and applications*, B.Dieny et al, Rev. Mod. Phys. 89, 025008 (2017).

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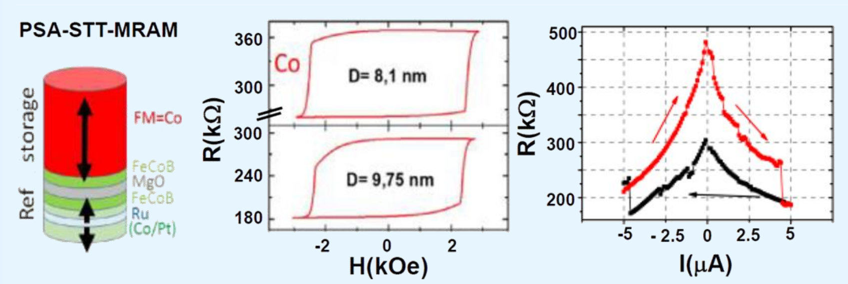
Towards sub-10 nm MRAM with perpendicular shape anisotropy

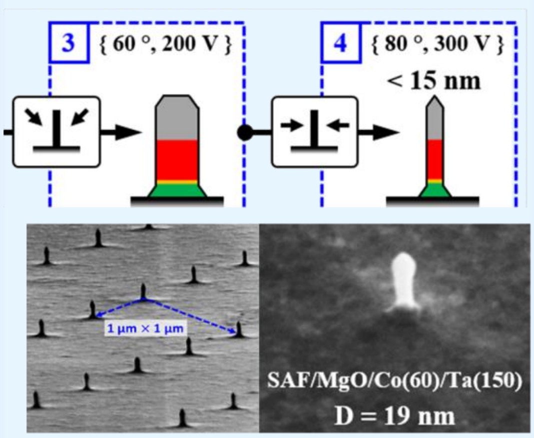
In conventional spin-transfer-torque (STT) magnetic random access memory (MRAM), lateral size reductions lead to limited storage retention. We proposed and validated a new MRAM cell concept using shape anisotropy suitable to achieve high retention at sub-10nm critical dimensions. In this concept, the thickness of the storage layer is significantly increased to values comparable to the cell diameter. A further advantage of perpendicular shape anisotropy is to be a robust source of bulk anisotropy less sensitive to temperature, while in conventional MRAM, the thermal sensitivity of the interfacial anisotropy is a limitation to MRAM applications requiring a wide range of operating temperatures.

Magnetic MRAM memories are entering volume production at major microelectronics foundries, as a replacement for embedded FLASH memories. Having contributed significantly to the development of the spin transfer MRAM technology (STT-MRAM) since 2008, we now propose advanced memory concepts to prepare future generations of MRAM. We are studying how to overcome physical and technological challenges regarding their density, write speed, endurance and power consumption. Lifting these barriers will allow applications as fast memories (SRAM cache) or even dense random access memories (DRAM).

Presently, conventional perpendicular MRAM cells have diameters over 20nm using CoFeB electrodes and MgO tunnel barriers in the stack. The thickness of the magnetic storage layer is typically between 1.4 and 2.5 nm. In such a stack magnetization remains stable out-of-plane thanks to the MgO/CoFeB interface, which provides the so called interfacial Perpendicular Magnetic Anisotropy (iPMA). The magnitude of the iPMA is important since it determines the thermal stability factor of the MTJ, defining the retention time of a stored bit in an MRAM cell. However, interface anisotropy alone does not provide enough thermal stability when the surface are of the cell reduces with diameter below 20nm. A concept providing a solution to downscale the diameter of MRAM cells to sub-10nm dimensions based on Perpendicular Shape Anisotropy MRAM has been independently introduced by SPINTEC and Tohoku University (PSA-STT-MRAM). It consists in increasing the thickness of the storage layer to values comparable to its diameter. This leads to a vertical shape anisotropy that adds up to the perpendicular anisotropy of the MgO/FeCoB interface.



Quasi-static measurements demonstrate the stability, as well as field- and current-induced switching by spin transfer torque for PSA stacks based on a 60 nm thick Co storage layer. The cell diameter is estimated from the electrical resistance of the tunnel junction.

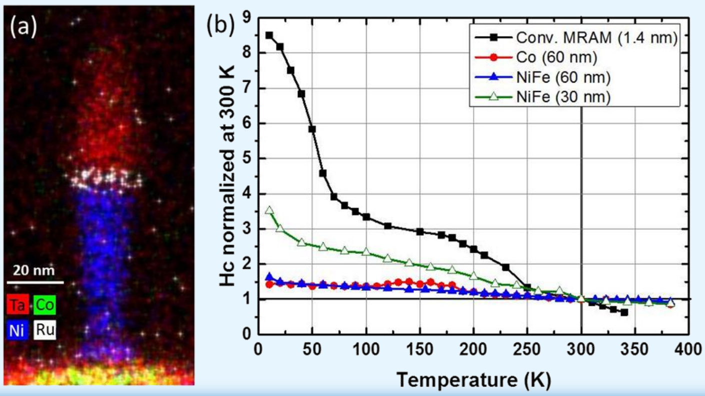


Ion beam etch sequence to trim the cell lateral size. Array of cells having sub-20nm sizes as observed by scanning electron microscopy.

The realization of these scalable cells required the development of a new process flow to fabricate cells below the E-beam lithography resolution. This was achieved by employing Ion beam etching at grazing incidence, reducing the cell diameter from around 30-50nm down to sub-10nm dimensions. The tunnel junction fabrication first proceeds in the usual etch sequence. The ion beam etch angle is then lowered to 10° from the wafer surface to laterally trim the cell diameter. The trim etch speed and time need to be controlled to achieve the desired dimensions after the initial scanning electron microscopy (SEM) measurement of the cell diameter. As can be observed in the first Figure, the fabricated cells have well-defined resistance states at zero field and these states are stable in a large field range. This new concept of

MTJ based on Perpendicular Shape Anisotropy (PSA) changes the final shape of the storage layer to become a cylinder instead of a disk. The resulting devices have typical thick storage layers 12 to 60 nm and diameters around 10nm. This geometry results in a natural perpendicular anisotropy arising from the shape. This anisotropy adds to the interface anisotropy and reinforces the total perpendicular anisotropy of the cell. Sub-10nm cells show coercive fields above 2 kOe necessary to reverse the stored state, increasing as the lateral dimension is reduced. Despite the unusual thickness of the storage layer, PSA MRAM could still be written by electrical current pulses as in conventional MRAM using spin transfer torque. Full electrical operation was also demonstrated by switching between the stable resistance states, the low or high resistance state is set by the current polarity. Memory cells with diameter 5nm and stable at 300K were realized, which could be switched with an extremely low current of 5uA.

PSA MRAM addresses another limitation of conventional MRAM, which is inherent to the temperature sensitivity of the interface anisotropy. This temperature dependence is a limiting factor for applications requiring a wide range of operating temperatures. This is the case in automotive applications with operation temperature requirements from as low as -40°C up to +150°C. Another stringent foundry process step is related to the retention of stored information during a solder reflow step (260°C for 1 minute), which is generally required in microcontroller applications. In our PSA MRAM stacks, the temperature evolution of the coercive field in a wide range from 10 K to 380K shows significant differences with conventional perpendicular interface anisotropy MRAM. In the operating range at room temperature and above, conventional MRAM loses stability rapidly. This is not the case for PSA, where the density of thermal fluctuations along the MgO/CoFeB interface at increasing temperature is reduced by magnetic stiffening associated with the use of thicker storage layers from high-Curie-temperature materials. This also yields a weaker thermal variation of the TMR ratio compared to conventional p-STT-MRAM devices. In terms of applications, the robustness of magnetic and transport properties against thermal variations thanks to the PSA concept can be used to enable operation on a wide temperature range.



(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 the 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).

The development of perpendicular shape anisotropy MRAM has provided a scalable cell to sub-10 nm dimensions. Further benefits of the technology are its lower temperature dependence and stability to thermal variations. This enables operation on a wide range of temperatures, as for instance for automotive applications, or to fulfill solder reflow compliance.

Teams: MRAM, Theory / Simulation

Funding: MAGICAL (H2020-ERC Advanced Grant)

Further reading: *A highly thermally stable sub-20 nm magnetic random-access memory based on perpendicular shape anisotropy*, N. Perrissin et al., Nanoscale, 10, 12187–12195, (2018), *Open access: hal-01824092*. *Thermal robustness of magnetic tunnel junctions with perpendicular shape anisotropy*, S. Lequeux et al., Nanoscale, 12, 6378–6384, (2020), *Open access: hal-03111525v1.*

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Ultrafast all-optical switchable magnetic tunnel junctions for spintronic-photonic memory

The development of magnetic-tunnel-junctions-based MRAM memories calls for technological breakthroughs intended to go well above the GHz operation speed, to match the speed of the processor. A very promising solution combines the spin-photon interaction, which enables the ultrafast reversal of the storage layer magnetization under the action of a laser pulse of few tens of fs duration. In the framework of the H2020 project called SPICE, SPINTEC demonstrated a conceptually new spintronic-photonic memory chip demonstrator with faster speed and lower energy consumption, as a cornerstone of a novel integration platform that combines photonic, magnetic and electronic components.

In the ongoing Big Data revolution, the semiconductor industry faces major issues associated to the energy cost and time delay of transferring data between the processor cores and the multiple levels of memory. While the microprocessor unit is running in the GHz range, the main external memory (DRAM) is very slow. To speed up operations, cache memories based on SRAM (static RAM) are inserted between the processor and DRAM to fill this so-called “memory gap”. SRAMs are very fast but have a large footprint and are volatile, which means that they require to be constantly powered and thus consume energy to retain information. With the downscaling of SRAM, this has become a major issue as the CMOS transistor current leakage has led to a large increase in the standby power consumption. As pointed by the ITRS, one of the best solutions to stop this trend is the modification of the memory hierarchy by the integration of non-volatility as a new feature of memory caches, which would immediately minimize static power as well as pave the way towards normally-off/instant-on computing. The development of an electrically-addressable non-volatile memory combining processor speed, infinite endurance and a higher-than-SRAM density is a crucial step towards higher performance and more energy-efficient computing platforms. MRAMs can be an alternative solution thanks to their non-volatility, low energy consumption, high endurance and their compatibility with CMOS processing. Yet, in order to reach the processor and cache level, MRAM has to be written at pulse durations in the range of pico-and femto-seconds.

An interesting trend that improves the write speed and power of MRAMs is the discovery of magnetization reversal by femtosecond laser pulses. This is a conceptually new way to control the magnetic state of a system, at the highest efficiency and shortest possible time-scale. 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. In the framework of the H2020 project SPICE SPINTEC demonstrated a conceptually new spintronic-photonic memory chip demonstrator with faster speed and lower energy consumption, as a cornerstone of a novel integration platform that combines photonic, magnetic and electronic components. The potential and envisaged benefits of this concept are the fast magneto-optical switching at low energy per bit, the non-volatility of the MTJ memory, and the low latency, and high bandwidth and bandwidth density of the optical network.

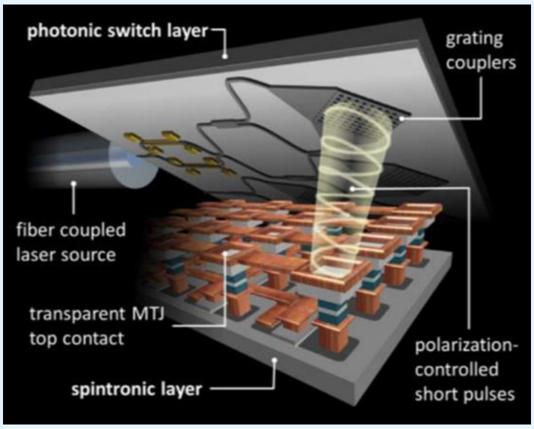

Figure 1: Schematic view of a hybrid spintronic-photonic demonstrator for ultrafast magnetic memories.

Unifying spintronics and photonics in the same nanosized element replies on a wise choice and combination of materials with unique electric, magnetic and optical properties. The magneto-electric response of the junction needs to be sufficiently large to insure a reliable reading operation. The data retention implies the use of full perpendicular magnetic stacks while the storage layer has to be switchable by fs to ps laser single pulse.

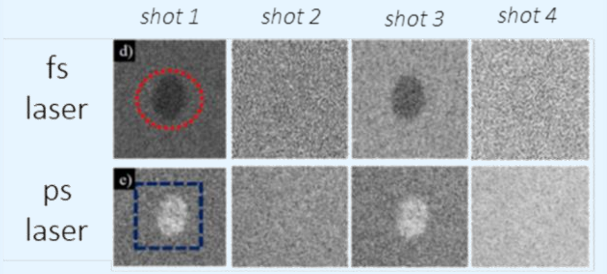

Figure 2: Proof of concept of the single shot all-optical switching of T/Co based magnetic tunnel junctions.

To achieve these ambitious goals, we have developed perpendicular magnetic tunnel junctions incorporating [Tb/Co] based electrodes, and we have demonstrated single-shot helicity-independent all-optical switching using ps- and fs-long single laser pulses. Toggling of the magnetization was observed using both 60 femtosecond- and 5 picosecond-long. The experimental results have been analyzed in the frame of atomic model coupled with a 2-temperature model.

Finally, we have realized the first worldwide integrated spintronic-photonic demonstrator by combining a spintronic chip having 8 inline MTJ-based memory elements with a photonic chip. These results represent a breakthrough for the development of perpendicular magnetic tunnel junctions controllable using single laser pulses. They offer a technologically-viable path towards the realization of hybrid spintronic-photonic systems featuring THz switching speeds.

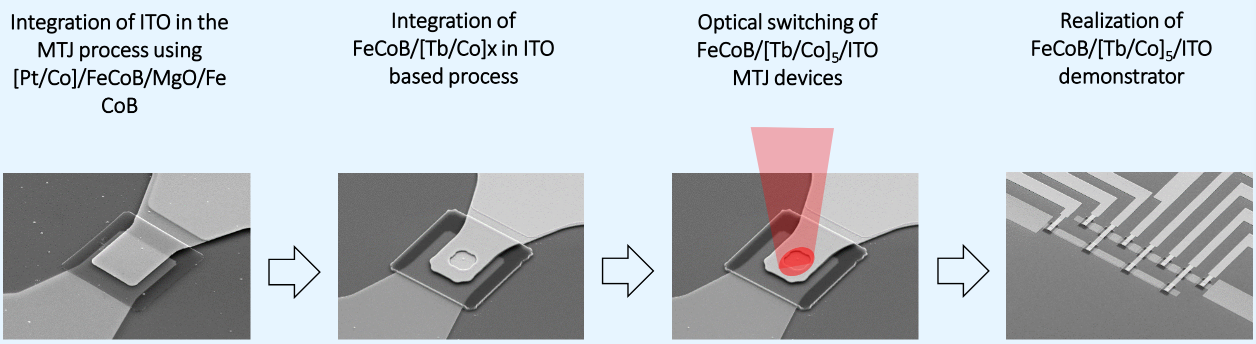

Figure 3: different technological steps for the development of an integrated spintronic-photonic demonstrator.

