# Highlights

# 2016 – 2017

SPINTEC, CEA Grenoble, – 17 rue des Martyrs – GRENOBLE (France)
http://www.spintec.fr direction.spintec@cea.fr

# CONTENTS


- FOREWORD 3
- Spin torque nano-oscillators: locking of damped and spin torque driven modes 4
- Magnetic skyrmions observed at room temperature 5
- Through disorder - A fluctuating magnetic order allows more spins to pass through an interface. 6
- Anatomy and Giant Enhancement of the Perpendicular Magnetic Anisotropy of Cobalt–Graphene Heterostructures 7
- Comparison of the use of NiFe and CoFe as electrodes for metallic lateral spin valves 8
- Giant and tunable spin-charge conversion at oxide interfaces 9
- Misalign to write faster 10
- Of spin super-conduction spin in electric insulators 11
- Magneto-optical micromechanical systems for magnetic field mapping 12
- A Novel Asynchronous Radiation-Hard Error Correction Structure Based on MRAM 13
- About SPINTEC 14



SPINTEC Highlights – December 2017 – Editor: Gregory Di Pendina

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

# FOREWORD

This booklet gathers a selection of scientific highlights of SPINTEC over the years 2016 and 2017. Besides these, several cornerstones in the life of the laboratory shall be mentioned over the same period.

We welcome the enlargement of the lab in Jan 2016, through merging with the laboratory Nanostructures and Magnetism also part of Institute INAC, which further strengthens our coverage of spintronic topics. Since that time we also welcomed three new permanents staff: François DUHEM in the team Spintronic IC design as a CEA researcher, Miguel RUBIO-ROY to support material synthesis and science as a CNRS research engineer, and Romain GIRAUD in the team Spinorbitronics as a CNRS researcher. For the first time our laboratory peaked at 100 total staff.

On the innovation side, SPINTEC confirmed its innovation footprint, with the creation of two new spin-off companies: HProbe to exploit instrumental developments and notably electric probers under three-dimensional configurations of magnetic field, and Antaïos to exploit our IP for SOT-MRAM.

Finally, we keep pushing forward our experimental capacities with the development of a magnetic scanning near-field optical microscope, and the emergence of a project for a cluster of chambers for the synthesis of 2D materials, supported both by CPER Minatec labs and IDEX Univ. Grenoble Alpes. Three European projects have also been starting, expanding our collaborative network and securing our funding.

We hope that you will enjoy browsing the following pages.

Lucian Prejbeanu, Executive Director

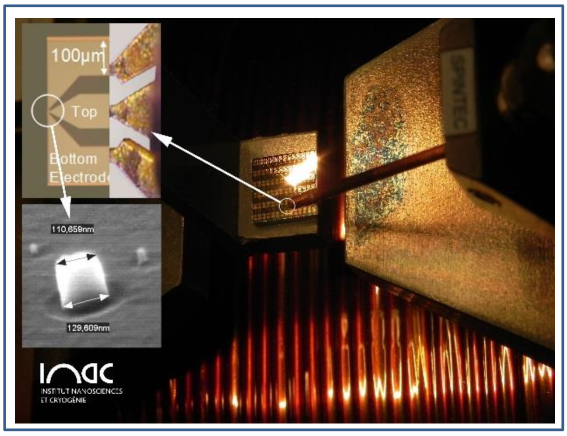
Olivier Fruchart, Deputy Director

## Spin torque nano-oscillators: locking of damped and spin torque driven modes

**Spintronic concepts and materials are well known for their applications in data storage, magnetic memory and hybrid logic devices. Besides, they can also bring novel approaches for the realization of microwave components such as rf signal sources or rf detectors. These applications are based on the fact that a spin polarized current can counteract the natural damping forces and induce large angle steady state (non-damped) excitations in the free layer of a magneto-resistive device.**

While most of the experimental results can be explained within a picture where the free layer of the magneto-resistive device, is excited independently, there are a number of observations that cannot be captured within this picture. For instance our experiments on spin valve nano-pillars, reveal non-continuous features such as gaps and kinks in the frequency field dependence.

