spintec
SPIN IN ELECTRONICS

Highlights

2019

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FOREWORD

This booklet gathers a selection of scientific highlights of SPINTEC over the year 2019. Besides these, we mention below a few cornerstones in the life of the laboratory, along with the prospects for SPINTEC in 2020.

2019 was a year full of events!

The scientific highlights in this booklet provide an insight in our key publications, signature for our mission to advance knowledge. In parallel to these, we maintained our high level of production of intellectual property, signature for our mission to contribute to innovation. Both missions have been supported this year by new funded projects, such as the extension of the DARPA project on skyrmions, institutional projects within the framework of H2020 and the ANR (5 new contracts this year) and bilateral international agreements (IFW Dresden, Tsukuba, KAUST), as well as new industrial partnerships (Intel, Hprobe, Crocus Technology, Antaios).

Contractual resources now exceed 3.5 M€ annually, providing us with a healthy financial situation. These have generated unflagged financial resources, allowing us to support strategic actions: co-funding for PhD grants, internal calls for new equipment, refurbishment of offices and meeting rooms. In addition, the national/ regional investment called Minatec labs enabled us namely to consolidate the hosting of most of our colleagues in our main building, and also supported investment in new equipment (a deposition cluster for the growth of 2D materials and an NV center microscope).

2019 saw the birth of the Interdisciplinary Research Institute of Grenoble (IRIG) to which SPINTEC belongs with. This new Institute is bringing new and exciting scientific opportunities for our lab, both within the Department for Physics DEPHY on various topics, like simulation, materials and quantum electronics, and with our biologist colleagues from other departments. The laboratory days held in Vercors mountains in October were an opportunity to discuss collectively the scientific and organizational challenges for the years to come, and sustain our collective life. Human is indeed the most valuable wealth of a research lab, and as such we are proud of our ten PhD students graduating in 2019, and the three new permanent staff joining us.

2020 is coming with new challenges!

We believe that, more than ever, spintronics offers opportunities at the cross-roads of research and societal challenges: in quantum electronics, neuromorphic and high-power computing, Internet of Things. In a highly competitive environment, we need to foster internal and networking synergies and ensure the development of these strategic research topics.

Materials are key in spintronics. In 2020 we will ramp-up the 2D epitaxy cluster, with an ambition for international visibility. We also need to resource our capacities in complex stacks and state-of-the-art tunnel junctions, for which we pursue a dual strategy: designing in-house a novel compact deposition cluster, while pursuing our efforts to set-up a full spintronic pilot line.

We will sustain our efforts to bring the innovative potential of spintronics better recognized, within SpintronicFactory, the European Magnetism Association and the IEEE Mag Soc, as well as through the scientific higher-education schools we are organizing: ESONN, InMRAM and ESM. Entering the era of the newly-created Grenoble Alpes University bringing together the universities and engineering schools is also an exciting prospect!

Finally, a particular focus will be dedicated to transverse topics, such as the ethics of science, and how to reduce the carbon footprint of our activities.

We hope that you will enjoy browsing the following pages.

Lucian Prejbeanu, Executive Director

Olivier Fruchart, Deputy Director

CONTENTS

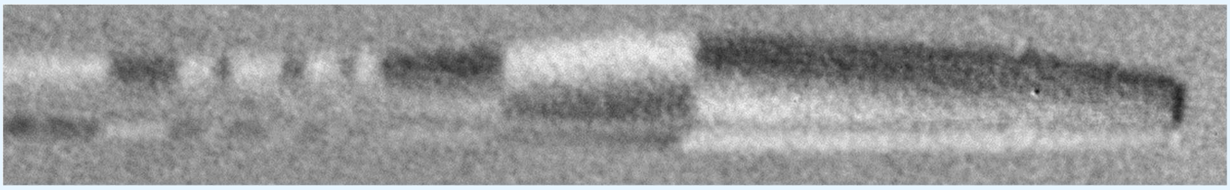
Electroless plating to produce flux-closure nanotubes for three-dimensional spintronics building blocks

The conceptual proposal for a so-called race-track three-dimensional data storage device based on domain walls in a dense array of vertical wires, revived the attention on cylindrical magnetic nanostructures. While mostly nanowires have been considered so far, nanotubes, i.e. a shell with an empty core, would open the door to core-shell structures, whose interfaces could be used to implement various spintronic effects. Here we report the development of a new building block: a material with azimuthal anisotropy based on electroless deposition, yielding flux-closure domains in tubes.

The common route for the fabrication of long cylindrical structures is deposition in a sacrificial template displaying pores, such as anodized aluminum or polycarbonate irradiated foils. Electroplating is the usual route to fabricate wires. Bath composition and plating parameters can be tuned to yield tubes, however the conditions are often critical to control. Instead, we used electroless plating. This is an in-solution conformal chemical synthesis, which unlike atomic layer deposition is suitable to deposit directly 3d magnetic metals Fe, Co, Ni and their alloys. We targeted FeNi and CoNi alloys, liable to serve as soft magnetic materials, while boron is also included to some extent, being the reducing agent used. The present tubes had a length of 30 µm, diameter 350 nm, and shell thickness of a few tens of nm. The templates were dissolved and the tubes laid on a supporting surface for further investigation.

We inspected these tubes using the high-spatial-resolution magnetic microscopy technique XMCD-PEEM and STXM at the French SOLEIL and Italian ELETTRA synchrotron facilities. This way, we provided the first images of well-defined domains and domain walls in magnetic nanotubes. Surprisingly, in the case of $(Co_{80}Ni_{20})B_x$ magnetization curls around the tube axis in a flux-closure fashion, the changing sign of circulation defining domains, while for anisotropic and very long objects such as our tubes, axial magnetization is expected. We believe, this results from an anisotropic strain between the azimuthal and axial directions, resulting from the inward radial growth. Indeed, the less magnetostrictive alloy $(Fe_{20}Ni_{80})$ B_x displays axial magnetization.

In terms of physics, the well-defined domain walls and the various possible directions of magnetization of these materials provide a toolkit to investigate domain-wall motion in tubes in the future, which so far have only been considered theoretically. In terms of functionality, the flux-closure $(Co_{80}Ni_{20})B_x$ material provides a mean to greatly decrease the considerable dipolar interactions existing between domain walls in wires, which are of head-to-head or tail-to-tail type, thus unavoidably associated with a magnetic charge.



10x1.5 µm magnetic image of a $(Co_{80}Ni_{20})B_x$ nanotube using the synchrotron-based shadow XMCD-PEEM technique. The wire appears at the bottom of the image, while the above part is the shadow, whose light/dark contrast reveals the curling of magnetization around the tube axis. The contrast alternation along the tube axis reveals domains with opposite sign or curling.

Team: Spin textures

Collaboration: Institut Néel, Univ. Darmstadt (Pr. W. Ensinger), Synchrotrons SOLEIL and ELETTRA.

Funding: Labex LANEF (Grenoble).