Teams: MRAM, Theory / Simulation, Materials-Nanofabrication-Instrumentation

Collaboration: Radboud University, Aarhus University, IMEC, Université de Lorraine

Funding: SPICE (FET-Open), COMRAD (H2020-MSCA-ITN) and UFO (ANR)

Further reading: *Integration of Tb/Co multilayers within optically switchable perpendicular magnetic tunnel junctions,* L Avilés-Félix et al., AIP Advances 9, 125328 (2019), *DOI: 10.1063/1.5129821*. *Single-shot all-optical switching of magnetization in Tb/Co multilayer-based electrodes,* Avilés-Félix et al., Sci Rep 10, 5211 (2020), *Open access: hal-03111530*. *Indium Tin Oxide (ITO) optical access for magnetic tunnel junctions in hybrid spintronic–photonic circuits*, A. Olivier at al.,Nanotechnology (2020), *DOI:10.1088/1361-6528/ab9c56*. *All-optical spin switching probability in [Tb/Co] multilayers*, L. Avilés-Félix et al., Sci. Rep. 11, 6576 (2021), *Open access: hal-03186985*.

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From noise study to magnetic sensor optimization

The Magnetic Sensor team of SPINTEC aims at conducting upstream research on physical phenomena potentially useful for future sensors, as well as developing expertise to support industrial sensor R&D. By performing fundamental physics research, the team has acquired a recognized expertise on noise, with leading results at the international level. Moreover, during a 6 years collaboration with Crocus Technology, the team has succeeded in improving the performance of magnetic field sensors by 2 orders of magnitude and has proposed innovative solutions to optimize vortex-based sensors. The acquired expertise is now used to develop a sensor for space exploration in collaboration with the LPC2E laboratory and the French space agency.

The demand for miniature magnetic sensors is growing rapidly in industry, for automotive and mobile applications. This growing market benefits many European companies: Bosch, Infineon & Sensitec (Germany), Micronas (Switzerland), Melexis (Belgium), Sensonor (Norway)... Spintronic devices have a huge potential for these sensor applications, as they can be easily integrated in chips, and have a higher versatility and sensitivity than Hall effect semiconductor sensors. By engaging in the research, development and optimization of magnetic tunnel junctions (MTJs) for sensors, SPINTEC can leverage its expertise in tunnel junctions as well as in noise measurement and analysis. Improving sensor performance requires considering various design aspects such as dynamic range, linearity, sensitivity and temperature stability. Above all, enhancing the signal-to-noise ratio is a major issue. Therefore, understanding the physical origin of noise, *i.e.*, its link with physical phenomena at the microscopic scale, is a prerequisite to reduce noise in devices. Our team has successfully performed various studies and obtained major results in this area.

One of the studies was devoted to shot noise in magnetic tunnel junction, which is directly linked to the existence of a probabilistic phenomenon: the flow of electrons through the barrier is a quantum effect, thus obeying a probability law. At the time, studies of shot noise in magnetic tunnel junctions published in the literature showed a shot noise smaller than the expected theoretical value. This incomplete shot noise was due to *indirect* tunneling of electrons via states in the insulator gap, and thus was a direct signature of the presence of defects in the tunnel barrier. At SPINTEC, we measured the shot noise at high frequency in the saturated magnetic state, and we were among the first to measure the theoretical value of shot noise in good-quality magnetic tunnel junctions with Al_2O_3 barriers.

A second and most important study addressed the question of noise due to thermal fluctuations of magnetization. In spintronic systems under low magnetic field, these fluctuations are responsible for the dominant source of noise. This is especially true at low frequency ($1/f$ noise); nevertheless, magnetization fluctuations give also rise to a noise peak in the GHz range, at the ferromagnetic resonance (FMR). By measuring this noise peak in a magnetic tunnel junction under various positive and negative currents, we were the first to observe and model the influence of subcritical spin-transfer torque on the magnetic thermal noise. We experimentally observed that spin-transfer torque either quenches or enhances thermally-activated FMR excitations, depending on the current sign. Our experiment was the first demonstration of a measurable effect of spin-transfer torque below the critical current.

Our expertise on noise was beneficial for Crocus Technology in their development of magnetic field sensors. A first joint study aimed at optimizing the performances of sensors based on MTJs. In these sensors, the sense element is a uniformly-magnetized layer within the junctions. The objective was to reduce noise in junction arrays to improve the sensor detectivity, which corresponds to the detection threshold of the sensor. Increasing the total volume of magnetic cell through thickness or lateral size is a known route to reduce the $1/f$ noise, by a statistical averaging. A difficulty is that increasing the volume of the free (sense) layer of a MTJ can lead to the appearance of magnetic domains or to the loss of coherent rotation. These physical phenomena can impose a limit on the maximum size of the magnetic dot. On the other hand, it is always possible to increase the number of junctions in a series/parallel array. Using this strategy, the team has demonstrated an improvement of two orders of magnitude in sensor detectivity with a proper choice of junction diameter, free layer thickness and number of junctions (Fig. 1). Nevertheless, there remains a limitation in increasing the free layer thickness and an optimal limit is reached around 20 nm, probably due to the appearance of an inhomogeneous micromagnetic structure within the layer thickness. For thicker cells, the low energy magnetic state is no longer a uniform magnetization but a vortex state, which led to a new research direction. In this configuration, magnetization is orthoradial, circling around a vortex core. At zero field, the vortex core is at the center of the dot. Under in-plane magnetic field, the vortex is expected to move along a direction perpendicular to the applied field, resulting in a linear variation of the magnetization, in turn giving rise to a linear response of magneto-resistance. Potentially, this linear response could be considered to develop a magnetic sensor. Experimentally, however, we have observed that the vortex core can be pinned by defects in the material, which results in a "jerky" displacement when the external magnetic field varies. But the most detrimental impact of this pinning is that there are two possible response curves of the sensor depending on the path taken by the vortex core during field sweep, for example either from right to left or from left to right. To obtain a single response, we have shown that it is possible to cut out a notch on the edge of the dot that will serve as a nucleation center for the vortex. This favors a single path for the vortex core, starting from the notch to the opposite side. This solution has proven its effectiveness and has led to the filing of a patent on the use of asymmetric dots. This concept can be combined with the statistical averaging in arrays implemented on standard sensors. Finally, the use of elliptical dots with an adequate form factor results in the elimination of the residual hysteresis linked to the missing material in the notch, and further improves the linearity of the sensor response, without loss of sensitivity (Fig. 2).

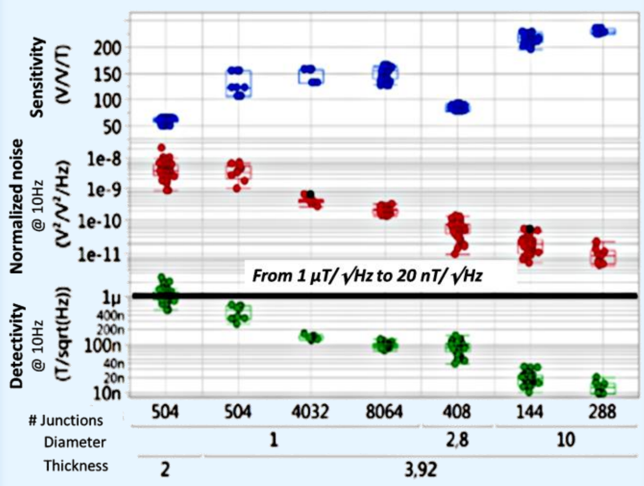

Fig 1. Progress in decreasing detectivity while increasing sensitivity, by increasing the magnetic cell volume and the number of junctions in the array (normalized parameters).

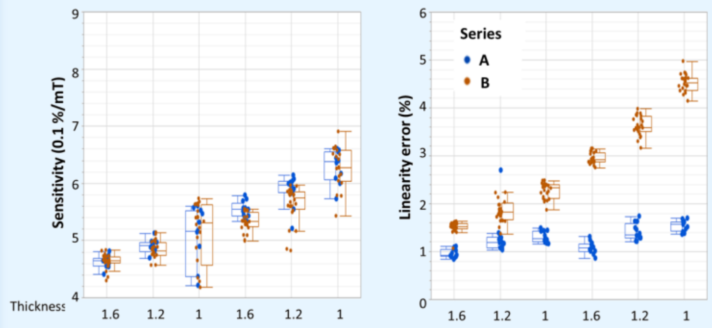

Fig. 2. Increase of the sensitivity (left) without damaging the linearity (right) for A series (blue dots) in elliptic vortex sensors.

Team: Magnetic Sensors

Collaborations: LPC2E, Crocus Technology, Institut Néel, Chemnitz University, IJL, LPSC, Osaka University, C2N, LMC, LPCNO

Funding: CNES R&T, French ANRT (CIFRE), European Commission (ATTRACT), CNRS (Instrumentation aux limites, Programme de prématuration), French ANR (ADMIS, ELECSPIN).

Further reading: *Spin-Torque Influence on the High-Frequency Magnetization Fluctuations in Magnetic Tunnel Junctions,* in Phys. Rev. Lett. (2007), Open access: hal-01636635. *Influence of spin-transfer torque on thermally activated ferromagnetic resonance excitations in magnetic tunnel junctions*, in Phys. Rev. B, 2008, Open access: hal-00997277. Correlation between write endurance and electrical low frequency noise in MgO based magnetic tunnel junctions, in Applied Physics Letters, February 2013, Open access: hal-00852046. *High Sensitivity Magnetic Field Sensor for Spatial Applications*, in IEEE Sensors Applications Symposium Proceedings, April 2016, Open access: hal-01959900. *Dispositif de mesure de champs magnétiques faibles*, Patent FR3068476 – 2019. *Elément magnétique comportant une plage de mesure améliorée,* Patent *WO2020217195 – 2020*

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Spin Orbitronics: from fundamental studies to Antaios start-up creation

The spin-orbit coupling to the crystal lattice generates very rich physical mechanisms, which can notably offer a new source of spin polarization, exploitable to manipulate the magnetization via more efficient torques. During the last 10 years, the SPINTEC laboratory has conducted several pioneering studies in this field, revealing the existence of these spin-orbit torques (SOT) and their efficiency. These studies started on the current-induced domain wall (DW) motion, and eventually led to the demonstration of the switching of magnetization of a nanopillar using a largely sub-ns (180ps) current pulse injected into the plane of the layers. These results had a huge impact in the academic community, giving birth to the spin-orbitronics research field, and in the industrial community through the development of a new MRAM technology, the SOT-MRAM. It is being developed by the company Antaios, spun off from SPINTEC in 2017.

The story began with the study of the current-induced DW motion in perpendicularly-magnetized materials. Even though this manipulation was the basis of many promising proposals for storage and logic devices, it proved to be experimentally extremely inefficient. We became interested in this problem around 2010 by focusing on stacks with structural inversion asymmetry (SIA). This structural symmetry breaking in magnetic materials has been revealed to be responsible for a variety of exceptional physical phenomena. Using a Pt/Co/AlOx ultrathin tri-layer, we demonstrated remarkable DW manipulation efficiencies with record DW speeds around 400m/s. We explained these results by revealing the primordial role of the spin-orbit interaction in particular through the generation of very efficient torques acting on the magnetization. The broad impact of this discovery is the following. In Spin-Transfer-Torque mechanisms, DW motion or current-induced magnetization reversal is achieved via the transfer of angular momentum from a spin polarized current to a ferromagnet. In STT-MRAM, this current is prepared by passing through an adjacent ferromagnet. Spin-orbit torques (SOT) and SIA provide an alternative way to produce a spin polarized current and spin torques. Contrasting with STT, in SOT the angular momentum comes directly from the crystal lattice.

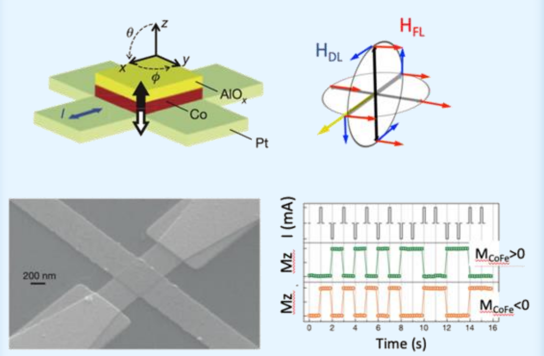

Fig. 1. The first observation of magnetization reversal driven by SOT. The magnetic Co/AlOx dot is trimmed on top of a Pt Hall bar. Two permanent magnets are added (SEM image) on top of the current injection line. The generated in-plane magnetic field breaks the mirror symmetry and allows the current pulse-induced magnetization switching. This reversal switch is bipolar both with the current and the in-plane magnetic field.

The next step was to quantify these torques. Using the same Pt/Co/AlOx ultrathin tri-layer, we revealed the existence of two SOTs. The first is equivalent to the presence of an effective in-plane magnetic field perpendicular to the current direction, the now-called field-like component (FL) (Fig.1, blue arrow). The second term, the damping-like component (DL), appears as an effective magnetic field $\mathbf{H}_{\mathrm{DL}} \sim \mathbf{m} \times \mathbf{u}_y$ where $\mathbf{u}_y$ is in-the-plane perpendicular to the current direction. It is equivalent to a constant torque oriented in-plane, perpendicular to the current (blue arrow in Fig.1). Our most important result was the demonstration, based on these torques, of the bipolar reversal of the magnetization of a perpendicularly magnetized magnetic dot (Pt/Co/AlOx) by means of a current injected in the plane of the layers (Fig.1). We quantified both torques accurately using low-frequency magneto-transport measurements. Their amplitude strongly depends on the nature of the heavy materials and the interface. The origin of these torques has been highly debated in the following years, involving the spin Hall effect induced by the current flowing in the bulk of the heavy metal and the Rashba spin orbit coupling at the interfaces.

Besides its fundamental interest, SOT-induced magnetization switching has led to a novel concept of a three-terminal magnetic memory device named the SOT-MRAM. In this memory technology, the magnetic bit is written by a current pulse injected through the bottom metallic electrode, while a magnetic tunnel junction (MTJ) is used to read the state of the magnetic bit. The key advantage of the SOT-MRAM is that the write and read operations are decoupled thanks to the different current paths, which elegantly solves the problems related to endurance and read disturbance of the STT-MRAM (Fig.2, top left). We have demonstrated the first proof of concept of a perpendicular SOT-MRAM cell (Fig.2, right) as well as sub-ns write operation. These results open a new way to develop three-terminal non-volatile magnetic memories with perpendicular magnetization, which can combine fast and low energy writing with high endurance.

In this vision, and based on the patents filed by Spintec on the core technology, the company *Antaios* was spun-off from Spintec in 2017 by J.-P. Nozières (CEO), G. Gaudin, W. Kula, J.-P. Bost and M. Drouard. Before it was even officially incorporated, Antaios won France's prestigious i-Lab 2016 Grand Prize, funded by the Ministry of Higher Education, Research and Innovation and supported by the Innovation and Industry Fund. The objective of Antaios is to develop the SOT-MRAM technology for the replacement of both embedded Flash and embedded SRAM to allow high performance with low-power consumption for application such as: edge AI chips, Internet of Things, Microcontrollers XIP, Image sensors/Display Controllers and Data Storage. Antaios' business model is to develop the technology, and then to license its intellectual property to major industrial companies, such as IDM and foundries. Antaios raised $11 million in 2020 to accelerate its development. In addition to the licenses on the 6 core patents filled at Spintec, it already holds 15 new patents of its own. Currently composed of 15 people, the company is expected to reach up to 20 people in 2022.