With the aid of macrospin simulations it could be shown that these deviations result from the dynamic dipolar interaction of the free layer steady oscillations with the damped oscillations of the polarizing layer. In fact the free layer steady oscillation frequency is down-shifted when increasing the spin polarized current density. When this frequency, or one of its higher harmonics, gets close to the frequency of one of the damped modes, dipolar interaction fields radiated by the oscillating free layer, can start pumping the damped mode. This generates a new hybridized mode in a certain range of current and fields, where the steady state and damped modes are frequency locked resulting in strong deviations in the frequency-field dispersion and even discontinuous jumps. A further interesting observation, accompanying this non-linear interaction, is that it can also lead to a reduction of the linewidth of the steady state mode.




These results have provided a first insight into the effect of interlayer coupling on the non-linear dynamics of spin torque driven excitation. They are of interest to further exploit interaction effects between layers within a magneto-resistive stack to improve the microwave performances for applications.

This work has been realized at INAC/SPINTEC in collaboration with CEA/LETI.

Further reading: *Influence of interlayer coupling on the spin-torque-driven excitations in a spin-torque oscillator*, M. Romera, E. Monteblanco, F. Garcia-Sanchez, B. Delaet, L. D. Buda-Prejbeanu, U. Ebels, Phys. Rev. B 95, 094433 (2017). DOI: 10.1103/PhysRevB.95.094433

@ Ursula.ebels@cea.fr

# Magnetic skyrmions observed at room temperature

**These nanoscale magnetic structures have been observed at room temperature in materials compatible with the microelectronics industry by O. Boulle and his colleagues from SPINTEC in Grenoble. These results break an important barrier for the use of skyrmions as nanoscale information carrier in our computers.**

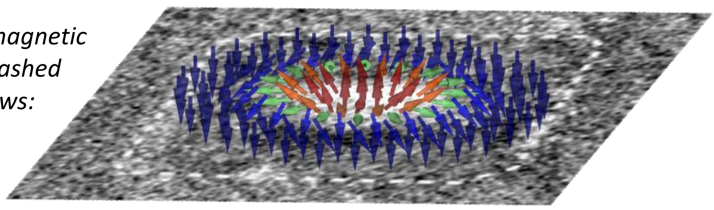
It's an important breakthrough that was recently made by O. Boulle and this colleagues from SPINTEC and Institut Néel in Grenoble by demonstrating magnetic skyrmions stable at room temperature. These structures are currently fascinating many research groups in the world, as they could offer a new way to store and process information in our computers. These nanoscale magnetic particles are composed of elementary nanomagnets that wind to form a stable spiral structure, like a well tighten node. Although predicted in the 80's, it has only been observed for the first time in 2009. Three years later, two research teams demonstrated that skyrmions can be manipulated by very low electrical currents, which opens a path for their use as information carriers in computing devices. Several groundbreaking memory and logic devices based on the manipulation of skyrmion in nanotracks have thus been proposed, that promise very large information density and low power consumption. However, these applications still remained distant as skyrmions had been observed only at low temperature or in the presence of large magnetic fields and in exotic materials far from any applications.

By demonstrating skyrmions stable at room temperature and in the absence of external magnetic field, O. Boulle and his colleagues have thus broken a major barrier. To reach this result, they deposited an ultrathin magnetic layer of cobalt (a few atom thick) in sandwich between a layer of a heavy metal (platinum) and a layer of magnesium oxide. The physical mechanisms at the origin of the helical shape of the skyrmion arising at the interfaces of heavy metal and oxides, the effects are here strongly enhanced. In addition, the deposition techniques used, named sputtering deposition, has the advantage of being fast and is commonly used in the microelectronics industry.

Once the material was identified, the next step was to shoot a picture of the skyrmion, in particular its internal spiral structure. The wavelength of the visible light being too large, it was necessary to highlight the skyrmion using the very pure X-Ray generated in synchrotrons. To observe the skyrmion and its internal structure, very high spatial resolution "XMCD-PEEM" magnetic microscopes have been used at the Elettra synchrotron in Trieste, Italy and in Alba synchrotron in Barcelona, Spain. The next step will be to move these skyrmions using electrical current, a move further toward the use of these particles to code and manipulate the information at the nanoscale in computing devices.

These results were obtained through a collaboration between several French laboratories: SPINTEC and Institut Néel in Grenoble, the laboratory of process and material sciences, Paris 13 University. The XMCD-PEEM magnetic imaging experiments were carried out in Alba synchrotron in Barcelona, Spain, and in Elettra synchrotron in Trieste, Italy.