Further reading: *Imaging magnetic flux-closure domains and domain walls in electroless-deposited CoNiB nanotubes,* M. Staňo, S. Schaefer, A. Wartelle, M. Rioult, R. Belkhou, A. Sala, T. O. Menteş, A. Locatelli, L. Cagnon, B. Trapp, S. Bochmann, S. Martin, E. Gautier, J. C. Toussaint, W. Ensinger, O. Fruchart, SciPost Phys. 5(4), 038 (2018). DOI: *10.21468/SciPostPhys.5.4.038*

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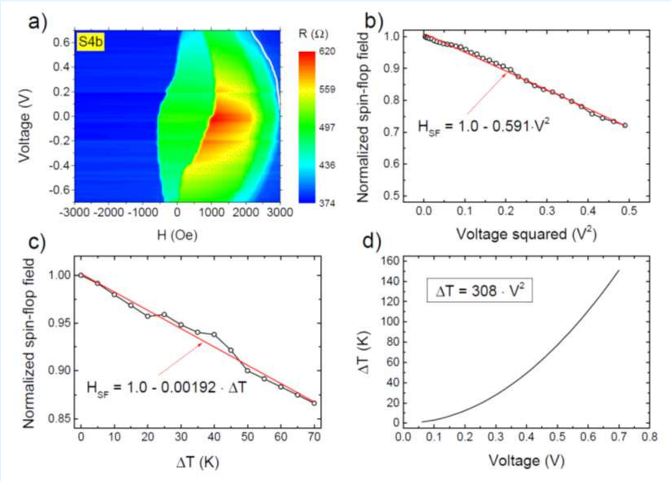
Impact of heating on the stability phase diagrams of perpendicular MTJs

Measured switching diagrams of perpendicular magnetic tunnel junctions exhibit an unexpected behavior at high voltages associated with significant heating of the storage layer. The boundaries deviate from the critical lines corresponding to the coercive field, which contrasts with the theoretically predicted behavior of a standard macrospin-based model. In this paper, we are proposing a modified model which considers the Joule heating during the writing pulse.

A large number of studies related to spin transfer torque switching in magnetic tunnel junctions (MTJs) were conducted over the past few years, in support of the development of spin transfer torque magnetic random access memory. This memory uses as storage elements out-of-plane magnetized MgO-based MTJs exhibiting large tunnel magnetoresistance and strong interfacial perpendicular magnetic anisotropy. This anisotropy originates from the MgO/FeCoB interface, which provides high thermal stability of the storage layer magnetization. Recent experimental observations and theoretical studies of switching diagrams give an almost complete description of STT-induced switching processes in MTJ. However, at high voltage, most experimental diagrams show a deviation from the theoretically predicted behavior. This effect might be associated with the heating due to Joule dissipation around the tunnel barrier and the resulting variation of the storage layer magnetic properties.



(a) Experimental stability diagram measured under dc voltage (b) Linear fit of normalized spin-flop field-voltage squared dependence. (c) Linear fit of normalized spin-flop field-temperature variation dependence. (d) Temperature elevation due to current flow versus voltage

In this paper, we present our experimental studies and their theoretical description using a macrospin model that takes into account the heating effects. These results point out the strong influence of the Joule heating on switching abilities of MTJs at high voltages. We measured the stability V-H diagrams in a variety of samples of different composition and diameters in which significant Joule heating take place during STT writing. We explained the high voltage anomaly of the V-H diagrams as due to heating effects in the storage layer. Two mechanisms of the asymmetry of the critical lines for positive and negative voltages were suggested: heating asymmetry induced by the asymmetric inelastic relaxation of tunneling electrons, and heating asymmetry due to the difference of the resistance in P and AP states. The second mechanism makes the largest contribution to the heating asymmetry versus bias voltage when the TMR is large. We also developed a modified macrospin-based model by including a dependence on the applied voltage, of the material parameters such as uniaxial anisotropy constant, spontaneous magnetization and STT prefactor. The model was used to numerically simulate the V-H diagrams. Very good agreement with the experimental results was obtained. The presented model can be used in pMTJ-based MRAM circuits design to take into account such unusual behavior of the MTJ properties at high bias voltages. Moreover, the predictions presented in this study can be extrapolated to similar multilayer stacks used for other applications.

Teams: MRAM, Theory and Simulation

Funding: ERC Advanced Grant MAGICAL no 669204

Further reading: *Impact of Joule heating on the stability phase diagrams of perpendicular magnetic tunnel junctions*, N. Strelkov et al, Phys. Rev. B 98, 214410 (2018), DOI: 10.1103/PhysRevB.98.214410

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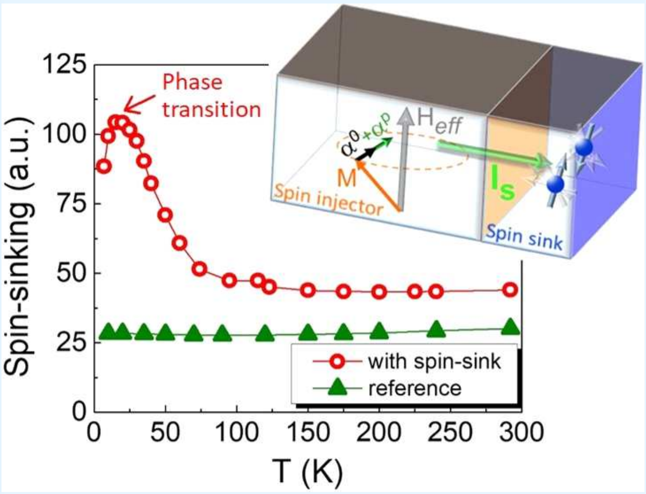
A generic probe for spin fluctuations in nanometer-scale films

In the field of spintronics, which relies on the spin-dependent transport properties of matter, exploring spin fluctuations and phase transitions in ultrathin films is essential as it provides key information to engineer materials for applications. Here, O. Gladii *et al* investigated the generic character of a novel method to probe spin fluctuations through demonstration with ferromagnetic and antiferromagnetic orders, metallic and insulating electrical states.



By scanning the temperature it is possible to find enhanced spin-sinking due to spin fluctuations. Inset: the spin pumping experiment.

Spin currents are key contributors to applied science. The spin pumping effect has attracted considerable attention in this area, due to its versatile capacity to unravel a variety of spin-dependent transport phenomena. The spin pumping method consists in bringing a ferromagnetic layer out-of-equilibrium, known as the spin injector, to generate a spin current and propagate this latter into a neighboring layer known as the spin-sink. In earlier experiments, the antiferromagnetic spintronics team demonstrated that spins propagate more efficiently in a spin sink where the magnetic order is fluctuating rather than static, thus providing a novel method to probe magnetic phase transitions. Experimental application of the method proved to be more useful for antiferromagnetic spin-sinks due to the absence until then of a benchtop technique to access paramagnetic-to-antiferromagnetic transitions in thin films. Whether the method applies for metallic and insulating spin-sink, and whether the underlying phenomenon is observed when spins are carried by conduction electrons (electronic transport) and by excitation of localized-magnetic-moments (magnonic transport) were still a subject of debate.

In this work, O. Gladii *et al* experimentally demonstrated that spin pumping can be used as a generic probe to identify spin fluctuations. By selecting representative materials - ferromagnetic and antiferromagnetic orders, metallic and insulating electrical states - and interacting environments to promote either electronic or magnonic transport, the results show that the phenomenon applies with all kinds of ordering and electrical states and all kinds of spin current. These findings should contribute to future advances in characterization and engineering of new materials.