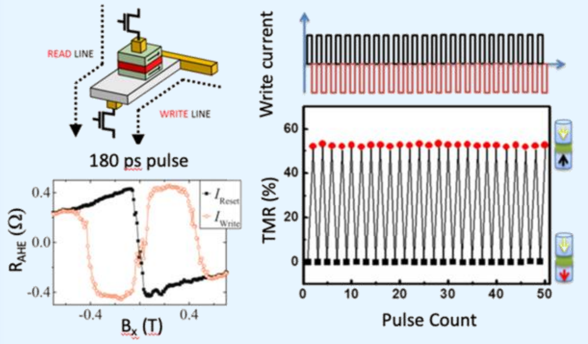

Fig. 2. Top-left: schematics of a SOT-MRAM. Right: Tunneling Magneto-Resistance vs write current pulses of a perpendicular three terminal MTJ (Ta/FeCoB/MgO/FeCoB). Bottom-left: Anomalous Hall resistance vs in-plane magnetic field showing the magnetization reversal induced by a 180ps long current pulse.

The story doesn't end there. For example, our works on DWs has revealed a chiral energy term, the Dzyaloshinskii-Moriya interaction (DMI) and, more recently, a chiral damping term. DMI in particular has allowed to revisit the idea of the structure of DWs and to reveal new magnetic objects, the skyrmions, which have emerged as a new branch of research at SPINTEC and is many other laboratories worldwide. These different developments and results have had a major impact both in the academic community and in the industrial field. Thus, almost all of the spintronics laboratories are currently working in the vast field opened up by this research. From an industrial point of view, the SOT-MRAM technology is now part of the spintronics roadmap and Antaios' competitors are major players in the field as shown by the communications in dedicated conferences, and the numerous patents filed and already published by these companies.

Teams: Spin Orbitronics, Theory / Simulation, Support Group

Collaboration: ICN Barcelona ; ETH Zürich ; Institut Néel, Forschungszentrum Jülich, Singulus Technology

Funding: ANR-10-BLANC-1011-3 'SPINHALL' ; FP7-ICT GA 318144, "spOt" ; FP7-PEOPLE-012-CIG "Sport for Memory" ; ANR-13-BS10-0005 "SOSPIN"

Further reading: *Fast current-induced domain-wall motion controlled by the Rashba effect*, Nature Materials 10, 419 (2011). DOI: 10.1038/nmat3020. *Current-driven spin torque induced by the Rashba effect in a ferromagnetic metal layer*, Nature Materials 9, 230 (2010), Open access hal-00459160. *Perpendicular switching of a single ferromagnetic layer induced by in-plane current injection*, Nature 476, 7359 (2011), Open access: cea-00903394. *Symmetry and magnitude of spin-orbit torques in ferromagnetic heterostructures*, Nature Nanotechnology 8, 587 (2013), DOI: 10.1038/nnano.2013.145. *Spin-orbit torque magnetization switching of a three-terminal perpendicular magnetic tunnel junction*, Appl. Phys. Lett. 104, 042406 (2014), arXiv: 1310.8235. *Ultrafast magnetization switching by spin-orbit torques*, Appl. Phys. Lett. 105, 212402 (2014), Open access: hal-02042391. *Ultra-Fast Perpendicular Spin-Orbit Torque MRAM*, IEEE Trans. on Magn. 54, 9300204 (2018), Open access: hal-01865470.

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Anatomy of spin-orbit phenomena in nanostructures: metals, oxides, 2D materials

Interfacial Dzyaloshinskii–Moriya interaction (DMI) in magnetic nanostructures have gained much attention in recent years since they play a major role in the formation of chiral magnetic structures. We have developed a first-principle-based methodology that allows elucidating the microscopic mechanisms of the Dzyaloshinskii-Moriya interaction (DMI) at the FM/NM, FM/Ox and FM/2D interfaces (FM, NM, Ox and Gr representing a magnetic metal, a non-magnetic heavy metal, oxide and two-dimensional materials). Our results help optimizing material combinations for maximizing and controlling DMI providing in particular a guidance for experiments performed at SPINTEC and worldwide on exploring chiral magnetism.

Among spin-orbit phenomena, Dzyaloshinskii–Moriya interaction (DMI) in magnetic nanostructures traditionally composed of metals and/or oxides have gained much attention in recent years since they play a major role in the formation of chiral magnetic structures, such as domain walls, 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), hexagonal boron nitride (h-BN) and 2D magnets are appealing as novel materials with exceptional properties that could replace conventional ones and open new prospects for information technology. During the last decade, we proposed a theoretical methodology based on first-principle calculations that allows clarifying microscopic mechanisms of DMI through the evaluation of orbital- and layer-resolved contributions to the total values of these phenomena, in stacks comprising FM/NM, FM/Ox and FM/2D interfaces [1-4].

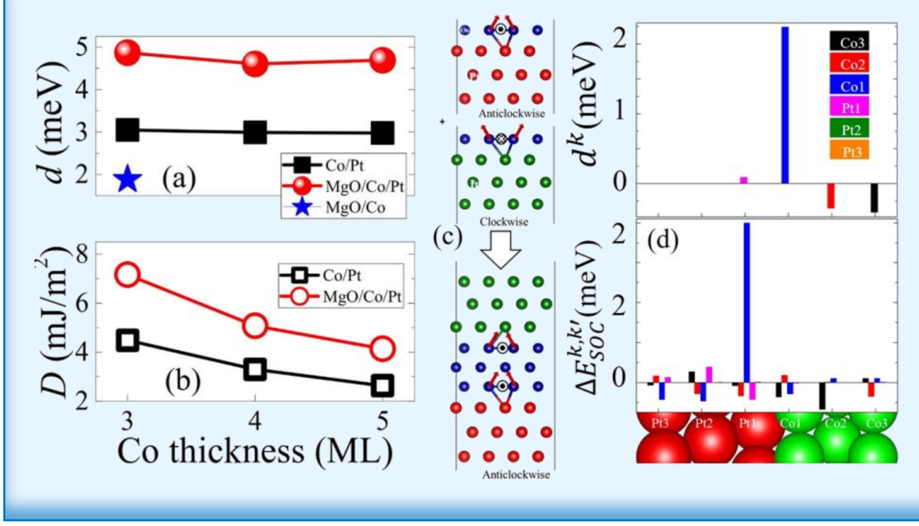

Figure 1. Dependence of the (a) microscopic and (b) micromagnetic DMI constants in Co/Pt, MgO/Co/Pt and MgO/Co structures as a function of Co thickness. (c) Schematic of enhanced DMI design in NM1/FM/NM2 trilayers using FM/NM1 and FM/NM2 bilayers of opposite chirality. (d) The microscopic constant of DMI in Co/Pt and corresponding localization of the associated energy source SOC resolved by layer [1,2].

First, we considered FM/NM [1] and Ox/FM/NM stacks [2]. Using our anatomy technique that allows resolving layer and orbital contributions of both DMI and spin-orbit coupling (SOC), we have unveiled different microscopic DMI mechanisms. Namely, the DMI between the Co spins at metallic Co/Pt interfaces is of Fert-Levy type, as its main contribution is entirely localized at interface but is associated with SOC in the adjacent atomic layer of Pt (Fig. 1d). A qualitatively different scenario of DMI occurs at FM/Ox interfaces, such as Co/MgO, where the SOC associated with DMI between interfacial Co spins originates from the interfacial dipole and can be attributed to the Rashba-type [2]. These findings helped explaining the further enhancement of the already significant DMI at the Co/Pt interface in MgO/Co/Pt structures [3], indicating an opposite contribution from the MgO/Co interface (Fig. 1a-b). Based on the same principle, the DMI can be also enhanced by sandwiching a FM layer between NM layers inducing additive DMI in NM1/FM/NM2 structures (Fig. 1c), or by using a FM layer comprising Fe and Co layers, *i.e.*, Ir/Fe/Co/Pt [2]. These results played an important role for the experimental demonstration of skyrmions both at SPINTEC and by other groups abroad [3].

Similar to the FM/ox case, we demonstrated that a graphene/ferromagnetic metal interface generates significant DMI of the Rashba type for a graphene-coated single atomic layer of Co (Fig. 2a) [4]. Experimental measurements of DMI in graphene/Co by means of SPLEEM on [Co/Ni/graphene]$_n$ are in very good agreement with our theoretical predictions. Based on these results we proposed heterostructures allowing the simultaneous enhancement of the DMI and PMA (Fig. 2c), based on our previous findings of graphene coating for PMA [5]. Furthermore, our technique predicted a significant Dzyaloshinskii-Moriya interaction (DMI) in a series of Janus monolayers [6] such as 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 (Fig. 2d). In particular, the DMI amplitudes of MnSeTe and MnSTe are comparable to those of state-of-the-art ferromagnet/heavy-metal heterostructures. We have also found that the ground states of the MnSeTe and

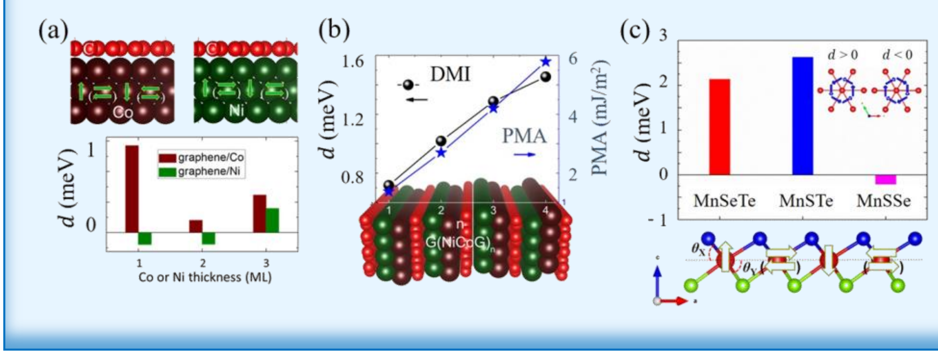

Figure 2. (a) Crystal structures, spin configurations and DMI as a function of metallic layer thickness (b) DMI and PMA for Gr/[Co/Ni/Gr]$_n$ multilayers as a function number of repetitions n. (c) DMI for MnXY (X,Y=S, Se, Te, X≠Y) Janus monolayers [4,6].

MnSTe monolayers can transform from ferromagnetic states with wormlike magnetic domains into the skyrmion states by applying an external magnetic field (Fig. 2d).

The calculation methodology developed helped also clarifying mechanisms of DMI in other 2D materials based systems [7], including their control by voltage, *i.e.*, VCDMI [2], or via hydrogenation [8]. This methodology is now employed by different groups around the world, and helps optimizing materials for experimental guidance towards next generations of spintronic devices.

Teams: Theory / Simulations, Spin-orbitronics, 2D Spintronics

Collaboration: CNRS/Thales, LPS, I. Néel, NIMTE (China), LBNL, Georgetown (USA), CDTN, UFMG (BR)

Funding: EU GRAPHENE FLAGSHIP, ANR SOSPIN, ANR ELECSPIN, EU HeuMEM

Further reading:

[1] *Anatomy of Dzyaloshinskii-Moriya Interaction at Co/Pt Interfaces*, Phys. Rev. Lett. 115, 267210 (2015), *Open access: hal-01576697.* [2] *Controlling Dzyaloshinskii-Moriya Interaction via Chirality Dependent Atomic-Layer Stacking, Insulator Capping and Electric Field*, Sci. Rep. 8, 12356 (2018), *Open access: hal-01864799.* [3] *Room-temperature chiral magnetic skyrmions in ultrathin magnetic nanostructures, Nat. Nanotech. 11, 449 (2016), Open access: hal-01271350.* [4] *Significant Dzyaloshinskii-Moriya interaction at graphene-ferromagnet interfaces due to the Rashba effect,* Nat. Mater. 17, 605 (2018), *Open access: hal-01817003.* [5] *Anatomy and Giant Enhancement of the Perpendicular Magnetic Anisotropy of Cobalt-Graphene Heterostructures*, Nano Lett. 16, 145 (2016), *Open access: hal-01260278.* [6] *Very large Dzyaloshinskii-Moriya interaction in two-dimensional Janus manganese dichalcogenides and its application to realize skyrmion states,* Phys. Rev. B 101, 184401 (2020), *Open access: hal-02611713.* [7] *Rashba-Type Dzyaloshinskii–Moriya Interaction, Perpendicular Magnetic Anisotropy, and Skyrmion States at 2D Materials/Co Interfaces*, Nano Lett. 21, 7138 (2021), *Open access: hal-03342479*. [8] *Reversible control of Dzyaloshinskii-Moriya interaction at the graphene/Co interface via hydrogen absorption,* Phys. Rev. B 101, 014406 (2020), *Open access: hal-02982691*.

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Spin-torque nano-oscillators

Spintorque nano-oscillators are nano-scale microwave signal sources based on two spintronics concepts: the spin transfer torque (STT) to induce large-angle steady-state magnetization oscillations, and the magneto-resistance effect to convert magnetization oscillations into oscillating voltage signals. SPINTEC's activity on spin-torque nano-oscillators started in 2006 with a first demonstration using a special perpendicular polarizer spin-valve structure, predicted to lead to maximum precession amplitudes. Subsequent research efforts by SPINTEC and collaborating partners contributed to understand in detail the non-linear and noise properties of these spin-torque nano-oscillators and to explore potential applications.

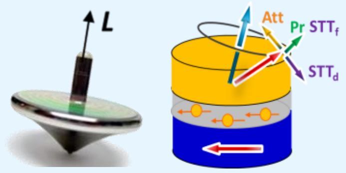

Fig. 1: Schematics showing the action of the STT on the magnetization dynamics, including a damping-like torque STT_d (counter-acting damping) and a field-like torque STT_f (adding to the precession torque).

The prediction (Slonczewski 1996, Berger 1996) and the experimental demonstration (Cornell 2003, NIST 2004) of the spin-transfer torque (STT) effect has revolutionized the means of controlling the magnetization dynamics in nanoscale magneto-resistive (MR) devices. While a spin-polarized current was used to *read out* the magnetization state of MR devices, Slonczewski and Berger predicted that a spin-polarized current can also apply a torque on magnetization via the transfer of spin angular momentum, which can induce magnetization reversal and magnetization oscillations. Magnetization, very much like a spinning top, reacts to external stimuli by precession around its equilibrium position. External microwave fields induce such resonance oscillations, which, however, are limited to very small amplitudes. In contrast to this, the STT from a DC current, by counteracting intrinsic damping (Fig. 1), can induce limit-cycle steady-state oscillations with amplitudes much larger than previously achievable by resonance oscillations. The potential of this conversion of a DC spin-polarized current into voltage oscillations at MHz-to-GHz frequencies, combined with the nanoscale size and the frequency tuning by the DC current amplitude, was immediately recognized to be of interest for the development of nanoscale signal sources. This has triggered important research efforts worldwide.

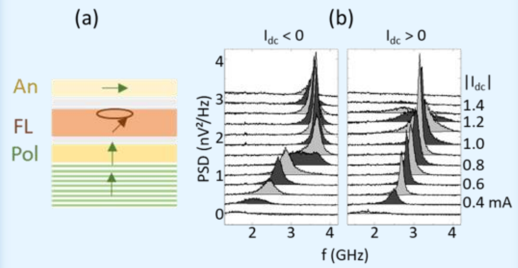

Fig. 2: Perpendicular polarizer: (a) Spin valve structure with a perpendicular polarizer (Pol), an in-plane free layer (FL) and an analyzer (AN) needed to convert the oscillations of FL into voltage signals. (b) Experimental spectra for positive and negative current I_{dc}.