*In black and white: magnetic microscopy image of a magnetic skyrmion in the middle of a squared nanodot (white dashed line, approximately 400 nm wide). Colored arrows: illustration of the magnetic structure of the skyrmion.*



Further reading: *Room-temperature chiral magnetic skyrmions in ultrathin magnetic nanostructures*, O. Boulle, J. Vogel, H. Yang, S. Pizzini, D. de Souza Chaves, A. Locatelli, T. O. Menteş, A. Sala, L. D. Buda-Prejbeanu, O. Klein, M. Belmeguenai, Y. Roussigné, A. Stashkevich, S. Mourad Chérif, L. Aballe, M. Foerster, M. Chshiev, S. Auffret, I. M. Miron, G. Gaudin, U. Ebels, Nat. Nanotech. 11, 449 (2016). DOI: 10.1038/nnano.2015.315

@ Olivier.Boulle@cea.fr

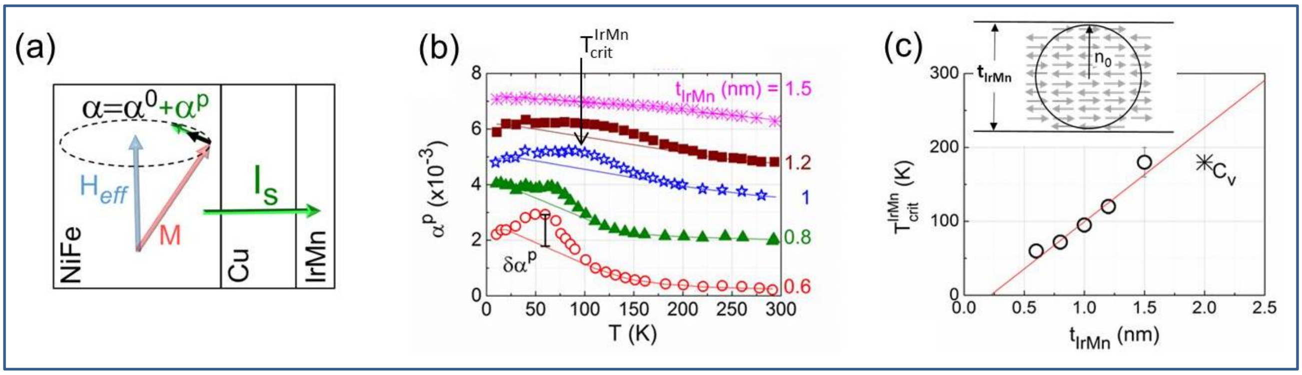
## Through disorder - A fluctuating magnetic order allows more spins to pass through an interface.

**Bringing a ferromagnetic layer to resonance creates non-equilibrium magnetization dynamics which generates a spin current. The spin current propagates from the ferromagnet into a neighboring layer if permitted by the interface. This is equivalent to saying that the air-flow generated by rotating the blades of a fan can propagate in a neighboring room if the door between the rooms is open. Our experiments show that spins propagate more efficiently in a neighboring zone where the magnetic order is fluctuating rather than static. Basically, a fluctuating order allows more spin orientations to pass through the interface.**

The samples were fabricated by sputtering. The ferromagnetic resonance measurements were conducted in a resonant cavity at a fixed frequency with variable magnetic field and temperature.

These experimental findings will help us progress towards the development of more efficient spin sources, while also providing an alternative method to probe magnetic phase transitions. This type of alternative method is particularly needed to deal with the case of thin materials with no net magnetic moments, such as thin antiferromagnets. Antiferromagnetic order is expected to have a high potential in next-generation spintronic applications, a field known as antiferromagnetic spintronics.

This study was financed by the French National Agency for Research via contract ANR-15-CE24-0015-01 'JCJC ASTRONICS'. It results from several collaborations within the INAC.




*(a) Diagram representing the spin pumping experiment. Non-equilibrium magnetization dynamics of a spin injector (NiFe) pumps a spin current ($I_S$) into an adjacent layer, called the spin sink (IrMn). This spin sink absorbs the current to an extent which depends on its spin-dependent properties. To eliminate direct exchange interactions and focus only on the effects due to the interaction between the spin current and the spin sink, the injector and the sink are separated by an efficient spin conductor (Cu). (b) Dependence of the IrMn spin pumping contribution to the NiFe damping ($\alpha^p$) on temperature (T). The data are obtained from $\alpha^p(T) = \alpha(T) - \alpha^0(T)$, where $\alpha^0$ is the damping for $t_{IrMn} = 0$. To facilitate reading, the data were shifted vertically. The enhanced spin pumping occurring during the IrMn magnetic phase transition is $\delta\alpha^p$. (c) Dependence of $T_{crit}^{IrMn}$ on $t_{IrMn}$, where $T_{crit}^{IrMn}$ is the critical temperature for the IrMn magnetic phase transition. Fitting the data returned the spin-spin correlation length ($n_0$).*