Team: Antiferromagnetic spintronics

Collaboration: LPS Orsay, OPTIMAG Brest, CIME Grenoble, SyMMES Grenoble

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

Further reading: *Spin pumping as a generic probe for linear spin fluctuations: demonstration with ferromagnetic and antiferromagnetic orders, metallic and insulating electrical states,* O. Gladii, L. Frangou, G. Forestier, R. L. Seeger, S. Auffret, M. Rubio-Roy, R. Weil, A. Mougin, C. Gomez, W. Jahjah, J.-P. Jay, D. Dekadjevi, D. Spenato, S. Gambarelli, V. Baltz, Appl. Phys. Express 12, 023001 (2019). DOI: *10.7567/1882-0786/aaf4b2*

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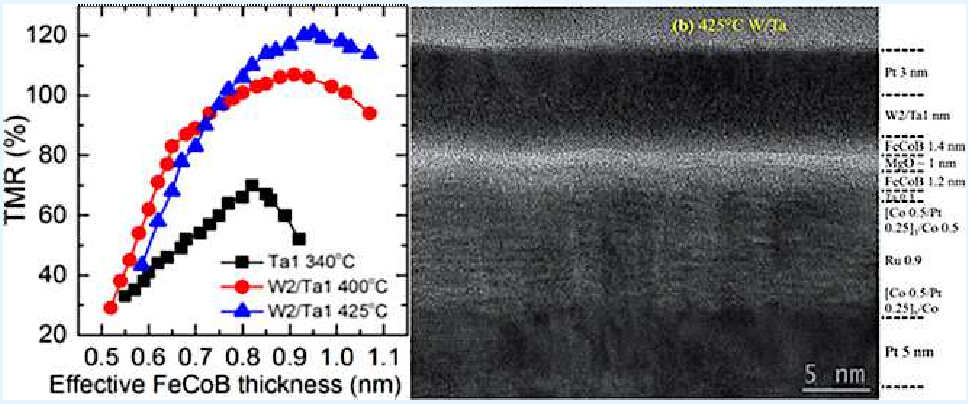
Physicochemical origin of improved MRAM cells with W capping layer

Increasing the thermal budget of magnetic random access memory (MRAM) cells beyond 400°C is a major goal to allow for seamless conventional electronics integration. At these temperatures, significant material diffusion can disrupt the interface properties of new generation perpendicular magnetization stacks targeting technology nodes below 20nm. This study highlights the origin in the improvement obtained with tungsten capping layers.

Recent offerings of Magnetic Random Access Memory (MRAM) in embedded CMOS designs is a trend emerging at the most advanced foundries. These cells rely on perpendicular anisotropy magnetic tunnel junctions, which are a typical layer stacks comprising thin layers of 8 or more materials, each one having a specific contribution to the cell performance. Improvements in tunnel magnetoresistance (TMR) and in cell retention are high up on the requirement list. TMR signal allows for faster read times with targets set at the ns level to achieve parity with SRAM cells. High TMR ca be achieved at higher annealing temperatures over 400°C. However, elemental diffusion forces to compromise at lower temperatures.



TMR signal of FeCoB storage electrode with W/Ta capping layers. Improvement by high temperature annealing is only possible with W cap. It prevents loss of Fe from the top FeCoB electrode, illustrated in stack cross section annealed at 425°C.

SPINTEC's research has highlighted that the loss of TMR at high temperatures can be traced back to diffusion of Fe away from the MgO tunnel barrier and towards the top electrode capping layer. For capping layers made of Ta the maximum annealing temperature is below 400°C. The present work demonstrated that adding a refractory material like W above the FeCoB top electrode, it is possible to increase the annealing temperature to 425°C, leading to almost a doubling of TMR from 70% to 120%. In fact, tungsten blocks the diffusion of Fe maintaining the perpendicular anisotropy at higher temperatures. As a welcome consequence the cell information retention time also improves by 50%, allowing for 10 year storage times at dimensions close to 20nm. Achieving a higher annealing stability is important for integration with CMOS devices, since typical high pressure deuterium annealing steps to improve transistor performance are done at 400°C.

Team: MRAM

Funding: ERC Adv grant (MAGICAL No. 669204)

Further reading: *Physicochemical origin of improvement of magnetic and transport properties of STT-MRAM cells using tungsten on FeCoB storage layer*, J. Chatterjee, E. Gautier, M. Veillerot, R.C. Sousa, S. Auffret, B. Dieny, Appl. Phys. Lett. 114, 092407. (2019). DOI: *10.1063/1.5081912*

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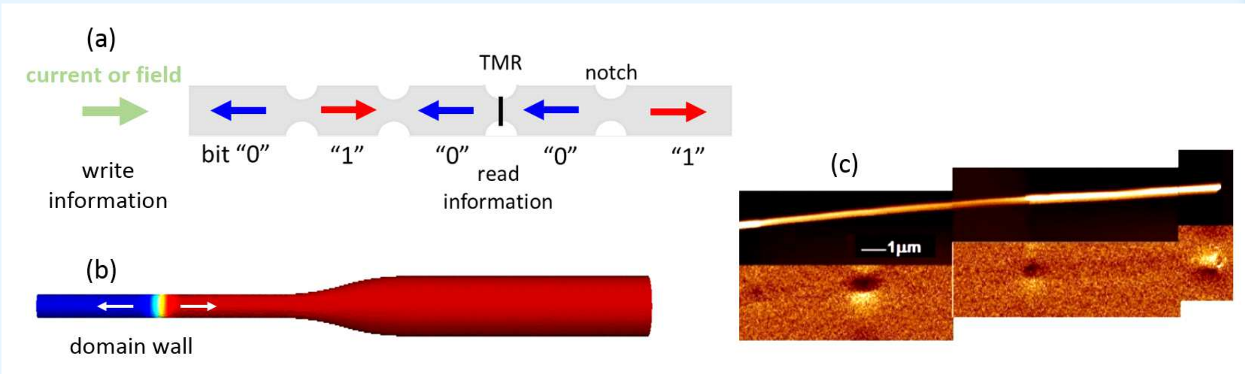
Modeling magnetic-field-induced domain wall propagation in modulated-diameter cylindrical nanowires

Abstract. Domain wall propagation in modulated-diameter cylindrical nanowires is a key phenomenon to be studied with a view to designing three-dimensional magnetic memory devices. In this framework, we quantified theoretically the driving force needed for a domain wall to overcome the potential barrier related to modulated diameter geometry in order to jump from one stable position to another.

The technique of electrochemical growth of cylindrical nanowires is continuously progressing, and is nearing compatibility with the design of a three-dimensional race-track memory. The information stored in this type of solid-state device would be encoded by magnetic domains separated by magnetic domain walls. The control of the domain wall position may be achieved by introducing geometrical inhomogeneities during the fabrication process. Smaller cross-section reduces the internal domain wall energy and thus plays the role of an energy well, which implies that some threshold driving force must be applied to overcome the barrier.



(a) Illustration of the domain wall based magnetic memory concept. (b) Illustration of the domain wall simulated in modulated-diameter cylindrical nanowire. (c) Topography and magnetic image of a NiCo alloy nanowire with three distinct segments of different diameter (from PhD thesis of B.Trapp).

In this context, we proposed both a quantitative micromagnetic description of the domain wall behavior using our home-made finite element micromagnetic software, and a simplified analytical model which relates geometric parameters to the critical driving force needed to unpin the domain wall. Qualitative analytical model for gently sloping modulations resulted in a simple scaling law. We focused on the case of wall motion under the conservative driving force produced by a magnetic field applied along the wire’s axis. It shows that the domain wall depinning field value is mostly proportional to the modulation slope. Our approach is quite general and may be extended further to study the effect of other driving forces such as spin-polarized current in order to assist experimental system design.