SPINTEC was well placed to engage and contribute to this exciting field of research on spin-transfer-torque nano-oscillators (STNOs), starting with an original magneto-resistive spin valve configuration, based on a perpendicular polarizer (pPol) and an in-plane (ip) free layer (Fig. 2a). Theoretical simulations by SPINTEC predicted that the pPol should lead to oscillations around the energy maximum at largest amplitude (magnetization oscillating between the P and AP states). SPINTEC's expertise on magnetic materials based on (Co/Pt) multilayers with strong perpendicular anisotropy, combined with the knowledge on enhancing the spin polarization via (Co/Cu) lamination layers, led to the experimental confirmation of the theoretical predictions of STT excitations in this unconventional spin valve structure. In particular, experiments confirmed the frequency increase with DC current (both positive and negative, see Fig. 2b) and the large oscillation amplitudes. The experiments also revealed an STT-induced, non-uniform magnetization configuration at large DC currents, in perfect agreement with micromagnetic simulations. These results were an important milestone to validate the theoretical descriptions of the STT induced magnetization dynamics in nanoscale structures. However, the low output power of spin-valve structures is not suitable for technological implementations. Therefore, it was important to move towards magnetic tunnel junctions, displaying much increased magneto-resistance values (100%) and of low resistance area products. Through a collaboration with Hitachi GST, SPINTEC was able to start its activity on MgO-based magnetic tunnel junctions and most importantly to characterize the phase noise of STNOs, which is a key performance parameter. Using the Hilbert transform applied to experimental time traces of the output voltage signal (Fig. 3), SPINTEC established an experimental technique and confirmed theoretical models of the STNO amplitude and phase noise: (i) enhancement of the phase noise at low offset frequencies, due to the non-linear amplitude-phase coupling, and (ii) characterization of the amplitude relaxation frequency f_p, an important non-linear parameter. This technique provided a very powerful tool to characterize STNO operation in the non-autonomous regime.

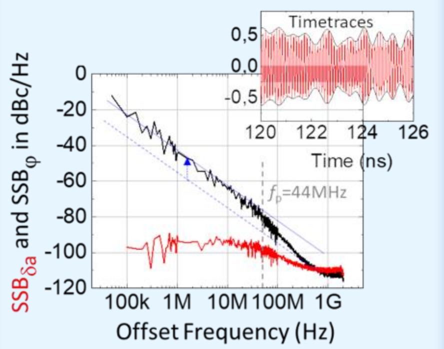

Fig. 3: Analysis of time traces (inset) via Hilbert transform to extract the amplitude (red) and phase (black) noise of the free running STNO, and the amplitude relaxation frequency f_p.

The non-linear amplitude-phase coupling, which allows tuning of the frequency via the DC current, enables also a multifunctional operation of STNO devices. Namely, adding to the DC current (inducing the steady-state oscillation) a time-varying control signal, one can injection-lock the oscillator to an external signal source, modulate the oscillation amplitude, frequency and phase or continuously sweep the STNO frequency. Using the developed noise analysis technique, we could demonstrate: (i) the strong reduction of the phase noise in the injection locked state and the role of phase jumps, (ii) that the amplitude relaxation rate sets an upper limit to the modulation rate, and (iii) that the instantaneous frequency can be swept over 1GHz range on time-scales as short as 50ns. These different concepts of non-autonomous operation were exploited to build the first system-level circuits to demonstrate: (i) operation of STNOs within a hybrid CMOS/PCB phase locked loop (Fig. 4); (ii) wireless communication over 10m distance using phase shift keying and (iii) ultra-fast spectrum analysis with the possibility to resolve frequency components of an unknown signal on time scales as fast as 50ns and with a frequency resolution given by theoretical limits. A key challenge remaining ahead, is to go from a single STNO device towards a network of coupled STNOs. To unravel and eventually master the collective states of a non-linear dynamically coupled STNO system will open the path to a large range of novel applications within wireless communications as well as for bio- and physics inspired computing.

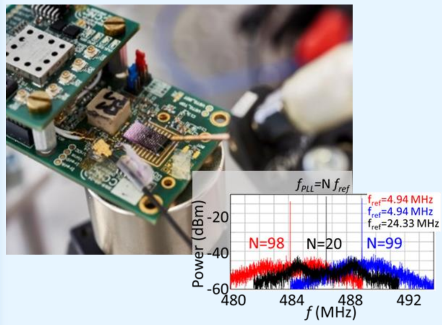

Fig. 4: Illustration of phase locked loop operation with STNOs using a hybrid CMOS/PCB chip, designed and realized by partner TU Dresden within the FP7 project MOSAIC.

Teams: RF Spintronics, Theory / Simulation, Materials and Nanofabrication, MRAM

Collaboration: LETI, UMPhy, Thales TRT, INL Braga, Hitachi, Oakland University, TU Dresden, Singulus

Funding: Anvar, ANR Magico, Carnot, FP7 MOSAIC, ANR Milestone, ANR Spinnova, ANR Spinnet, MCSA-Milestone, CEA-Eurotalent programme, CNES, ERC Magical, H2020 GREAT

Further reading: *Spin-torque oscillator using a perpendicular polarizer and a planar free layer*, Nat. Mat. **6**, 447 (2007). *Modeling of the perpendicular polarizer-planar free layer spin torque oscillator: Micromagnetic simulations,* Phys. Rev. B **78**, 024437 (2008). *Amplitude and phase noise of magnetic tunnel junction oscillators,* Appl. Phys. Lett. **97**, 182507 (2010). *Vortex spin-torque oscillator stabilized by phase locked loop using integrated circuits,* AIP Advances **7**, 056653 (2017). *Analog and Digital Phase Modulation and Signal Transmission with Spin-Torque Nano-Oscillators,* Phys. Rev. Appl. 16, 024048 (2021).

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Room temperature skyrmions controlled by gate voltage and light

Magnetic skyrmions are chiral, nanoscale magnetization textures. In 2016 we were the first to observe them at room temperature in materials compatible with the microelectronics industry. These results have lifted a major bottleneck to envision their use as an information storage medium. More recently, our demonstration of their creation and annihilation by gate voltage (together with Institut Néel) and ultra-fast laser pulses opened the way to ultra-fast and very low energy manipulation.

Magnetic skyrmions are magnetic quasiparticles composed of spins that wind up to form a stable, topologically non-trivial and homochiral spin texture (Fig.1a). Their size can go down to a few nanometers. Theoretically predicted in the 1980's, skyrmions have been firstly observed in 2009. Three years later, two teams have demonstrated that these skyrmions can be manipulated by small electric currents. Innovative memory and logic devices based on the manipulation of these skyrmions in magnetic nanostrips were then proposed, promising high information density and very low energy consumption. However, at that point skyrmions had only been observed at low temperatures and under strong magnetic fields in exotic materials, all incompatible with any application.

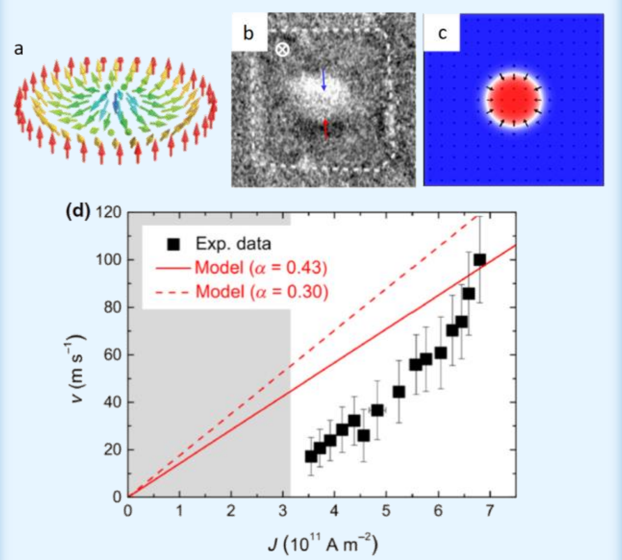

Fig1 (a) Schematic representation of a magnetic skyrmion. (b) First XMCD-PEEM image of a magnetic skyrmion (130 nm diameter) at room temperature and zero magnetic field, in an ultrathin Pt/Co/MgO nanostructure. (c) Spin structure from micromagnetic simulations.

In 2016, we made the first direct observation of magnetic skyrmions at room temperature and in the absence of applied magnetic field: high spatial resolution X-ray magnetic circular dichroism-photoemission electron microscopy (XMCD-PEEM) revealed the internal chiral structure of the skyrmions, with a diameter of about 100 nanometers (Fig.1b). These skyrmions were observed in ultrathin Pt/Co(1nm)/MgO multilayered nanostructures, based on a stack previously developed at SPINTEC in the context of magnetic random access memories (MRAM) and where the first spin orbit torque perpendicular magnetization reversal was demonstrated. The chiral spiral structure of the skyrmion arises from a "chiral" exchange interaction, named Dzyaloshinskii-Moriya interaction (DMI). In this material, it arises from the breaking of symmetry and the spin orbit coupling at the interfaces between the magnetic metal (here Co), and a heavy metal, (here Pt). In contrast to the molecular beam epitaxy samples showing skyrmion in ultrathin film until then, our deposition technique, namely sputtering, is commonly used in industry, taking the applicability of skyrmions a step further. Additionally, we have shown that skyrmions can be moved rapidly by electric currents, up to 100 m/s (Fig. 1d), *i.e.*, an order of magnitude lower power consumption compared to previous results, due the ultrathin nature of the stack.

To write information into skyrmion-based devices, it is crucial to be able to individually manipulate skyrmions with the lowest possible energy consumption and on very small timescales. SPINTEC has made several important breakthroughs in this direction. First, demonstrated in collaboration with Institut Néel, we have that magnetic skyrmions can be locally nucleated and annihilated in a controlled and low-energy manner using a gate voltage (Fig. 2a). This results from the gate voltage control of the magnetic anisotropy (VCMA), a fundamental effect discovered in 2009, which has been developed worldwide for MRAM writing with reduced power consumption. In the present case, tuning the interfacial perpendicular magnetic anisotropy using gate voltage provides a direct handle to control the stability of the skyrmions and the associated energy barriers. Through a fine material optimization, we have furthermore shown that it is possible to obtain very strong relative variations of another interfacial magnetic property, namely the DMI interaction, using a gate voltage, in Ta/CoFeB/TaOx and Pt/Co/AlOx ultrathin layers. We have demonstrated that a change of the DMI sign by a gate voltage leads to an inversion of the chirality of skyrmions (Fig. 2b). Such a change of chirality is promising to perform logic operations in skyrmion-based devices as it inverts the direction of current-induced skyrmion motion. It opens perspectives to individually and dynamically manipulate skyrmions.

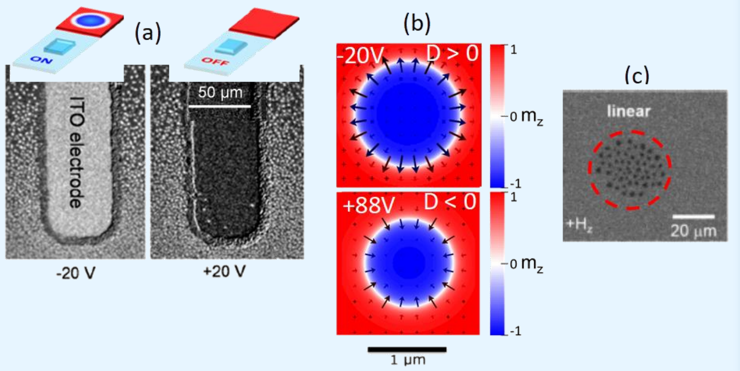

Figure 2 (a) Skyrmion creation and annihilation with a gate voltage, observed by Magneto-optical Kerr effect microscope in Pt/Co/AOx samples. (b) Micromagnetic simulations of inversion of skyrmion chirality with a gate voltage due to sign inversion of DMI sign (c) Skyrmion nucleation with fs-laser pulse, observed by magneto-optical Faraday effect microscope in Ta/FeCoB/TaOx samples. The dashed circle shows where the laser pulse was applied.

Finally, in collaboration with Institut Jean Lamour, we have recently demonstrated that skyrmions can be nucleated in these ultrathin layers by local heating with a single ultrashort (35 fs) laser pulse. This was observed in a Ta/FeCoB/TaOx trilayer, in which skyrmions cannot be nucleated using a magnetic field. Thus, this method allows overcoming high nucleation energy barriers, with the additional advantage of higher stability of skyrmions. It paves the way for ultrafast writing in skyrmion-based memories and logic devices.

Now the next objective is to make one more step towards applications. This includes the stabilization of sub-10 nm magnetic skyrmions at room temperature as well as their ultra-fast manipulation (> 1000 m/s). Magnetic skyrmions have also unique potential for logic operations by leveraging their mutual repulsions. This could be exploited in beyond-Von-Neumann logic-in-memory devices, which intrinsically combine high density memory and fast and low power logic capabilities. These include not only standard Boolean logics but also non-conventional computing schemes, such as neuromorphic and reservoir computing, where the natural complexity of skyrmions dynamics can be leveraged to achieve fast complex patterns recognition and tasks at ultra-low energy.

Teams: Spin-orbitronics, Sensors, Theory / Simulations, Materials, Instrumentation, MRAM

Collaboration: Institut Néel, Institut Jean Lamour, Université Paris 13, Laboratoire Charles Coulomb

Funding: 3 ANR grants (coordination), US DARPA grant (coordination)

Further reading: *Room-temperature chiral magnetic skyrmions in ultrathin magnetic nanostructures*, O. Boulle et al., Nat. Nanotechnol., 11, 449 (2016), *Open access: hal-01271350. Current-Driven Skyrmion Dynamics and Drive-Dependent Skyrmion Hall Effect in an Ultrathin Film,* R. Juge et al., Phys. Rev. Appl., 12, 044007 (2019), *Open access: hal-02356080. The Skyrmion Switch: Turning Magnetic Skyrmion Bubbles on and off with an Electric Field, M. Schott et al., Nanolett., 17, 3006 (2017), Open access: hal-01639157. Large-Voltage Tuning of Dzyaloshinskii–Moriya Interactions: A Route toward Dynamic Control of Skyrmion Chirality, T. Srivastava et al., Nanolett., 18, 4871 (2018), Open access: hal-01873478. Electric Field Control of Interfacial Dzyaloshinskii-Moriya Interaction in Pt/Co/AlOx Thin Films, M. Schott et al., JMMM, 520, 167122 (2021), Open access: hal-02944910. Creation of Magnetic Skyrmion Bubble Lattices by Ultrafast Laser in Ultrathin Films,* S.-G. Je et al., Nanolett., 18, 7362 (2018), *Open access: hal-01903085.*

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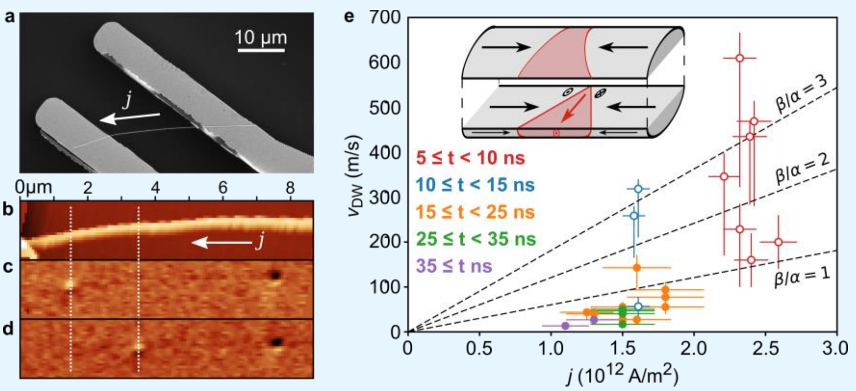
Domain wall dynamics in nanowires and nanotubes

Domain-wall motion in one-dimensional conduits is both a textbook case for understanding magnetization dynamics and spin torques, and of practical importance for novel spintronic devices. However, instabilities known as Walker breakdown limit their speed in most cases. Following two decades of theoretical reports, we have confirmed experimentally that these instabilities are circumvented in cylindrical nanowires, related to the specific topology of their walls, in a joint effort with experts in electrochemistry at the University of Erlangen-Nürnberg. Yet, we show that the Œrsted field plays a crucial role in the process, while previously overlooked. We expect that this demonstration motivates further work in curvilinear magnetism, such as seek the magnonic regime of wall motion, and investigate engineered structures in the form of axially-modulated nanowires and core-shell tubes.