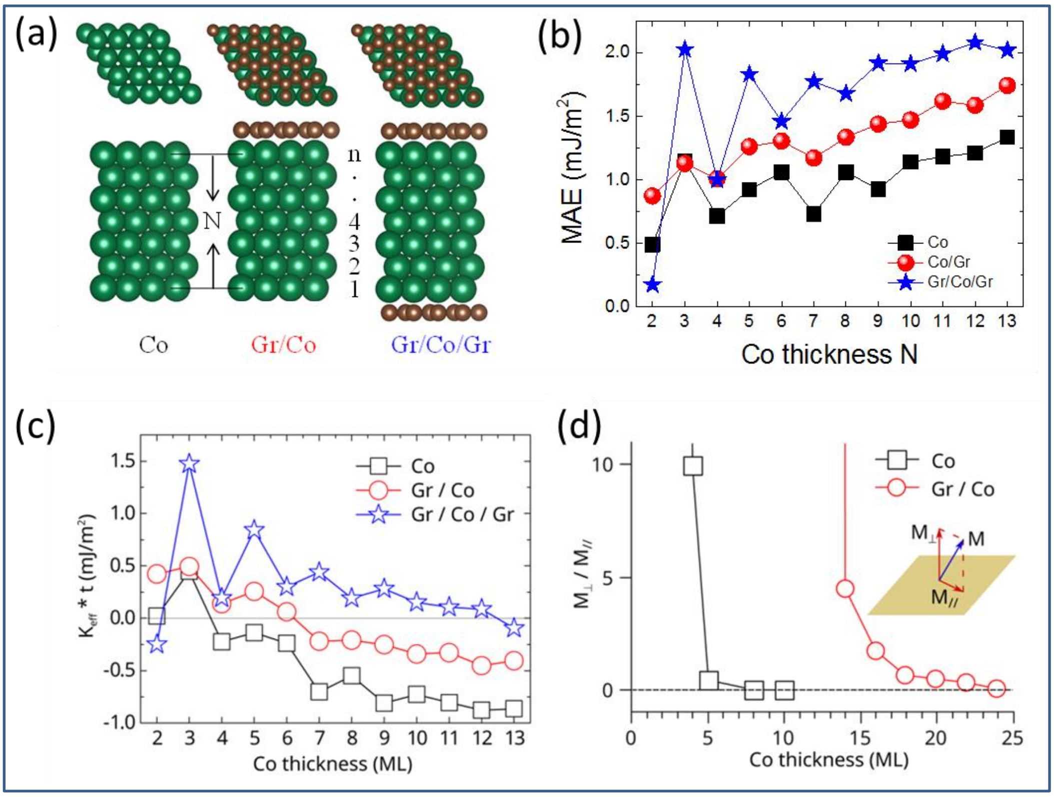
Further reading: *Enhanced spin pumping efficiency in antiferromagnetic IrMn thin films around the magnetic phase transition*, L. Frangou, S. Oyarzún, S. Auffret, L. Vila, S. Gambarelli, V. Baltz, Phys. Rev. Lett. 116, 077203 (2016). DOI: 10.1103/PhysRevLett.116.077203

@ Vincent.Baltz@cea.fr

## Anatomy and Giant Enhancement of the Perpendicular Magnetic Anisotropy of Cobalt–Graphene Heterostructures

**Traditional Perpendicular magnetic anisotropy (PMA) engineering uses Ferromagnetic/oxide interfaces or multilayer structures comprising two Ferromagnets or Ferromagnetic/nonmagnetic metal interfaces. Here, we propose a Co−graphene-based system to realize electrodes with giant PMA that might be of high importance for both traditional and graphene spintronics. Our calculations show that graphene can enhance the surface anisotropy of Co films up to twice the value of its pristine counterpart and can extend the out-of-plane effective anisotropy up to thickness of 2.5 nm.**

Our results are supported by experiments on graphene coating on Co films grown on Ir substrate. These findings point toward a possible engineering of giant anisotropy graphene−Co heterostructures, which stands as a hallmark for future spintronic information processing technologies in a view of the long-standing challenge to promote large PMA in small size spintronic devices with weak spin orbit coupling.