Teams: Theory/Simulations and Spin textures

Funding: ANR JCJC MATEMAC-3D, FP7/2007-2013 M3d n°309589

Further reading: *Modeling magnetic-field-induced domain wall propagation in modulated-diameter cylindrical nanowires*, J. A. Fernandez-Roldan, A. De Riz, B. Trapp, C. Thirion, M. Vazquez, J.-C. Toussaint, O. Fruchart, D. Gusakova. Scientific Reports, 9, 5130 (2019). DOI: *10.1038/s41598-019-40794-1*

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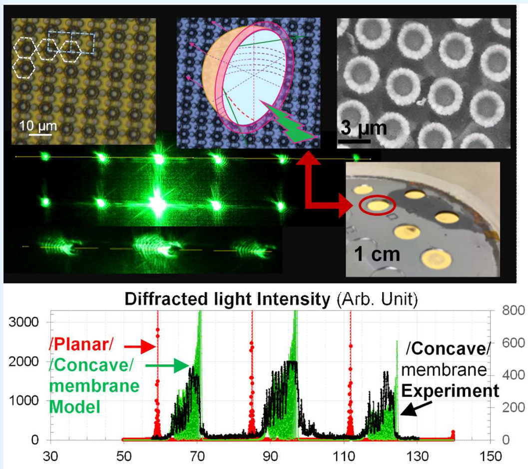
Magnetic control of optical responses of biocompatible magneto-elastic membranes

Numerous studies investigated the use of synthetic membranes for photonic or biomedical applications. We report here on a recent type of biocompatible magnetically actuated membranes, partly originating from studies on magnetic particles for biology, consisting of PDMS/Au bilayers with embedded arrays of micrometric magnetic pillars. Flat at zero field, concave in an applied magnetic field, they turned out to constitute magnetically tunable diffraction gratings, with magnetically controlled optical responses fitted by our analytic magneto-mechanical-optical model in excellent agreement.

Artificial membranes are increasingly explored for various applications. In particular in biology, for understanding the living or acting on it with therapeutic purposes, or in optics-related fields as flexible photonic devices, biology and optics being potentially linked for instance in vision studies. Moreover, the great potential of elastic membranes embedding magnetic particles, lies in their ability to be remotely actuable by an external magnetic field.

On this basis, we report here on a new type of magneto-elastic membrane recently developed at SPINTEC. Our films are constituted of polydimethylsiloxane (PDMS)/Au bilayers (5µm/100nm-thick) with embedded arrays of permalloy pillars, prepared by lithography techniques at the Platform PTA. PDMS films are indeed renowned for their tunable elastic modulus, biocompatibility and optical properties (high transparency).

Our membranes, suspended over apertures created in their silicon substrates, were tested by a set of optical experiments. The study included their magnetic and elastic characterization and modelling. In particular, the expression of magnetic forces exerted by a permanent magnet, enabled the membranes deflections calculation.



Sketch and photo of suspended magnetoelastic membranes (8mm-diameter) on their Si substrate, and optical/SEM imaging of the embedded magnetic micro-pillars arrays, yielding flexible and magnetically tunable diffraction gratings.

We showed that membranes, flat or deformed by the applied magnetic field, illuminated by a laser beam, produced a very strong optical response to the magnetic field in reflection, depending on their microstructure and concave.

Our membranes turned out to constitute thus magnetically tunable optical diffraction gratings for visible light wavelengths, in reflection. The diffraction patterns of the ~1 cm-diameter-membranes could be significantly modified by slight membrane deflections, in the range of 50 µm down to a few hundreds of nm.

More generally, these results suggest that this type of biocompatible actuable magneto-elastic membranes presents potential applications in adaptive optics, photonic devices, as well as in biophysics, biology and biomedical applications. Highly multidisciplinary, such studies may address micro- nano- magnetism, optics and photonics science, as well as biological and biomedical research.

Team: Health and Biology

Collaboration: IRIG / SyMMES (biochemistry and surfaces treatments). Technology at PTA.

Funding: EU's Horizon 2020 research and innovation program under grant agreement No 665440.

Further reading: *Optical response of magnetically actuated biocompatible membranes*, H. Joisten, A. Truong, S. Ponomareva, C. Naud, R. Morel, Y. Hou, I. Joumard, S. Auffret, P. Sabon and B. Dieny, Nanoscale 11, 10667 (2019). DOI: *10.1039/C9NR00585D*

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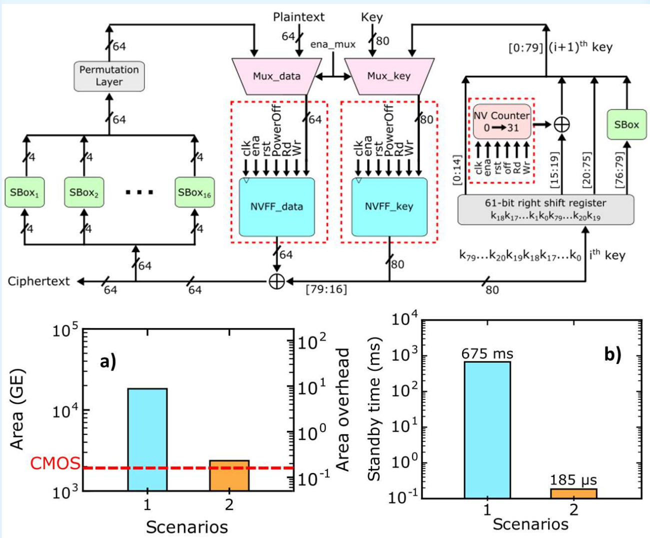
Light-Weight Cipher Based on Hybrid CMOS/STT-MRAM: Power/Area Analysis

Internet of Things (IoT) applications deployment relies on low-power and security constraints. In this perspective, lightweight cryptography has been developed. This field enables, with a reduced area and power consumption, to encrypt sensitive data processed in an integrated circuit and transmitted to a connected object. This work proposes to implement the PRESENT lightweight cryptographic algorithm using STT-MRAM in order to improve its performance compared to a pure CMOS cipher.

The number of communicating data exploded with the IoT deployment. However, with time-to-market pressing demand, the security of this data is not always guaranteed. In this context, this work proposes to design a hybrid CMOS/STT-MRAM PRESENT cryptographic algorithm in different technology nodes in order to reach a better power efficiency compared to a CMOS cryptographic algorithm, enabling then its integration in the IoT.



Proposed hybrid CMOS/STT-MRAM PRESENT cryptographic algorithm. a) Evaluation of the area in GE (Gate Equivalent) and the overhead evolution compared to the pure CMOS structure. b) Sleep energy evolution (nJ).

The first implementation of this structure was realized using a 180 nm bulk CMOS process and 200 nm STT-MRAM junction diameter (scenario #1 in the figure). Electrical simulations of this hybrid algorithm has demonstrated a better power efficiency of this architecture for "normally-off" applications. Actually, the hybrid CMOS/STT-MRAM algorithm of scenario #1 is power efficient after 675 ms of inactivity compared to the CMOS version, which is already interesting for many IoT applications. Indeed, unlike the CMOS that has standby power consumption, the hybrid version does not consume energy while it is off. However, its physical implementation is 9 times larger than the pure CMOS one. Several evaluations were realized for different technology nodes down to the 28 nm FD-SOI and a junction size diameter of 40 nm (scenario #2). In this case, the area overhead is limited to only 23 % and the power efficiency is reached after only 185 µs. Therefore, such a configuration is clearly interesting for energy saving in many applications not limited to IoT.