During domain-wall motion under the stimulus of either external magnetic field or spin-transfer torques, the core of walls tend to enter a precessional motion. While this is counterbalanced by internal torques (exchange, dipolar etc.) under moderate stimulus, no balance is possible above a certain threshold. This induces a drop of the wall mobility called the Walker breakdown, associated with a stochastic behavior. For two decades, numerous theoretical reports predicted that the Walker breakdown is suppressed in cylindrical conduits, owing to a specific topology of the domain walls, called Bloch-point walls. However, this peculiar situation had never been confirmed experimentally.

We addressed this challenging problem in a joint effort between SPINTEC and Institut Néel for electric contacting, measurements, and micromagnetic modeling, also bringing together experts from other key fields: chemical synthesis to fabricate nanowires with tailored magnetic properties, with colleagues from University Erlangen-Nürnberg; and advanced magnetic microscopies, with colleagues from Elettra, Alba and SLS synchrotrons.

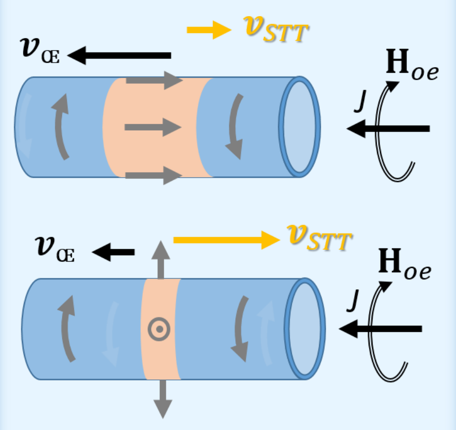
We developed a specific clean-room process to contact electrically chemically-synthesized cylindrical nanowires with a low contact resistance. This allowed us to conduct the first spintronic experiments of purely current-induced domain-wall motion in cylindrical nanowires in Elettra and Alba, with a few nanosecond time scale, monitored by both X-ray Magnetic Circular Dichroism combined with Photo-Emission Electron Microscopy, and magnetic force microscopy ($Co_{30}Ni_{70}$, diameter 90 nm). We evidenced that Bloch-point walls are robustly stabilized by the Œrsted field arising from the charge current, contrasting with instabilities that we evidenced previously under pulses of magnetic field. This comes with wall speed in excess of 500 m/s under current density circa 2×10^{12} A/m^2, a five-fold increase compared to all other cases of direct spin-transfer-torque wall motion of large-magnetization ferromagnets such as 3d elements. We reproduced the stabilization effect by micromagnetic simulations, which however provided a picture more complex than expected for the right/left switching of circulation of Bloch-point walls, possibly involving the nucleation and annihilation of Bloch points.



(a) Contacted nanowire. (b-d) AFM topography, and MFM monitoring of domain wall motion under current in the wire displayed in a. Schematic open view of a Bloch-point domain wall, and experimental determination of its speed versus electric current strength and duration. Lines are guide to the eye following the simple one-dimension motion of domain walls.

We evidenced directly the dramatic effect of Œrsted fields, by using time-resolved imaging of magnetization dynamics using Scanning Transmission X-ray Microscopy (STXM) combined with X-ray Magnetic Circular Dichroism, 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 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.

Following this demonstration of the importance of Œrsted fields in the cylindrical geometry, we considered nanotubes with azimuthal domains, sometimes also called bamboo-type domain, which is ideal to be addressed by Œrsted fields. While such nanotubes have been exhibited recently at SPINTEC/Néel, in a first stage we explored which specific physics may be sought in such objects, combining theory based on an analytical 1D model to draw trends and highlights the physics at play, with micromagnetic simulations for an accurate description. We show the existence of spin-transfer torque and/or Œrsted dominated regime, large domain wall speeds reaching potentially 800 m/s and the presence of a so-called Walker breakdown. We paid particular attention to features which are analogous to flat strips, and which are specific to tubes. Some are very unusual, such as the change of direction of motion of some domain walls across the Walker current, due to the competition of spin transfer and Œrsted field (see figure).



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 Œrsted field or by the spin-transfer torque.

These results illustrate the specific physics that can arise in three-dimensional magnetization textures and their topology, a topic of rising interest in the broader context of three-dimensional and curvilinear magnetism. We expect that these first experimental reports and associated new theoretical predictions, motivate further experimental work in the field. In particular, we are now not far from the 1 km/s limit, beyond which a strong coupling is expected between domain walls and spin waves, and called the magnonic regime. We are also exploring more complex structures, such as nanowires with axial modulations of composition, and core-shell nanotubes. The former should enable one to control the position of domain walls along a wire. This is required to implement pump-probe time-resolved fundamental investigation, but would also be required to design memory and logic devices. The latter would further broaden the spectrum of cylindrical conduits to spintronics, which intrinsically requires the use of stacked materials of various natures.

Teams: Spin textures, Theory / simulation

Collaboration: Institut Néel, Univ. Erlangen Nürnberg, Synchrotrons Elettra, Alba and SLS.

Funding: EU M3d, ANR JCJC Matemac 3D

Further reading: *Fast domain walls governed by Œrsted fields in cylindrical magnetic nanowires*, Phys. Rev. Lett. 123, 217201 (2019), *Open access: hal-02075418. Mechanism of fast domain wall motion via current-assisted Bloch-point domain wall stabilization*, Phys. Rev. B 103, 024434 (2021), *Open access: hal-03042301. Time-resolved imaging of Œrsted field induced magnetization dynamics in cylindrical magnetic nanowires*, Appl. Phys. Lett. 118, 172411 (2021), *Open access: hal-03134319. Theoretical Study of current-induced domain wall motion in magnetic nanotubes with azimuthal domains*, Phys. Rev. B 103, 024434 (2021), *Open access: hal-02958749.*

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Ferroelectric control of the spin-charge conversion for ultralow power spintronics

Researchers in SPINTEC have developed, in collaboration with the CNRS/Thales Joint Physics Unit and Politecnico di Milano, a new approach to generate and detect spin currents by exploiting the interplay between spin-orbit effects and ferroelectricity, in two classes of materials: two-Dimensional Electron Gases (2DEGS) appearing at oxides surfaces and interfaces, and ferroelectric semiconductors. The conversion between spin currents and charge currents, which is usually done in spinorbitronics using spin Hall effect heavy metals, can then be controlled in a non-volatile way. Such a control can lead to the emergence of a ferroelectric spintronics, which could result in a reduction of the power consumption of non-volatile spintronic devices by a factor of one thousand.

To generate and detect spin currents, spintronics traditionally uses ferromagnetic materials in which the spins are all aligned in the same 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 the devices. However, the energy required to reverse the magnetization by application of a magnetic field or electric current remains significant.

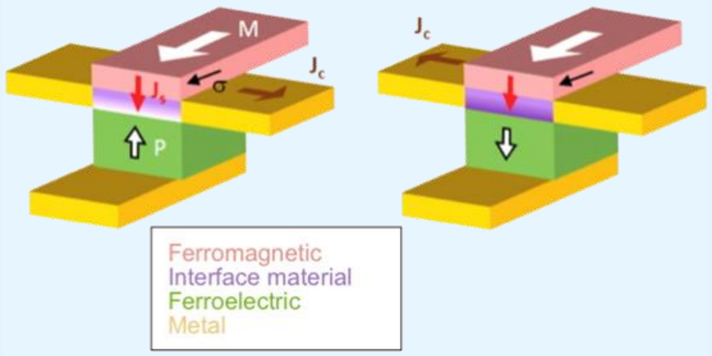

*Fig. 1: Example of a device, a ferromagnetic material is used to generate a vertical spin current **J_S** and injecting it into an interface material in which it is converted into a lateral **J_C** charge current. The spins **σ** are represented by the small black arrow and their direction is fixed 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 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. 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 in the transverse direction. The way in which spin and charge currents are thus interconverted (and in particular their sign) is determined by the material.

Researchers from the SPINTEC laboratory performed transport and spin-pumping experiments, with the help of the SyMMES Laboratory, in $SrTiO_3$-based 2DEGs (in collaboration with the CNRS/Thales Joint Physics Unit) and in GeTe (in collaboration with Politecnico di Milano). For the first time, they demonstrated in both case that the spin-to-charge conversion, due to the spin-orbit coupling, can be controlled in a remanent way through the ferroelectric polarization.

This is providing new opportunities for creating spin-based devices, such as the MESO transistor proposed recently by Intel, which relies on the writing of a magnetic information through magnetoelectric coupling, and of its reading by spin-charge conversion.

In $SrTiO_3$-based 2DEGs, we were able to control the sign of the interconversion via electrical polarization (cf. fig. 1). To do this, we 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 the information in the polarization of the oxide ferroelectric element, and of using the spin-charge conversion to read this polarization state.

Another opportunity to control spin currents using ferroelectricity is the use of Ferroelectric Rashba semiconductors (FERSCs), which 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 have shown (cf. fig. 2) 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 showed that the spin-to-charge conversion in GeTe 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. These results also suggest that FERSCs could potentially be used to develop all-in-one devices that integrate spin generation, manipulation and detection, with the interest of a ferroelectric state at room temperature.

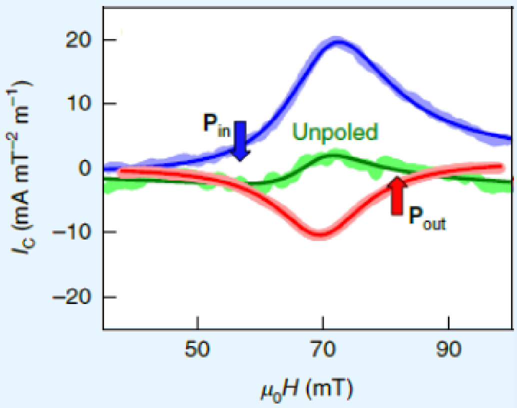

Fig. 2: Normalized current produced by spin-pumping, for three different ferroelectric polarization states. The blue and red curves correspond to opposite polarization states. They are leading to opposite spin pumping signals, which means that opposite polarization states corresponds to opposite signs spin-to-charge conversion signs. The green curve in 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 configuration.

The ferroelectric control of the spin-charge conversion, demonstrated in oxide-based 2DEGS and in ferroelectric semiconductors, provides a new degree of freedom for the control of spins. By replacing or complementing the usual magnetization switching by spin-orbit or spin-transfer torques, it provides the opportunity to develop innovative architectures for ultralow power spintronics. This opening of a new field of research represents a turning point for the involved researchers of SPINTEC, who are now aiming at demonstrating the ferroelectric control electrically, in functional devices.

Team: Topological spintronics

Collaboration: Unité Mixte de Physique CNRS/Thalès, PoliMi, CEA Symmes, Paul-Drude-Institut

Funding: ANR TOPRISE, OISO, CONTRABASS

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. *Room-temperature ferroelectric switching of spin-to-charge conversion in germanium telluride*, S. Varotto et al., Nature Electronics 4, 740 (2021), DOI: 10.1038/s41928-021-00653-2

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Molecular Beam Epitaxy growth of 2D materials on large areas for electronics, valleytronics and spintronics

The 2D spintronics team of Spintec develops a ultrahigh vacuum (UHV) cluster connecting molecular beam epitaxy (MBE) reactors dedicated to the growth of 2D transition metal dichalcogenides (TMDs) and their van der Waals heterostructures. Single crystalline 2D materials grown on large area by MBE exhibit superior electronic properties than mechanically exfoliated flakes from the bulk crystal. We highlight here three recent achievements. First, $PtSe_2$ epitaxially grown on ZnO exhibits high electron mobility. Then we demonstrate the valley Nernst effect (VNE) in WSe_2 single layer and could accurately control the composition of Fe_5GeTe_2 to obtain room temperature ferromagnetism.

2D materials hold great promises for microelectronics, owing to their atomic thickness and van der Waals character. The atomic thickness ensures the high tunability of their electronic properties at very low energy cost and allows for the development of a sustainable electronics using less material and simplifying device processing (like etching). To date, most of their exceptional properties have been demonstrated on flakes (1-10 µm) mechanically exfoliated from the bulk crystal preventing any upscaling for practical applications.

At Spintec, we have been developing for the last 7 years the MBE growth of TMDs (MX_2 with M=transition metal and X=Se,Te) on 1-inch wafers (Fig. 1a). More recently, we started to build a UHV cluster connecting MBE reactors dedicated to the growth of TMDs (Se and Te) and their van der Waals heterostructures on 2-inch wafers as depicted in Fig. 1b. This cluster has been funded by the AURA Region (Minatec Labs project), the Grenoble Alpes University (EPI2D project), the Grenoble LABEX LANEF (project 2DMAT) and the Equipex+ project 2DMAG. Beyond the Grenoble scientific community, this cluster is meant to provide French laboratories working on 2D materials with high quality TMDs and vdW heterostructures on large areas.