*(a) Top and side view of bare Co slab, Co on graphene, and Gr/Co/Gr (b) Magnetocrystalline anisotropy energy as a function of Co thickness N (monolayers). (c) Effective anisotropy $K_{eff}$·t as a function of Co thickness for bare Co film (Co), one surface of Co film coated by graphene (Co/Gr), and both surfaces of Co film coated by graphene (Gr/Co/Gr), respectively. (d) Thickness dependence of the $M_\perp/M_{//}$ ratio for bare Co and for graphene/Co films.*

The authors acknowledge B. Dieny, S. Roche, F. Ibrahim, and A. Fert for fruitful discussions. This work has been supported by the European Union Seventh Framework Program under Grant Agreement Nos. 604391 GRAPHENE FLAGSHIP, the ANR-2010-BLAN-1019- NMGEM, and ANR-12-BS-1000-401-NANOCELLS projects. Experiments were performed at the Molecular Foundry, Lawrence Berkeley National Laboratory, supported by the Office of Science, Office of Basic Energy Sciences, Scientific User Facilities Division, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Further reading: *Anatomy and Giant Enhancement of the Perpendicular Magnetic Anisotropy of Cobalt-Graphene Heterostructures*, H. Yang, A. D. Vu, A. Hallal, N. Rougemaille, J. Coraux, G. Chen, A. K. Schmid, M. Chshiev, Nano Lett. 16, 145 (2016). DOI: 10.1021/acs.nanolett.5b03392

@ Mair.Chshiev@cea.fr

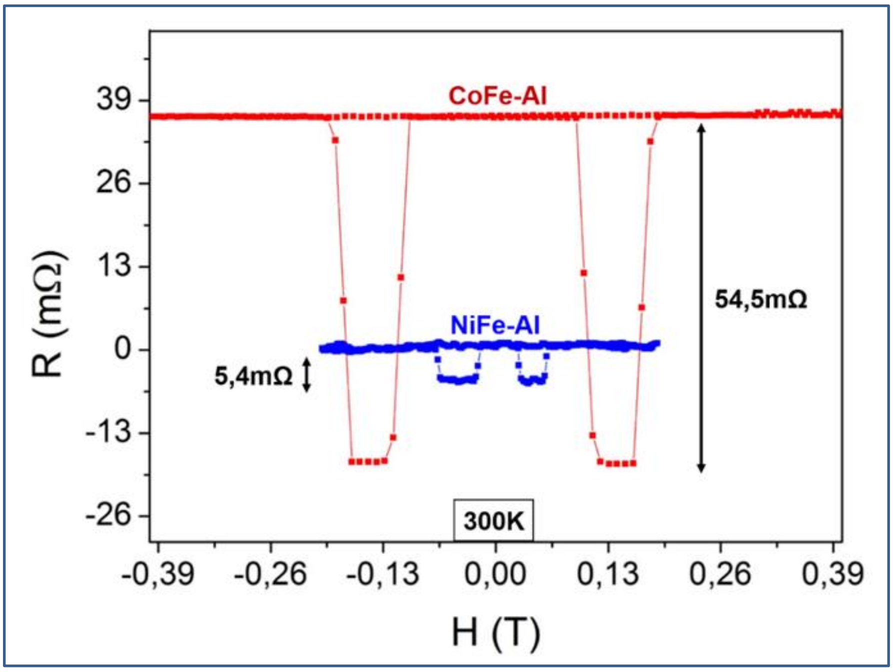
## Comparison of the use of NiFe and CoFe as electrodes for metallic lateral spin valves

**A CoFe based ferromagnetic alloy has been used in lateral spin valves to replace NiFe alloys, which are overwhelmingly exploited as ferromagnets electrodes in lateral spintronic devices. By using this second material, emitted signals are found to be one order of magnitude larger.**

In addition to using the electric charge of the electron, spintronic technologies also manipulates the spin of electrons to handle data processing. Most of the applications based on magnetoresistance effects, such as hard disk drive read-head or MRAM, are based on multilayers composed of stacks alternating ferromagnetic and non-magnetic layers. The interest of multilayers is that the layer thicknesses can become smaller than typical lengths of the spin-dependent electronic transport. Thanks to progresses in the nanofabrication processes, it is now possible to create similar devices with an in-plane geometry, by patterning small heterostructures. These in-plane structures, named ‘lateral’ devices, open the path to new functionalities. Nevertheless, emitted signals on such devices are too low to be technologically applicable.