In perspective, the circuits that have been fabricated (CMOS and scenario #1) as part of the GREAT project will be shortly tested in order to determine their response facing physical attacks, aiming to retrieve the secret data.

Team: Spintronics IC design

Collaboration: CEA tech (Gardanne), IM2NP – Aix Marseille University (Marseille).

Funding: GREAT European project, MASTA ANR project.

Further reading: *Light-Weight Cipher Based on Hybrid CMOS/STT-MRAM : Power/Area Analysis*, M. Kharbouche-Harrari, G. Di Pendina, R. Wacquez, B. Dieny, D. Aboulkassimi, J. Postel-Pellerin and J-M. Portal, In 2019 IEEE International Symposium on Circuits and Systems (ISCAS). DOI: *10.1109/ISCAS.2019.8702734*

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Impact of eddy currents in nanostructures destined for use in spintronics

In the field of spintronics, ferromagnetic/non-magnetic metallic multilayers are core building blocks for emerging technologies. Resonance experiments using stripline transducers are commonly used to characterize and engineer these stacks for applications. Here, we investigated the incompletely understood impact of eddy currents below the microwave magnetic skin-depth and explained the line shape asymmetry and phase lags reported in stripline experiments.

In ferromagnetic resonance (FMR) experiments, eddy currents need to be carefully considered to accurately determine damping and other related spintronic properties such as spin-mixing conductance and the spin-Hall angle in spin-pumping experiments, especially when characterizing low-damping materials. This type of effect has been thoroughly studied for film thicknesses above the skin-depth limit. In contrast, below this limit, the effects of eddy currents were most often neglected, except for series of comprehensive studies focused on microwave screening/shielding in ferromagnetic/non-magnetic(F/NM) metallic multilayers.

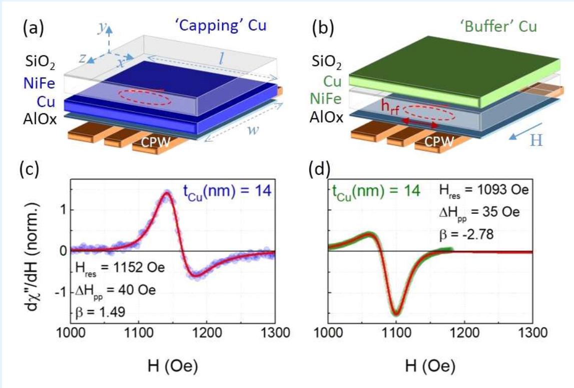

Illustration of the stacking order-dependent sign-change of microwave phase due to eddy currents in nanometer-scale NiFe/Cu heterostructures.

Using a coplanar stripline transducer, we investigated experimentally the broadband FMR response of few nanometer-thick NiFe/Cu and Cu/NiFe bilayers. The main contribution of our study is that it represents systematic experimental evidence of a stacking-order-dependent sign-change of the microwave phase. The effect could be ascribed to eddy currents generated in the Cu layer in the sub-skin-depth regime by the time varying magnetic fields in the experiment. Distinct sets of experimental data - layer thickness-, frequency- and size- dependences, were consistent with a simple quantitative analysis encompassing the main features of the phenomenon. Remarkably, the model could account for the difference in the thickness-dependence of Cu-resistivity due to the inversion of the growth order.

These results contribute to our understanding of the impact of eddy currents below the microwave magnetic skin-depth and explain the contributions to lineshape asymmetry reported in stripline experiments. They also provide a straightforward way to detect the contributions of eddy currents from NM-adjacent conductors, as a caveat for the need in some cases to take these contributions into account.

Teams: Antiferromagnetic spintronics, Microwave devices

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

Further reading: *Stacking order-dependent sign-change of microwave phase due to eddy currents in nanometer-scale NiFe/Cu heterostructures,* O. Gladii, R. L. Seeger, L. Frangou, G. Forestier, U. Ebels, S. Auffret, V. Baltz, Appl. Phys. Lett. 115, 032403 (2019); DOI: *10.1063/1.5093150*

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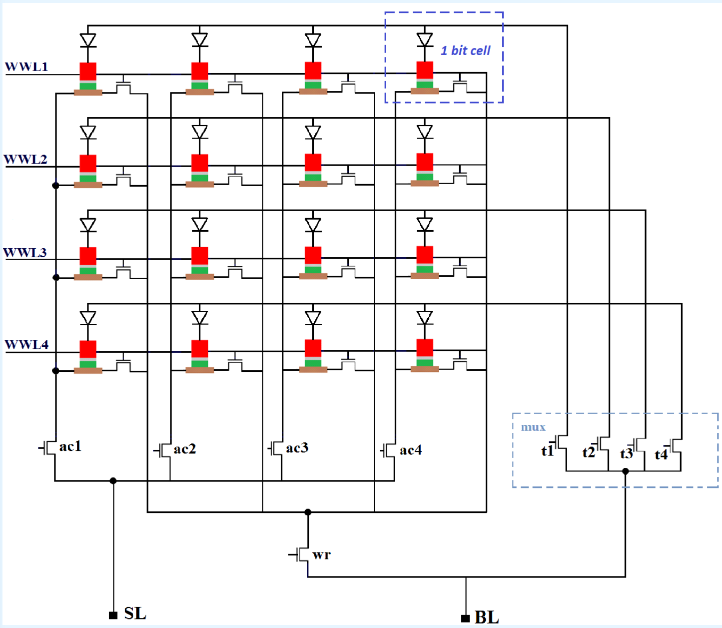
High-density SOT-MRAM memory array based on a single transistor

Spin Orbit Torque Magnetic RAM (SOT-MRAM) approach represents a new way to overcome Spin Transfer Torque (STT) memory limitations by separating the reading and the writing paths. It is particularly interesting for high-speed applications that do not require very high density because of two transistors per bit cell. This work introduces a high-density SOT-MRAM memory based on a single transistor and a unidirectional diode.

The key idea to improve the area density of SOT-MRAM is to use one transistor per bit cell so that we can obtain a comparable density as DRAM and STT-MRAM.



Equivalent schematic of 4x4 SOT-MRAM memory array based on a single transistor and one diode

The figure presents the architecture of 4x4 SOT-MRAM memory array based on a single transistor for writing and a unidirectional diode for reading. The diode passes unidirectional current through MTJ during reading operation only, so zero leakage current is passing during write mode. When a bit cell memory is selected in programming mode, all the transistors (ti) of multiplexer are kept deactivated. WWL1, write (wr), and access column (ac1) transistors are set to VDD to write the first cell. Positive write voltage on BL (or SL) is applied so that the current is flowing from BL to SL through the conductive layer to write ‘1’ logic (or ‘0’). On the other hand, when a memory cell is selected in reading mode, wr transistor and WWLi are kept low and the diode selector has to be polarized in forward mode to deliver the maximum current through the memory point.