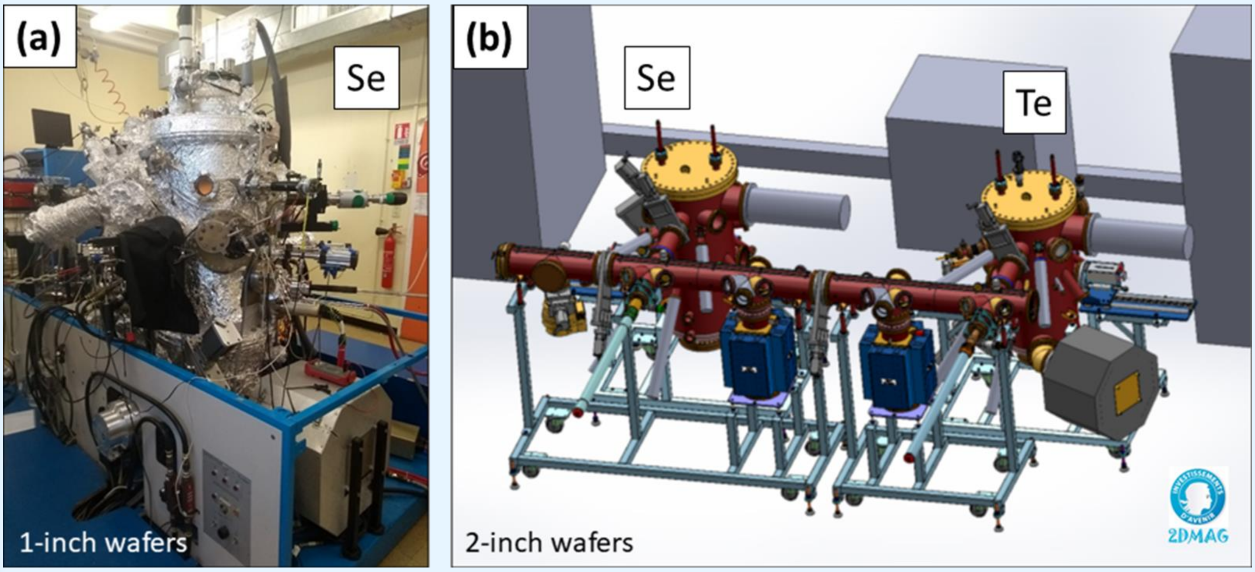
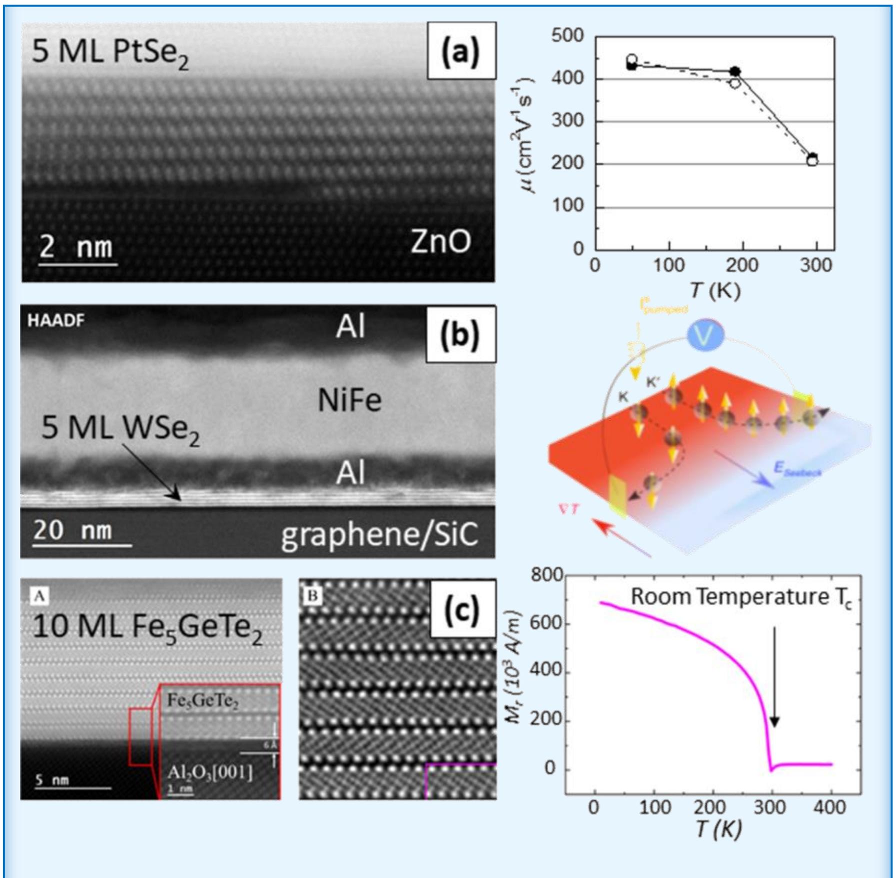


Figure 1: (a) Picture of the MBE reactor for 1-inch wafers dedicated to the growth of transition metal diselenides. (b) Drawing of the future UHV cluster connecting 2 MBE reactors to grow selenides and tellurides independently (to avoid cross-contamination) and their van der Waals heterostructures.

We selected three families of TMDs: $PtSe_2$ or $HfSe_2$ for their high electron mobility and integration in electronic devices like RF transistors; $MoSe_2$, WSe_2 and $MoTe_2$ exhibiting inversion symmetry breaking and large spin-orbit coupling for valleytronic applications; and $W_{1-x}V_xSe_2$, VSe_2, $CrSe_2$, $CrTe_2$ and Fe_xGeTe_2 alloys for 2D ferromagnetism and spintronic applications. We show in Fig. 2 three recent achievements in the fields of electronics, valleytronics and spintronics. High electron mobility is the key parameter of RF transistors and we demonstrated in (a) that 5 ML of $PtSe_2$ epitaxially grown on ZnO exhibit very high electron mobility compatible with such device. The room temperature mobility is one order of magnitude larger than in previous reports on polycrystalline $PtSe_2$ layers and comparable to the one of exfoliated flakes. In (b), we have grown WSe_2 mono and multilayers in epitaxy on single crystalline graphene on SiC. In the single layer limit, we could demonstrate the VNE by using the spin pumping ferromagnetic resonance technique. The VNE generates a pure transverse valley current by applying a longitudinal heat flow. This is a consequence of opposite Berry curvatures in K and K' valleys. The experimental evidence of the VNE is a key advance for the field of valleytronics using the valley degree of freedom instead or in addition of the charge and spin.



<u>Figure 2:</u> (a) 5 ML of $PtSe_2$ epitaxially grown on ZnO and electron mobility as a function of temperature. (b) WSe_2 epitaxially grown on graphene/SiC. The valley Nernst effect was detected on a single layer. (c) 10 ML of Fe_5GeTe_2 epitaxially grown on sapphire and showing RT ferromagnetism.

Finally, in 2017, ferromagnetism was reported in the literature for CrI_3 and $Cr_2Ge_2Te_6$ monolayers. The existence of ferromagnetism in these 2D materials (which contradicts the Mermin-Wagner theorem) is due to crystalline magnetic anisotropy and field-induced anisotropy respectively. Since then, the field of 2D magnets has expanded very quickly. A motivation is that, thanks to their ultimate thinness, their magnetic properties can be manipulated at very low energy cost, which makes them promising materials for next generation spintronic devices. We have been able to achieve the MBE epitaxy of 10 monolayers of Fe_5GeTe_2 on sapphire, with perfect control of the ternary composition (Fig.2c), and observe room temperature ferromagnetism. Again, this result is a key feature for the use of 2D magnets in practical spintronic devices like ultra-compact MRAMs.

<u>Teams:</u> 2D spintronics, Theory / Simulation

<u>Collaboration</u>: IRIG-MEM, Institut Néel, LMGP, C2N, IRIG-SyMMES.

<u>Funding</u>: AURA Region Minatec Labs, LABEX LANEF 2DMAT, University Grenoble Alpes EPI2D, Equipex+ 2DMAG, ANR MoS2ValleyControl, ANR MAGICVALLEY, H2020 FET-OPEN NANOPOLY

<u>Further reading</u>: *F. Bonell et al., 2D Mater.* ***9****, 015015 (2021), M.-T. Dau et al., Nat. Commun.* ***10****, 5796 (2019), M. Ribeiro et al., npj 2D Mater. Appl. 6, 10 (2022), Open access: hal-03271458*

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Proximity Effects Induced in Graphene in the framework of the European Flagship

Graphene spintronics became one of the most promising directions of innovation thanks to long-spin lifetimes and the ability of graphene to be easily interfaced with other classes of materials, allowing proximity effects to be harvested. In the framework of the European Graphene Flagship project, we demonstrated that robust spin polarization could be induced in graphene via proximity with magnetic and multiferroic insulators. These findings let do novel class of spin-dependent transport phenomena in graphene based lateral devices.

Graphene has emerged as one of the most promising materials with exceptional properties and led to the 2010 Nobel Prize in Physics awarded to A. Geim and K. Novoselov. Since 2013 we have taken part in the Graphene Spintronics Work Package of the European Graphene Flagship, whose aim is to establish the ultimate scientific and technological potential of graphene and other 2D materials for spintronics. In particular, we have been working on inducing magnetism in graphene, a fundamental challenge required for the development of ways to control spin-dependent transport in graphene-based spintronic devices. Possible approaches include using defects or letting it in contact with magnetic materials. We have demonstrated that among the latter magnetic insulators are very promising for inducing magnetism in graphene since they allow large spin polarization in it via the exchange-proximity interaction.

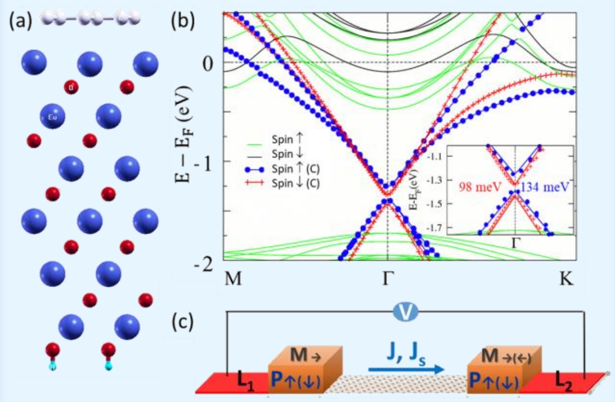

Figure 1 (a) Side view and (b) band structure of graphene on EuO. (c) Model multiresistive device consisting of two multiferroic regions on top of a graphene sheet.

First, we demonstrated the possibility of inducing spin polarization in graphene by means of magnetic insulator proximity effect, using graphene on EuO [Fig. 1(a)]. We found that the interaction with the magnetic substrate remarkably affects the magnetic properties of graphene. In particular, the traditional linear dispersion of the graphene band structure is modified, yielding strongly spin-polarized band gap opening at the Dirac point [Fig. 1(b)], a promising feature for possible spin-gating engineering. Next, we have explored magnetic proximity effects induced in graphene in the case of high-Curie-temperature oxides such as cobalt ferrite $CoFe_2O_4$ (CFO) and yttrium iron garnet $Y_3Fe_5O_{12}$ (YIG), the latter giving rise to particularly strong exchange-split gaps. Based on these findings, we finally proposed the concept of a six-resistance device based on multiferroic-induced proximity effects in graphene in contact with a bismuth ferrite $BiFeO_3$ (BFO) film, via exploiting the ferroelectric polarization in the BFO that affects the spin-dependent electronic structure of graphene [Fig. 1(c)]. This is possible thanks to the prediction of three types of proximity resistance effects: proximity electroresistance (PER), proximity magnetoresistance (PMR), and proximity multiferroic resistance (PMER). These findings paves a way towards controlling of magnetic properties in 2D materials and engineering of graphene spin gating by proximity effects.

Team: Theory / Simulations

Collaboration: ICN2 (Spain), CEA/Pheliqs (FR), CNRS/Thales (FR), U. Nebraska (USA)

Funding: EU GRAPHENE FLAGSHIP, ANR NANOSIM_GRAPHENE

Further reading: *Graphene spintronics: the European Flagship perspective, 2D Mater. 2, 030202 (2015), Open access: cea-01735125v1. Proximity Effects Induced in Graphene by Magnetic Insulators: First-Principles Calculations on Spin Filtering and Exchange-Splitting Gaps, Phys. Rev. Lett. 110, 046603 (2013), Open access: hal-02052069. Tailoring magnetic insulator proximity effects in graphene: first-principles calculations, 2D Mater. 4, 025074 (2017), Open access: hal-01516992. Proximity magnetoresistance in graphene induced by magnetic insulators, Phys. Rev. B 100, 104402 (2019), Open access: hal-02280073. Unveiling multiferroic proximity effect in graphene, 2D Mater. 7, 015020 (2020), Open access: hal-02393681.*

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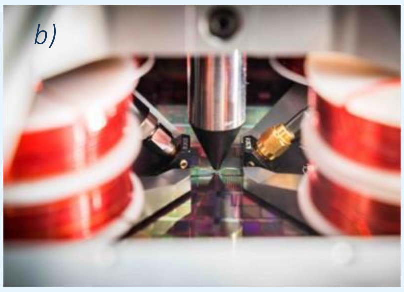
Hprobe: 5 years of development

Founded in March 2017 as a spin-off from SPINTEC, Hprobe is specialized in the design, manufacture and installation of test probers to realize electrical characterizations under magnetic field of spintronic devices, like MRAM, at wafer level. It started its industrial and commercial deployment with research laboratories, both academic and industrial, followed by production sites of microelectronics companies. Hprobe also rapidly extended its market to a second field of application: magnetic sensors, and reaches now 19 staff.

Microelectronic components embedding spintronic and magnetic elements is a rapidly-developing market (MRAM, sensors, Mems, etc.). Over fifteen years of activity, the SPINTEC MRAM team has developed magneto-transport test procedures suitable for MRAMs on semi-automatic wafer probers, in collaboration with the Instrumentation team for the design of versatile magnetic field generators, contributing with electromagnetic finite element simulations to optimize the electromagnet design. From a technological point of view, the magnetic head developed and patented by SPINTEC, allows the generation of a configurable field along the three dimensions of space at the level of the devices to be tested, for characterization and selection. Previously, researchers were restricted to testing single components under 3D magnetic fields, or wafer level testing under a single magnetic field direction. The SPINTEC developments allowed moving to the industrial stage, requiring tests at the wafer scale under a 3D field. Algorithms developed by Spintec make it possible to retrieve the physical properties that characterize individual components to validate the technology, materials or processes during the flow or post-process. The data processing algorithms allows statistics, parameters extraction and failure analysis. These routines cover quasi-static measurements as well as pulses of electric current all the way down below 1ns.

a)

b)



a) First generation of Hprobe test equipment

b) Magnetic field generator capable of generating a 3D field in which each spatial axis is driven independently. Sweeping rate controllable in amplitude and angle at up to 10,000 step samples per second. © Hprobe

The 3D magnetic generator and the test procedures invented by SPINTEC served as foundation of the incubation project "MAGNUS" submitted by Ricardo Sousa and Jean-Pierre Nozières in June 2015 to the SATT (Technology Transfer Acceleration Company) Linksium. It allowed Laurent Lebrun, the co-initiator of the project, to finalize the mechanical design of the 3D magnetic generator, to carry out the next development phase and market proof with the support of Linksium during his stay at SPINTEC. The collaboration work between Laurent Lebrun, Ricardo Sousa and Isabelle Joumard has been fruitful leading to two major events: the patent of the 3D electromagnet and the signature of the incubation convention with the SATT for the start-up Hprobe co-founded by Laurent Lebrun (CEO) and Jean-Pierre Nozières (Strategic Advisor).

After a first machine was installed in the Imec laboratory in Belgium (February 2018), Hprobe built and installed a first industrial machine in Taiwan at one of the largest wafer manufacturers in the world. The machine has been qualified and several more testers were subsequently delivered to Europe and China. The team has grown to about 20 people with a large amount of engineers arriving from Spintec, after a PhD or Post-Doc. The collaboration with SPINTEC is still running with service contracts and scientific advice, leading to the development of a new generation of magnetic test head H3DM-XL with a larger field area and uniformity, allowing wafer sort of MRAM in mass production.

Teams: MRAM, Instrumentation

Further reading: *Génerateur de champ magnétique*, I. Joumard, R. Sousa, Patent PCT/FR2017/050034.

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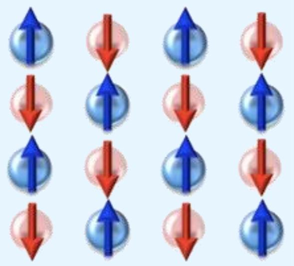
Antiferromagnetic spintronics: a paradigm shift for new concepts and devices

The use of spin-dependent transport properties of antiferromagnetic (AF) materials is a paradigm shift for the development of new spintronic components. Researchers at SPINTEC are among the pioneers in this field of research, which was born some 15 years ago. It is now known as AF spintronics, and we and close collaborators described it extensively in what has become an authoritative review article [1]. On this basis, our objective was to explore the various facets of the physics inherent in AF materials. To this end, three main research directions were investigated: i) to determine the characteristic lengths promoting spin dependent transport, whether the transport be of magnonic, single electron and Cooper pair nature, ii) to understand how the symmetries of AF spin structures and interface spin textures influence transport, and iii) to understand how the dynamics of the AF order parameter can favour spin transport in the THz range.



Spin structure of a staggered antiferromagnet.

Antiferromagnetic materials have several potential advantages for application, thanks to the interesting features they combine: they produce no stray fields, allowing for increased storage densities; they are robust against perturbation due to magnetic fields, an advantage for data security; and they display dynamics in the picosecond time scale and generate large magneto-transport effects, allowing for ultrafast information handling.

From a fundamental point of view, AF materials have two sublattices of magnetic moments, giving them two degrees of freedom. One is related to the net magnetization present at rest or dynamically induced, and is expressed macroscopically in a direct way. The other, local, is linked to the Néel vector and is expressed macroscopically in an indirect manner. This is why the physics of AF materials is very rich, sometimes unique and unexpected compared to their ferromagnetic counterparts. **New types of effects allowed in AF materials include for example : pseudospin magnonics, staggered topology, self-compensating skyrmions, and superconducting compatibility. We investigated research efforts to explore such specificities.**

i) <u>Characteristic lengths promoting spin dependent transport in AF materials [2,3]</u>

The use of the spin pumping method allowed us to overcome obstacles related to the difficulty of measuring AF materials, which have no global magnetization. **We thus paved the way for studies of spin current injection, propagation and conversion in AF materials, as a prerequisite for the development of new components.**

We determined the spin filtering of interfaces (spin mixing conductance) and the characteristic spin penetration lengths in metallic AFs (IrMn, FeMn). These parameters are important because they are involved in many experimental methods, as soon as a spin current crosses an interface, to induce for example a spin transfer or a spin-orbit torque.

We also demonstrated a spin pumping effect linked to fluctuations in the AF order parameter [2], and have shown that this is a universal effect that also applies to fluctuations in the ferromagnetic order parameter (with the example of Tb provided by LPS), and superconducting order parameter (with NbN provided by CIME). The origin of the effect lies in the direct link between the spin filtering of the interfaces and the dynamic susceptibility. This work opened the way to the study of critical phenomena of AFs in the thin film regime, which are difficult to access by existing 'volume' techniques. By selecting AFs of various electrical natures - metallic (IrMn, FeMn) and insulating (NiO, $BiFeO_3$ fabricated by OPTIMAG), **we extended the scope of our results to the electronic and magnonic transport regimes**.

Besides single electron transport, in collaboration with CIME (fabrication of the NbN superconductor) and IRIG/PHELIQS & LOMA Bordeaux (theoretical support), **we demonstrated how the superconducting proximity effect can be used to evaluate the penetration of Cooper pairs in the IrMn metallic AF.** These findings represent a stimulating example of how AFs and superconductors may envision a common future[3].

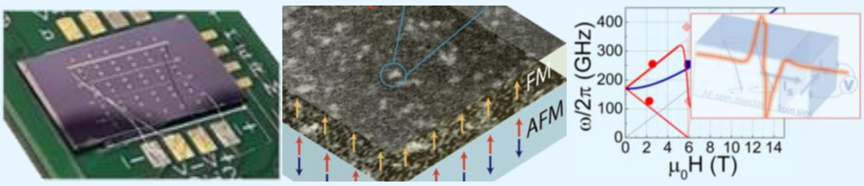
ii) How symmetries of the AF spin structures and interface spin textures influence transport [4,5]

Beyond the extrinsic scattering effects mentioned above, symmetries are particularly important concepts that have implications for physical properties, such as transverse conductivity. The causal link can be formulated in the language of Berry curvature. Non-zero Berry curvature requires breaking spatial or temporal inversion symmetry ; and as such, intrinsic effects are allowed in AFs, contrary to what was misthought until recently. In a collaboration with CINaM, TU Dresden, JGU Mainz and Charles Uni. Prague, **we demonstrated the existence of a large spontaneous Hall effect in the Mn_5Si_3 AF, due to a novel time reversal symmetry breaking mechanism involving staggered spin-splitting.** This work opens perspectives for the study of a whole new class of topological phase compatible with low atomic numbers, collinear magnetism with weak spin-decoherence, and vanishing net magnetization [4].

With respect to spin textures, *i.e.*, the local inhomogeneous phases of the spin structure, in search of the skyrmion nucleation in AFs, **we took advantage of the exchange bias interaction between the IrMn AF and an adjacent NiFe ferromagnet to stabilize several types of spin textures at the AF interface**. The results obtained open a new avenue for the investigation of associated spintronic effects and eventually benefit from the self-compensation due to the presence of two-sublattices in AFs [5].

iii) Dynamics of the AF order parameter to promote transport in the sub-THz to THz regimes [6]

The dynamics of the AF order parameter is a property that also depends radically on the spin structure. It is related to the very large internal exchange between the sublattices, generating resonances in the near THz range. A quasi-optical bench at LNCMI combines very high frequencies, high fields and a wide temperature range. In collaboration with LNCMI and CNRS/Thales, we designed an electrical part to adapt the bench to our studies. We now have access to an experiment that is almost unique in the world to understand how sub-THz AF dynamics can promote spin pumping, and with what efficiency, notably with regard to the damping parameter of the AFs, or the transfer of angular momentum at the interface from the AFs. In a study related to propagating modes and magnonic birefringence, **we demonstrated a record low-damping in the AF of α-Fe_2O_3 through resonance experiments** [6], thus laying the foundation for further investigations.



(Left) Device used to measure IrMn/NbN hybrids. (Middle) Spin textures observed in IrMn by XMCD PEEM. (Right) Sub-THz resonance and dispersion spectra of α-Fe_2O_3

Teams: AF spintronics, Spinorbitronics, Microwave devices, Topological spintronics, Theory / Simulation

Collaborations: IRIG/SyMMES, IRIG/PHELIQS, LNCMI, CINaM, CNRS/Thales, L2C, CIME, LOMA, LPS, OPTIMAG, JGU Mayence (DE), TU Dresden (DE), FHI Berlin (DE), Uni. York (UK), KAUST (KSA)

Funding: ANR JCJC 'ASTRONICS', ANR-DFG 'MATHEEIAS', Kaust Collaborative Research Grant, CEA Programme Exploratoire 'ELSA', CEA bourses Phares, PHC Alliance 'ASK'

Further reading: [1] *AF spintronics, V. Baltz et al,* Rev. Mod. Phys. **90**, 015005 (2018), *DOI: 10.1103/RevModPhys.90.015005.* [2] *Enhanced spin pumping efficiency in AF IrMn thin films around the magnetic phase transition, L. Frangou et al,* Phys. Rev. Lett. **116**, 077203 (2016), *DOI: 10.1103/PhysRevLett.116.077203.* [3] *Penetration depth of Cooper pairs in the IrMn AF, R. L. Seeger, et al,* Phys. Rev. B **104**, 054413 (2021), *DOI: 10.1103/PhysRevB.104.054413.* [4] *Macroscopic time reversal symmetry breaking by staggered spin-momentum interaction, H. Reichlova et al, arXiv:2012.15651.* [5] *Imprint from F skyrmions in an AF via exchange bias, K. Rana et al,* Appl. Phys. Lett. **119**, 192407 (2021), *DOI: 10.1063/5.0066766.* [6] *Long-distance spin-transport in single crystals of the AF α-Fe_2O_3,* R. Lebrun et al, Nat. Comm. **11**, 6332 (2020), *DOI: 10.1038/s41467-020-20155-7*.

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Coherent coupling of two distant macrospins by chiral phonons

A new form of spintronic is emerging, exploiting electrical insulators. Recent spectroscopic studies performed at SPINTEC have revealed the collective magnetic dynamics that may establish between two distant macrospin layers, though separated by a non-magnetic dielectric spacer layer. The coherent coupling is mediated here by circularly-polarized acoustic phonons that carry angular momentum information over millimeter distances inside a monolithic dielectric device. This long-range effect represents an important progress in magnonics and spin wave computing.

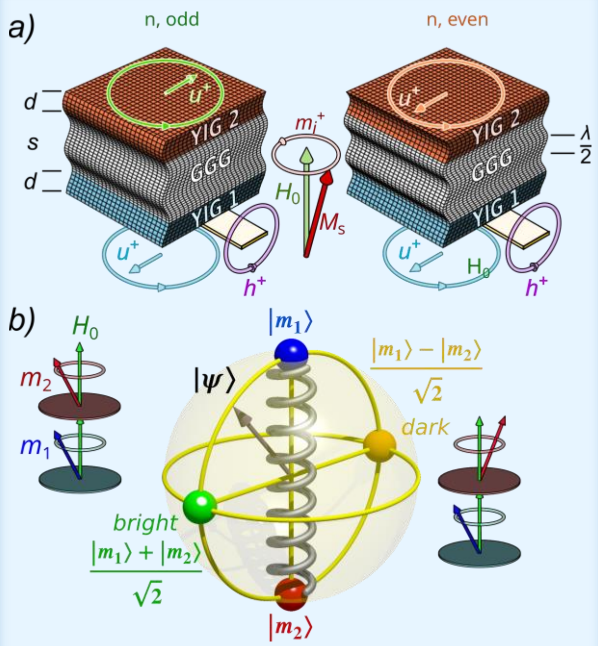

Fig. 1: a) Schematic representation of the dynamical coupling between two macrospin layers $|m_1>$ and $|m_2>$ mediated by chiral phonons. The magnetic precession generates a circular shear deformation u^+ of the crystal lattice that can be tuned into an acoustic resonance. The polarity of the mutual coupling is switched between tones separated by half a phonon wavelength. The orange/green colors indicate even/odd acoustic resonances. b) Bloch sphere representation of the generic hybridization of $|m_1>$ and $|m_2>$. The equatorial plane is reached when resonance of $|m_1>$ and $|m_2>$ are matched. It can evolve there to bright and dark states, which correspond to the extrema coupling to an inductive antenna.

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 may also pass through non-magnetic insulators by coupling to circular vibrations of the crystal lattice, called chiral phonons. However, the extent to which these phonons can mediate spin currents in a circuit remains to be demonstrated. In two recent experiments, a collaboration lead by researchers at SPINTEC used a microwave field to excite a current of chiral phonons through a thick non-magnetic dielectric spacer.

Fig.1(a) illustrates the coupled dynamics of two garnet magnets on opposite sides of a large single-crystal spacer. The magnets communicate by acting as "speakers" and as "microphones" for sound waves. Our solid-state realization consists of a half-millimeter-thick slab of nonmagnetic gallium gadolinium garnet coated epitaxially on both sides by the ferrimagnet yttrium iron garnet. The frequency can be tuned by applied magnetic field strength and directions, while we measure the magnetization dynamics electrically by induced voltages in Pt contacts and microwave absorption. Being in a regime where the interaction strength between the magnetic excitations is larger than their decay rate, the system is in the strong coupling regime, in which the entire system of magnetization and lattice can only oscillate coherently. One can illustrate the appeal of our method at the hand of the Bloch sphere shown in the Fig.1(b) that spans the phase space of the bonding and anti-bonding states that is relevant for a large community. Here it models the magnetic states of our double-sided YIG garnet sample, but the same notion is relevant for many other systems.

In an even more recent work, we expose for the first time the high cooperativity that can be achieved between the two macrospins, by showing that illumination of the bright / dark state by an external microwave field. The collective dynamics is here revealed by a simple electrical measurement using spin pumping effects (see Fig.2). By tuning the ferromagnetic resonances of the two magnets to an acoustic resonance of the intermediate, we control a coherent three-level system. We show that the parity of the phonon mode governs the indirect coupling between the magnets: the resonances with odd / even phonon modes correspond to out-of-phase / in-phase lattice displacements at the interfaces, leading to bright / dark states in response to uniform microwave magnetic fields, respectively.

We believe our demonstration to be a milestone in the field of magnetism. It is also a crucial step in the quest of developing integrated solutions in quantum technologies, in which long-range transport of coherent information between distant quantum gates is a key technological challenge. Furthermore, the additional knob to control the parity of the coupling is, to the best of our knowledge, unique. We envision that our findings will establish fruitful connections between the fields of magnetism and quantum information. Our work shows that acoustic phonons in garnets are probably the best waveform to couple coherently distant spins. This is because mechanical vibrations at microwave frequencies benefit there from very low damping. We expect that the next step is to merge our experiment with strongly coupled microwave cavity, which would add hybridization with microwave photons. While our demonstration is performed at room temperature, we envisage then quantum information exchange and distant entanglement of magnons, phonons, and microwave photons at low temperatures.

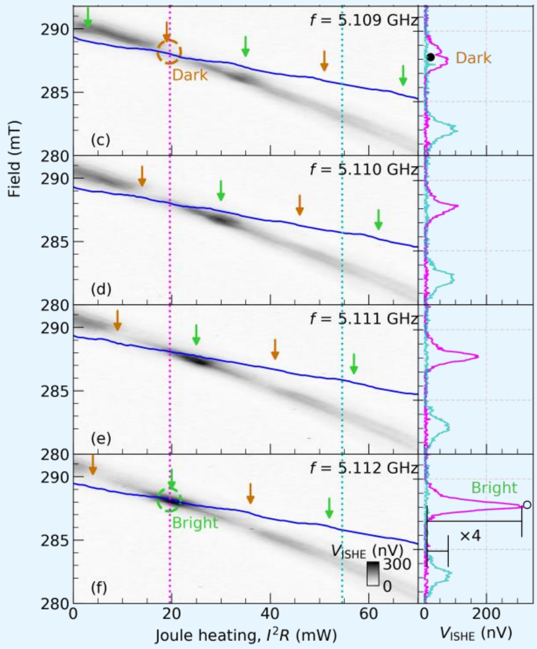

Fig. 2: Density plots of the spin-pumping-induced voltage, V_{ISHE}, in a Pt contact on the top YIG2 layer, as a function of vertical thermal gradient (Joule heating) and magnetic field observed at different frequency tuning relative to acoustic resonances. The blue solid lines are the maxima of the microwave absorption by YIG1. The right panel compares the modulation of the spin pumping signal measured either at zero detuning between the two Kittel resonances (purple vertical dotted line) or at large detuning (cyan vertical dotted line). The green and orange arrows indicate the positions of odd and even phonon resonances. The circles in (c) and (f) emphasize the triple resonance at which all frequencies agree. (c) At the intersection with an even lattice mode the peak splits and becomes ``dark". (f) At the intersection with an odd mode, the intensity gains a factor of 4, which confirms that the magnetization amplitudes of both YIG1 and YIG2 interfere constructively into a ``bright" mode.