Compared to conventional SOT-MRAM, which is based on two transistors, the area density is approximately improved by 20%. For further density improvement, this diode can be developed by materials elements since minimizing the bit cell area is limited by the design rules. For a matrix of order n rows and m columns, the number of transistors in our proposed architecture is m.(n+1) compared to conventional structure which is 2.(nxm) transistors.

Team: Spintronics IC design

Funding: CEA LETI, Minatec campus

Further reading: *High density SOT-MRAM memory array based on a single transistor*, 18th Non-Volatile Memory Technology Symposium (NVMTS), 2018. DOI: 10.1109/nvmts.2018.8603114

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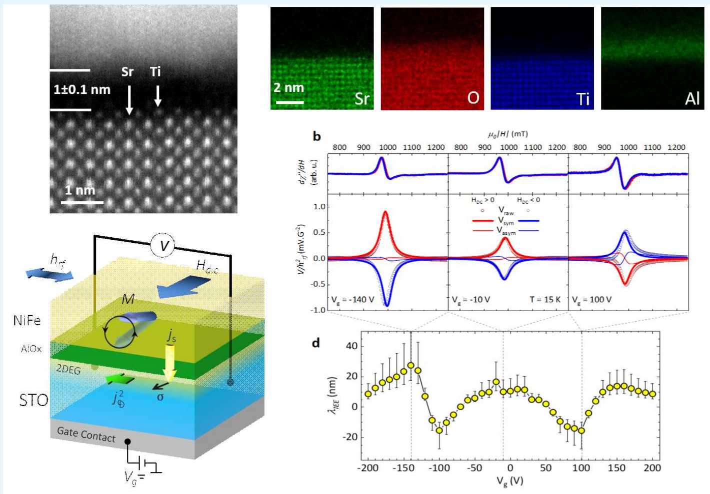
Mapping Spin-Charge conversion in a topological oxide 2DEG

Spin-charge conversion phenomena harnessing the spin orbit coupling are promising for the future of spintronics, allowing in one way (charge–to-spin) the generation of torque on magnetic elements and in the other way (spin-to-charge) the detection of spin current for spin logic or neuromorphic operations. We report a highly tunable and record spin-to-charge conversion in a simple system, consisting of an aluminum layer deposited on a SrTiO3 substrate, and map its dependence on the SrTiO3 band structure.

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



Z-contrast scanning transmission image of the NiFe/Al/SrTiO3 interface with elemental EDX spectra (top). Schematic of the dynamical spin injection and spin charge conversion (left). At ferromagnetic resonance, a spin current is injected into the 2D electron gas and converted into a transverse charge current by the inverse Edelstein effect. (b) The three panels correspond to experiments made at different back gate voltages. (d) Evolution of the conversion yield, expressed as the inverse Edelstein length, as a function of the back gate voltage applied to the SrTiO3 substrate.

For the latter, oxide 2DEGs are promising as their spin-charge conversion efficiency is large (see *our earlier work with LaAlO3/SrTiO3 2DEGs*). In a new paper published in Nature Materials, we demonstrate a very large spin to-charge conversion effect in an high carrier-density SrTiO3 2DEG generated by the sputter-deposition of Al at room temperature, and map the dependence of this effect to the band structure (as measured by ARPES). We show that the conversion process is amplified by enhanced Rashba-like splitting due to orbital mixing, and in the vicinity of avoided band crossings with topologically non-trivial order.

Our results also alleviate the need of high quality crystalline growth of the LAO oxide layer that is usually required for the formation of the 2DEG at the STO surface. Moreover, due to the multi-orbital nature of STO, a gate voltage allows tuning the conversion, both in sign and in amplitude. Respect to our previous results a zero gate voltage allows obtaining a large conversion (see figure) and conversion rates are enhanced by a factor of 4, from 6 nm to about 25 nm. These results indicate that oxide 2DEGs are strong candidates for spin-based information readout in novel memory and transistor designs, and emphasize the promise of topology as a new ingredient to expand the scope of complexe oxides for spintronics.

Team: Spinorbitronics

Collaboration: Unité Mixte de Physique CNRS/Thalès, CEA-IRIG in Grenoble, the Martin-Luther-Universität Halle-Wittenberg, the LPEM at ESPCI Paris, the Laboratoire de Physique des Solides in Orsay, the University of Geneva and the Helmholtz-Zentrum Berlin

Funding: ANR TOPRISE, ANR OISO

Further reading: Mapping spin-charge conversion to the band structure in a topological oxide two-dimensional electron gas. D. C. Vaz, P. Noël et al. Nature Mater. 18, 1187 (2019) DOI: *10.1038/s41563-019-0467-4*

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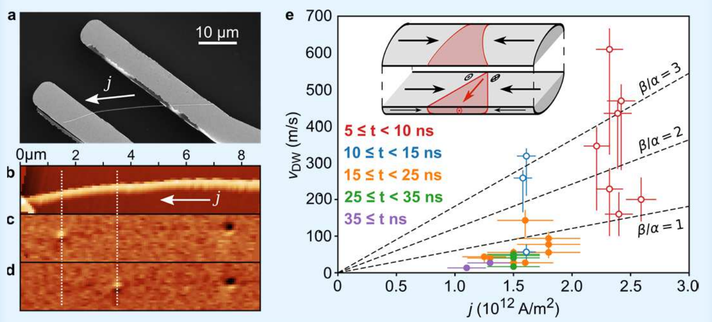
Topology and Œrsted field prevent Walker breakdown in cylindrical nanowires.

Domain-wall motion in one-dimensional conduits is both a textbook case for magnetization dynamics and the understanding of spin torques, and of practical importance for the design of novel spintronic ICT devices. However, instabilities known as Walker breakdown limit the speed in most cases. We have shown experimentally and confirmed by simulation, that these instabilities are circumvented in cylindrical nanowires, under the combined effects of the Œrsted field and the specific topology of their walls.

During domain wall motion, the core of walls tend to enter a precessional motion under the stimulus of either external magnetic field or spin-transfer torques. While this is counterbalanced by internal torques (exchange, dipolar etc.) under moderate stimulus, no balance is possible above a given threshold. This induces a drop of the wall mobility called the Walker breakdown, associated with a stochastic behavior. For more than a decade, numerous theoretical reports predicted that the Walker breakdown is suppressed in cylindrical conduits, due to a specific topology of the domain walls, called Bloch-point walls. However, disappointedly, a recent report of ours suggests that this may not be the case for walls moved under magnetic field.



(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.

Following this, we developed a specific clean-room process to contact electrically chemically-synthesized cylindrical nanowires with a low contact resistance, presently $Co_{30}Ni_{70}$ with diameter 90 nm. This allowed us to conduct the first experiments of purely current-induced wall motion in cylindrical nanowires, with a few nanosecond time scale, monitored by both XMCD-PEEM and magnetic force microscopy. We evidenced that Bloch-point walls are robustly stabilized by the Œrsted field arising from the charge current, contrasting with the instability we reported earlier under magnetic field. This comes with wall speed in excess of 500 m/s under current density circa $2x10^{12}$ A/m^2, a five-fold increase compared with all other cases of direct spin-transfer-torque wall motion of large-magnetization ferromagnets such as 3d elements. These results are reproduced quantitatively by simulations, which confirms the unique absence of Walker breakdown in this cylindrical geometry.