Team: Spin insulatronics

Collaboration: CEA-Saclay, UBO Brest, Dassault Aviation, U of Tohoku (JAP) and U of Oakland (USA)

Funding: ANR MAESTRO, ANR-MARIN, EU-Pathfinder k-net, EU-Pathfinder PALANTIRI

Further reading: *Spin insulatronics* Arne Brataas et al., Physics Reports 885, 1 (2020). *Coherent long-range transfer of angular momentum between magnon Kittel modes by phonons* K. An et al. Phys. Rev. B 101, 060407 (2020). *Bright and dark states of two distant macrospins strongly coupled by phonons*, K. An et al., accepted to Phys Rev X (arXiv:2108.13272). *Roadmap on spin-wave computing concepts* A. Chumak et al., IEEE Transactions on Quantum Engineering (2022)

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Applying mechanical stress to cells: Towards innovative magnetism-based therapies

Mechanobiology, at the interface between physics and biology, studies the interactions between the cell and its physical environment. Of particular interest are the cellular reactions to the various mechanical stresses to which they are subjected. We have developed an original approach where mechanical stress results from the vibrations of magnetic particles, in contact with cells. This work, in partnership with our colleagues from INSERM BrainTech Lab, CNRS LTM and IRIG/SyMMES, highlights the cytoskeleton sensitivity to vibrations and the associated biological reactions of the cells. This field in which magnetism offers unique means of exerting a remote actuation on the cells, can open innovative therapies against cancer and other diseases.

The wide field of biophysics has attracted a tremendous interest over the past two decades, revealing for instance the key role of mechanical forces and transduction at the cell level. Crucial findings such as the PIEZO transmembrane proteins that form the basis for mechanically activated ionic channels involved in the sense of touch (2021 Nobel Prize in medicine), underlined the importance of the field of mechanobiology.

SPINTEC has been active in this area over the past 10 years, demonstrating that magnetic nanoparticles provide a unique tool to remotely exert forces and torques, at the nanoscale, on living cells.

Depending on the details of the mechanical stimulation, many cells reactions can be triggered, including activation of necrosis or apoptosis pathways in cancer cells, insulin secretion in pancreatic cells, change in the motility of diffusing cells, stem cell differentiation, etc. The literature reports studies in this field in which the stress was applied locally, on single cells, e.g. with an AFM probe, or applied globally, e.g. by stretching the underlying substrate. In this regard, the originality of SPINTEC's approach is that it is both local and global: the vibrating particles are either bound to the cells membrane or dispersed within the cytosol, providing a local cell stimulation. At the same time, the vibration is applied globally by an alternating magnetic field to a large number of in vitro or in vivo cells. Their reactions are subsequently characterized both locally (by microscopy) and globally (i.e. by colorimetric measurements).

Our first goal has been to design magnetic particles that, when put into vibration with a remote magnetic field, give rise to forces up to the nano-Newton range. As the forces and torques scale with the particle magnetic moment, it was realized that the small superparamagnetic particles often used for biomedical application were not suited. We needed to consider significantly larger, micron-sized ferromagnetic particles. One challenge to overcome was that ferromagnetic particles in this range of size tend to form large agglomerates when they are in a liquid, due to their dipolar interactions. To overcome this, we had to conceive particles with the lowest possible remanent moment and self-polarization. In a first approach, we have synthesized various types of particles fulfilling these requirements by a top-down technique, in particular synthetic antiferromagnetic particles, ferrimagnetic iron oxide particles, and Py disks with a vortex micromagnetic structure. Among those, the vortex particles, with their high magnetization and low saturation fields, constitute the best compromise in terms of magnetic properties and ease of fabrication (Fig. 1). In a second approach, we have developed a new type of magnetic particles, made from ball-milled magnetite, allowing high volume production of magnetic particles.

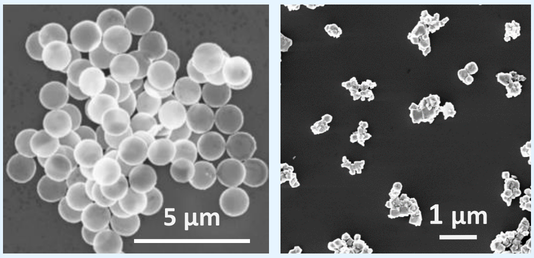

Fig. 1. Left: Vortex magnetic particles. The particles are gold-coated thin disks with a permalloy core. Right: Ball-milled magnetite iron-oxide particles.

Another requirement is that the particles should have a low intrinsic cytotoxicity. For nanoparticles that underwent endocytosis, this toxicity could arise due to the harsh intracellular environment, resulting in a slow surface degradation and metal ions release (which, for instance, precludes the use of rare-earth magnetic materials). In our case, the low toxicity was demonstrated in vitro with vortex particles and magnetite, for a variety of cells lineages (SKRC-59 human renal cancer cells; U87 glioblastoma cells; 3T3 mouse fibroblast cells…). In most cases, in vitro cells show no sign of particles-related stress at doses corresponding to a few hundred particles per cell (Fig. 2).

Although the particles are non-toxic, they have a devastating effect on cells when put into vibration using a remote alternating magnetic field. This was observed in a series of in vitro studies with our partners from SyMMES (Marie Carrière, Yanxia Hou-Broutin) and from INSERM BrainTech Lab (François Berger), where gentle vibration of the particles, typically at 20 Hz for 20 minutes, led to massive destruction of cancer cells. This is an important finding regarding glioblastoma, given that it is a form of brain cancer with a very poor prognosis, for which there is currently no effective treatment. However, the positive results obtained with in vitro experiments were not confirmed in vivo, with tumor-bearing mice, for which no increase in survival rate was observed after treatment with vibrating particles. This underlines the important differences between investigations carried out in a 2D in vitro environment vs. with living tissues. Therefore, as an intermediate step, we are now conducting studies on 3D cell spheroids in gel with structure and mechanical properties more related with those of real tissues.

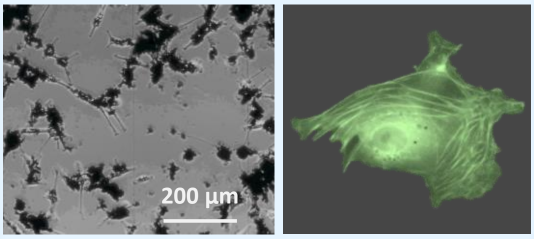

Fig. 2. Left: Snapshot of a toxicity test with U87 glioblastoma cancer cells incubated with vortex magnetic particles. Right: 3T3 mouse fibroblast cell with vortex particles in its cytosol, to the right of the nucleus. Here the cytoskeleton is made visible thanks to actin staining.

Besides being efficient cell-killers (at least in vitro), vibrating particles can trigger more subtle cells reactions, especially when lower mechanical energy is delivered to the cells. In a first experiment, we have demonstrated that more gentle mechanical vibrations promote apoptosis rather than necrosis. This was demonstrated with magnetite nanoparticles covered with a variable thickness layer of flexible PEG polymer chains (longer PEG chains resulting in damped vibrations). Although the signaling pathways leading to apoptosis are complex, this observation may be ascribed to the vibration-induced stress or damages to the actin skeleton. In addition, our partners from BrainTech Lab have observed a significant decrease in cells mobility following mechanical vibrations due to the disorganization of the cytoskeleton. Taken together, these findings indicate that magnetic particles can be used as a probe to reveal the cells response to local mechanical stimulation. With this in mind, we have looked more closely at the effect of mechanical vibrations on the organization of the actin cytoskeleton (Fig. 2). For that purpose, we have established a collaboration with the CNRS LTM laboratory (Alice Nicolas). This lab has developed a Traction Force Microscopy technique that allows measuring the stress field generated by a cell's cytoskeleton deposited on a soft gel. The biophysical modeling of the results will provide clues on the dynamical re-arrangement of the cytoskeleton driven by the vibrations, not only in cancer cells - where mobility is a key element for tumor invasion and metastasis - but also in stem cells where mechanotransduction is a key factor for the onset of differentiation.

These studies in biomedical and biophysical sciences illustrate the role that SPINTEC can play in fields that, at first glance, may seem aside of its core activity. Nevertheless, the expertise of the laboratory in magnetism and its know-how in the fabrication of nanostructures allow it to collaborate in an original and fruitful way with the biology/biomedical community.

Teams: Health and Biology, Instrumentation

Collaborations: Alice Nicolas (CNRS/LTM), François Berger (INSERM/BrainTech Lab), Marie Carrière and Yanxia Hou-Broutin (SyMMES)

Funding: ERA-NET COFUND NANOVIBER, FET ABIOMATER, Projet UGA/IRGA Magcell

Further reading: *Magneto-mechanical treatment of human glioblastoma cells with engineered iron oxide powder microparticles for triggering apoptosis,* C. Thébault et al., Nanoscale Adv. 3, 6213 (2021), *Open access: hal-03375349.*

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Strengthening the relationships between magnetism and microelectronics communities

Bringing spintronics to industrial applications requires combining expertise in magnetism and microelectronics. This is true in particular for MRAM. Historically, the magnetics and microelectronics communities have been working independently from each other. Very soon, we realized the need to strengthen the relationships between these two communities. For this purpose, we launched in 2013 the annual Introductory Course on Magnetic Random Access Memory (InMRAM) and organize every year a MRAM Global Innovation Forum at IEDM, the main annual international microelectronics conference.

For more than 50 years, microelectronics has progressed along the roadmap guided by Moore's law without requiring the use of any magnetic materials. The Hard disk drive industry was separated from microelectronics with almost no relationship between them. No education in magnetism was given to students in electrical engineering. Besides, microelectronic technologies are based on a very limited number of materials (Si, SiO2, Cu, HfO_2,…), the introduction of a new material in fabrication lines was each time a revolution, and magnetic materials were considered among the worse types of impurities contaminating the wafers. As a result, when researchers working in spintronics started to present their results on MRAM in microelectronic conferences, the first reactions were not positive: "this is much too complex", "this will be impossible to manufacture with so many layers of different materials", "impossible to control thicknesses with 0.1nm accuracy"… All this despite the fact that spin-valves and magnetic tunnel junctions were in commercial production for hard-disk-drive read heads since 1998. It was clear that the cultural gap between magnetism and microelectronics was wide and deep and this was hampering the development of MRAM technology and more generally of all spintronic technologies.

We therefore decided to act to reduce this gap. First, we organized an annual Introductory Course on Magnetic Random Access Memory (InMRAM). The first edition took place in 2013. InMRAM has a pedagogical goal. It aims at helping students, researchers and engineers having little or no background in magnetism to better understand the physics and working principles of MRAMs as well as at giving to young researchers in magnetism this specific training to ease their integration in industry. The courses are organized during two and a half days. They cover various aspects of MRAM technology: the basic spintronics phenomena involved in MRAM, the materials, the various categories of MRAM (pros/cons, performances, degree of maturity, R&D trends), a comparison with other technologies of non-volatile memories, the fabrication process, and the perspectives that they provide for sustainable electronics. A visit of SPINTEC is also proposed during InMRAM so that attendees can see what a spintronics lab looks like. Every edition received an average of about 70 attendees, both from academia and industry. The latest (virtual) edition had 130 attendees.

A second series of events that we organize annually are the MRAM Global Innovation Forums. This series of Forums was initiated by Samsung in 2012. However, since 2017, the responsibility of their organization was given to SPINTEC. These Forums are organized every year the day following IEDM, the main annual conference of the IEEE Electron Devices Society. These Forums usually gather about 250 attendees. Their purpose is to bring together experts in magnetism and microelectronics and jointly discuss recent developments in MRAM and future spintronic technologies.

9th MRAM Global Innovation Forum organized in San Francisco in December 2017. 280 attendees participated to this Forum. The Forum consisted in 10 invited talks from industry and academia and a panel discussion.

Funding: ERC HYMAGINE, ERC MAGICAL

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ESM and ESONN Schools – Two higher-education events chaired by SPINTEC

Production of new knowledge and know-how in science and technology is the main mission of SPINTEC. Contributing to this mission provides SPINTEC with an ideal situation to disseminate forefront knowledge. We endorse our responsibility here, by chairing two major European Higher-Education Schools: the European School on Nanoscience and Nanotechnology (ESONN), and the European School on Magnetism (ESM).

The European School on Nanosciences and Nanotechnologies (ESONN) is an annual course aimed at providing training for about 50 graduate students, postdoctoral and junior scientists coming from universities and research centers all around the world, a major and fast-growing field both in academia and industry due to its considerable potential for economic development. Organized by Univ. Grenoble Alpes (UGA), Grenoble INP – UGA Institut d'ingénierie et de management (G-INP) and with participation of CNRS and CEA, ESONN is promoted for advanced learning based on leading-edge research in collaboration with European universities and research centers. It proposes annually a three-week program comprising both lectures and laboratory courses aiming to offer young researchers a structured view of principles involved in the elaboration and functioning of nanostructures, nanocomponents and nanodevices. ESONN program is endowed with two key points. The first one is interdisciplinarity with lectures delivered by scientists from European universities and centers covering selected areas of nanosciences and nanotechnologies in physics, chemistry and biology. The second point emphasizes the role of laboratory hands-on courses within Grenoble labs (including four topics of SPINTEC) providing a unique opportunity to address a complete set of aspects, such as nanofabrication, elaboration, techniques of measurements, characterization and the physical principles behind them. ESONN is guided by an organizing committee composed by colleagues from UGA, G-INP, CNRS, CEA, and advised by a scientific advisory committee composed by leading scientists. ESONN is currently directed by Mairbek Chshiev and Liliana Buda-Prejbeanu from SPINTEC.

The European School on Magnetism (ESM) is a major higher-education event in the field of Magnetism, alongside its worldwide counterpart, the Summer School of the IEEE Magnetics Society. ESM is a two-week-long event gathering every year circa 100 participants in a hosting place traveling in Europe. Participants are primarily PhD candidates plus 10-20% post-docs, coming from 30-40 countries, mostly in Europe. The program covers the broad basics of magnetism the first week, then addresses a specific topic during the second week. Activities are diverse to contribute to learning, self-thinking and networking: formal lectures, question sessions, tutorials and practicals, access to a dedicated library, industry perspectives, projects and poster presentations from the students. ESM finds its roots in a French-Romanian School, initiated in the 1990's and led by Grenoble on the French side. ESM has been progressively enlarged for broad participation of lecturers and participants at the scale of Europe. It is now embedded in the European Magnetism Association, and guided by a steering committee and a scientific advisory committee. Yet, it remains chaired in Grenoble by O. Fruchart at SPINTEC, with the support of O. Isnard at Institut Néel.

We believe that these events contribute to the reputation of Grenoble in research and education, and are proud to currently lead their organization. Yet, both share the challenge to maintain high quality and visibility, while tackling the societal issue of greenhouse gas emission and global warming. Our strategy is to turn these events in a mixed format, a move that was accelerated by the unfortunate advent of the COVID pandemi

Partners: Institut Néel, the European Magnetism Association (EMA).

Further information: ESONN: *http://www.esonn.fr*; ESM: *http://magnetism.eu/school*.

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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

The team aims at unraveling spin-dependent transport properties of antiferromagnets. Antiferromagnetic materials could indeed 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.

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 team contributes to the 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 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. candidates, 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 spintronic 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**, the 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, electric and magnetic characterization, condensed-matter theory, numerical simulations, and the design of dedicated integrated circuits.

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.

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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