These results illustrate the use that can be made of three-dimensional magnetization textures and their specific topology, a topic of rising interest in the broader context of three-dimensional and curvilinear magnetism. We expect that this first experimental report motivates further work to seek confirmation of the many theoretical predictions of wall motion in cylindrical nanowires. In particular, we are now not far from the 1 km/s limit, at which speed a strong coupling is expected between domain walls and spin waves, and called the magnonic regime.

Teams: Spin textures, Theory and simulation

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

Funding: EU M3d, ANR JCJC Matemac 3D.

Further reading: *Fast domain walls governed by OErsted fields in cylindrical magnetic nanowires*, M. Schöbitz, A. de Riz, S. Martin, S. Bochmann, C. Thirion, J. Vogel, M. Foerster, L. Aballe, T. O. Menteş, A. Locatelli, F. Genuzio, S. Le Denmat, L. Cagnon, J. C. Toussaint, D. Gusakova, J. Bachmann, Olivier Fruchart, Phys. Rev. Lett. 123, 217201 (2019). DOI: *10.1103/PhysRevLett.123.217201*.

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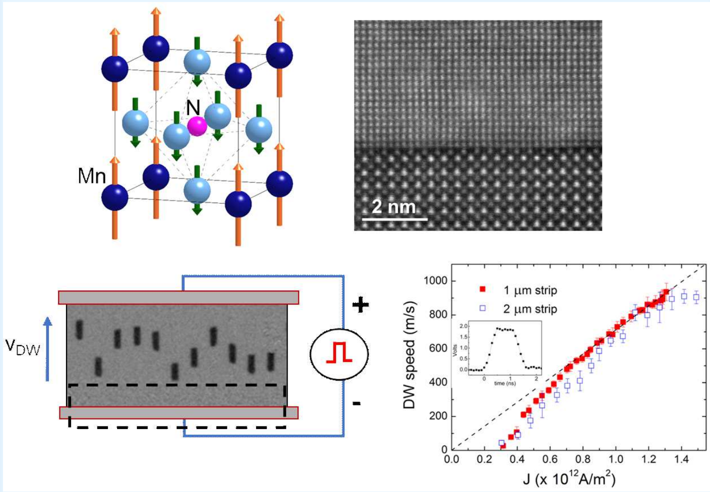
Large Current-Driven Domain Wall Mobility by pure spin transfer torque in Ferrimagnetic Mn_4N Thin Films

We found that Mn_4N, a rare-earth free ferrimagnet made of abundant elements, is an exciting candidate for the development of sustainable spintronics devices. This material possess exciting properties, and in particular domain walls can be moved at record speeds by spin-polarized currents, in absence of any external magnetic field. This is explained by the large efficiency of the adiabatic spin transfer torque, due to the conjunction of a reduced magnetization, of the perpendicular anisotropy, and of a large spin polarization.

Tsukuba university has developed the growth by molecular beam epitaxy of X_4N thin films, with X=Fe,Ni,Co,Mn. Among this material family, Mn_4N ferrimagnetic thin films grown epitaxially on SrTiO3 substrates possess remarkable properties, such as a low magnetization, a perpendicular magnetization, a very high extraordinary Hall angle (2%) and smooth domain walls at the millimeter scale.



(Top) Schematic of the atomic structure and Mn magnetic configuration. TEM image. (bottom) Domain wall displacement and deduced domain wall velocity as function of the current pulse.

We show that in this material record current-driven domain wall velocities can be obtained at room temperature, of nearly 1 km/s. The observed domain wall velocities largely surpass those obtained using spin transfer torques up to now, and are comparable to the best results reported for noncentrosymmetric stacks with interfacial Dzyaloshinskii-Moriya interaction (DMI) favoring chiral Néel walls. The low critical current is a consequence of the Perpendicular Magnetic Anisotropy (PMA) and of the low magnetization of this ferrimagnetic material, which leads to a low barrier for initiating the precession of the DW magnetization. Indeed the structure consist of two Mn sub-lattices antiferromagnetically coupled. The high DW mobility observed in the linear regime is a consequence of the small magnetization and of the high spin polarization. Whereas in the past years the whole spintronics community shifted its focus from spin−transfer torques to spin−orbit torques, these results show that classical spin−transfer torques remain highly competitive for current-induced domain wall (DW) motion and would allow reducing the operating power of memories based on DW displacement. In this article, we also show that the application of gate voltages through the $SrTiO_3$ substrates allows modulating the Mn_4N coercive field with a large efficiency. Moreover, Spintronics usually requires cobalt, rare-earth elements, and heavy metals (especially tungsten and platinum). These materials are based on elements identified as critical by the government agencies of developed countries because of the likelihood and impact of supply shortfalls, and of various geopolitical and environmental factors. As Mn_4N is made of cheap and abundant elements and does not include critical materials such as precious metals and rare-earths, it appears as a worthy candidate for sustainable spintronics applications.

Team: Spinorbitronics

Collaboration: Tsukuba University (T. Suemasu), Néel Institute (S. Pizzini, J. Vogel)

Funding: ISP project DOMINO (IDEX UGA)

Further reading: *Large current driven domain wall mobility and gate tuning of coercivity in ferrimagnetic Mn_4N thin films.* T. Gushi et al., *Nano Lett 19, 8716* (2019). DOI: *10.1021/acs.nanolett.9b03416*

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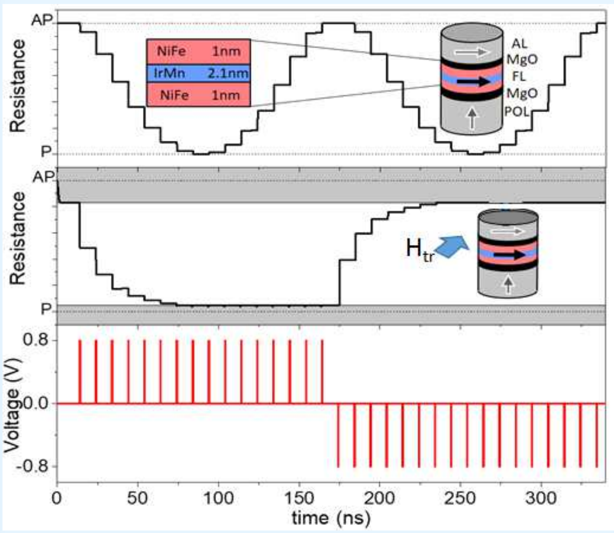
Spintronic memristor based on an isotropically coercive magnetic layer

We propose an original concept of spintronic memristor based on the angular variation of the tunnel magnetoresistance (TMR) of a nanopillar comprising several magnetic layers. We have experimentally developed the appropriate magnetic free layer and integrated it in a full nanosized magnetic tunnel junction pillar. In parallel, we developed a model describing the magnetization dynamics of this free layer under pulses of current with an additional dry friction dissipative term. The simulations confirm the memristive behavior of such device able to operate as a synapse for neuromorphic computing.



Resistance variation without (top panel) and with (middle panel) transverse in-plane field (H_{tr}) under a train of current pulses (bottom panel). Insets : schematics of the device and of the composite free layer.

Our goal is to develop a compact device able to reach multiple resistance states upon injecting nanosecond pulses of current and thus mimicking a synaptic function for neuromorphic circuits. The device is based on an in-plane magnetized magnetic tunnel junction composed of an analyzer layer (AL) with static magnetization and a free layer (FL). The key feature consists of stabilizing the FL's magnetization at different in-plane angles with respect to the AL's magnetization direction, enabling thus to sweep progressively the resistance between its minimum and maximum value thanks to the TMR effect. We have experimentally implemented and demonstrated this concept with a composite FL having an antiferromagnetic layer (IrMn) inserted between two thin NiFe layer (see inset of the Figure). The thickness of the antiferromagnet has been adjusted to get a negligible exchange bias (the hysteresis loops are centered on zero field) and a fairly large coercive field. This composite layer is experimentally exhibiting the desired in-plane isotropic properties relying on the spin frustration phenomena at the ferromagnet/antifferomagnet interfaces. To describe these experimental results, we have built a model based on the Landau-Lifshitz-Gilbert (LLG) equation by adding an additional dry friction term (by analogy to mechanics). The main effect of this term is to change the static equilibrium condition, enabling the magnetization to be stabilized in any in-plane direction at zero field. Under a large enough rotating field, the magnetization rotates behind the field with a certain drag angle. This was experimentally characterized by planar Hall effect measurements and confirmed by simulations. To control the state of free layer in an actual memristive device, spin transfer torque (STT) can be advantageously used. For this purpose, a second magnetic junction is placed at the bottom of the device serving as perpendicular spin polarizer (POL). In such configuration, the out-of-plane polarized spin-current induces a precessional motion of the FL magnetization. If the duration of the injected current pulses is equal to a fraction of the precession period, then the magnetization rotates step by step in the plane of the layer, clockwise or anticlockwise depending on the current polarity. The application of a transverse field allows to limit this angular rotation between 0° and 180° which is required to achieve a monotonous variation of resistance for each current pulse polarity. These combined experimental and numerical results are essential for the development of future synaptic-like memristor compact devices.

Team: MRAM

Funding: ERC Adv Grant MAGICAL No. 669204, CEA funding for "sujet phare"

Further reading: *Realizing an Isotropically Coercive Magnetic Layer for Memristive Applications by analogy to Dry Friction*, M. Mansueto, A. Chavent, S. Auffret, I. Journard, J.Nath, I.M. Miron, U. Ebels, L. D. Buda-Prejbeanu, I.L. Prejbeanu and B. Dieny, Phys. Rev. Applied 12, 044029 (2019). DOI: *10.1103/PhysRevApplied.12.044029*

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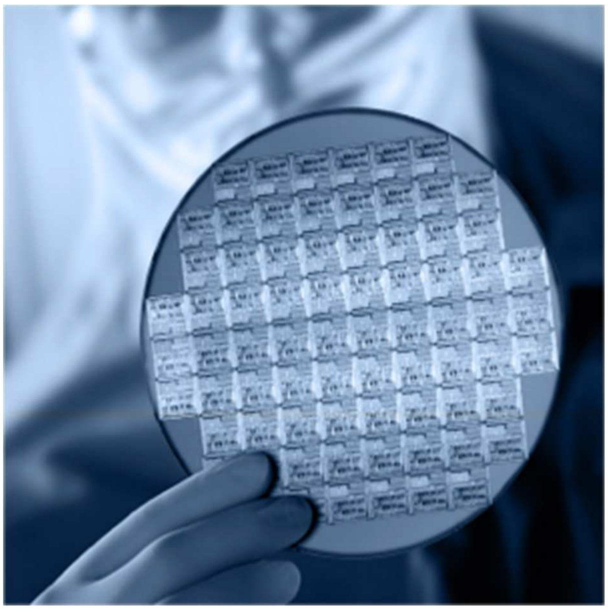
About SPINTEC

Positioned at the crossroad of science and technology, SPINTEC (SPINtronique et TEchnologie des Composants) is one of the leading spintronics research laboratories worldwide. Ideally located on the *MINATEC* campus in Grenoble, SPINTEC gathers, in a flexible and project-oriented organization, physicists and engineers from the academic and the industrial world. The laboratory was created in 2002 and rapidly expanded to currently reach 100 persons of which 38 Permanent staff and about 40 Ph.D. students, post-docs and international visitors. **The scientific institutions taking part in the lab are**: *CEA*, *CNRS*, the *University of Grenoble Alpes*.



SPINTEC objective is to **bridge fundamental research and innovative device technology in the fast growing field of spin electronics** (spintronics). The *international technology roadmap for semiconductors (ITRS)* now reckons that spintronics devices will play a major role in tomorrow's semiconductor chips, with the potential to totally displace the stand alone (e.g. DRAM) and embedded memory market. Other fast-developing fields include magnetic field sensors and bio-applications. In this context, it is our strategy to be at the forefront of scientific research, to generate a strong IP position and to establish the proper partnerships for technology transfer.

SPINTEC unique positioning brings together top-level scientists and applicative engineers that work in close collaboration in order to ensure that new paradigms can be swiftly translated into technology proof of concepts and functional devices. As such, **the outcome of the laboratory is not only scientific publications and communications in international conferences**, but also a **coherent patents portfolio** and implementation of **relevant functional demonstrators**.

Whereas the fundamental research is mostly operated through collaborative (financed) projects with other research laboratories, **the applied research is very often carried out in partnership with private actors**. These can be large corporations (Applied Materials, ST Microelectronics, Thales, Samsung, Seagate,…), SME's (SNR, Singulus,…) or start-ups (Crocus Technology, Menta, Spin Transfer Technologies,…). **SPINTEC has spun-off several start-up companies**, *Crocus Technology*, in 2006, *eVaderis* in 2014, and two others are emerging: *HProbe* and Antaïos.

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Research topics

MRAM MEMORIES

The Magnetic Random Access Memories (MRAM) team develops advanced concepts in this emerging technology. The goal is to realize cells with improved thermal stability, lower power consumption and/or faster switching. The research covers material stack deposition, nano-fabrication and electrical test evaluation, for applications as standalone memory and non-volatile logic.

MAGNETIC SENSORS

The team activities cover up-stream research on physical phenomenon potentially useful for future sensors, 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 measurements.

SPINTRONICS IC DESIGN

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

HEALTH AND BIOLOGY

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

SPIN ORBITRONICS

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

MICROWAVE DEVICES

Microwave oscillations of the magnetization around its equilibrium are the natural dynamical response to external perturbations. Identified devices include local oscillators, microwave filters, detectors, and non-reciprocal devices. Understanding the dynamics of these nano-objects, applying general concepts of microwave oscillator techniques and defining from this novel microwave applications is the major aim of this activity.

2D AND SEMICONDUCTOR SPINTRONICS

The « semiconductor and 2D spintronics » team deals with spin dependent phenomena in two important classes of materials: Si and Ge which are the materials of today’s microelectronics and transition metal dichalcogenides which are emerging 2D materials with exceptional optical and spin-orbit properties. We are studying model systems grown by molecular beam epitaxy and their spin properties.

ANTIFERROMAGNETIC SPINTRONICS

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

SPIN TEXTURES

The team is interested in novel spin textures, such as magnetic skyrmions and Bloch-point domain walls, which can be topologically-protected. This involves the three components of magnetization and/or three-dimensional distributions of magnetization. The team designs the systems, image the spin textures, and ultimately aim at addressing these with spin-polarized currents. The applied background includes the proposed concept of 3D race-track memory.

THEORY AND SIMULATION

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

Downtown Grenoble hill Bastille at the foreground, and 10 000-feet Belledonne mountains at the background, directly viewed from SPINTEC offices

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