The replacement of NiFe by CoFe allows obtaining signals up to ten times larger. This result, along with other recent experiments, suggest that laterally shaped spintronic devices could be used for hard disk drives read-heads.

This study has been performed within the SPINTEC laboratory. The different steps of nanofabrication were performed in the cleanroom Plateforme Technologique Amont, CEA.



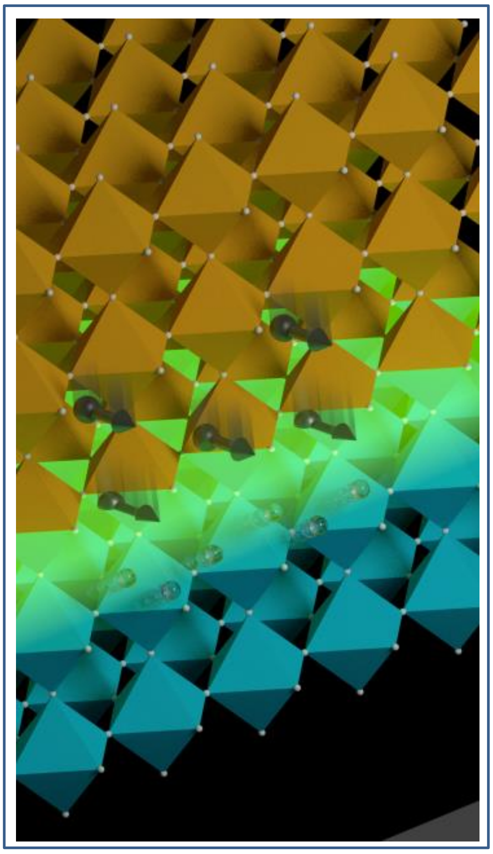

*Non-local spin signal measurement performed on NiFe and CoFe based lateral spin valves.*

Further reading: *Comparison of the use of NiFe and CoFe as electrodes for metallic lateral spin valves*, G. Zahnd, L. Vila, V. T. Pham, A. Marty, P. Laczkowski, W Savero Torres, C. Beigne, C. Vergnaud, M. Jamet, J-P Attané, Nanotechnology 27, 035291 (2016). DOI: 10.1088/0957-4484/27/3/035201

Laurent.Vila@cea.fr
Jean-Philippe.Attane@cea.fr

## Giant and tunable spin-charge conversion at oxide interfaces

**At the interface between the strontium titanate and the lanthanide aluminate forms a 2 dimensional electron system. By using a dynamical spin injection technique, we were able to demonstrate a record conversion yield between spin and charge current in this system, moreover that is tunable in amplitude and sign by an electrostatic gate, a premiere.**



The spin–orbit interaction couples the electrons' motion to their spin. As a result, a charge current running through a material with strong spin–orbit coupling generates a transverse spin current (spin Hall effect, SHE) and vice versa (inverse spin Hall effect, ISHE). The emergence of SHE and ISHE as charge-to-spin interconversion mechanisms offers a variety of novel spintronic functionalities and devices, some of which do not require any ferromagnetic material. However, the interconversion efficiency of SHE and ISHE (spin Hall angle) is a bulk property that rarely exceeds ten percent, and does not take advantage of interfacial and low-dimensional effects otherwise ubiquitous in spintronic hetero- and mesostructures. In a recent study just in Nature Materials, we make use of an interface-driven spin–orbit coupling mechanism—the Rashba effect—in the oxide two-dimensional electron system (2DES) LaAlO3/SrTiO3 to achieve spin-to-charge conversion with unprecedented efficiency. Through spin pumping, we inject a spin current from a NiFe film into the oxide 2DES and detect the resulting charge current, which can be modulated, for the first time, in amplitude and sign by a gate voltage. The amplitude of the effect and its gate dependence is a direct consequence of the electronic structure of the 2DES and highlight the importance of a long scattering time to achieve efficient spin-to-charge interconversion.

This work was done in collaboration with the SPINTEC and Symmes lab of the Institut Nanosciences et Cryogénie (Univ. Grenoble Alpes, CEA, CNRS) and the unite Mixte de Physique CNRS/Thales (University Paris Orsay, CNRS, Thales).

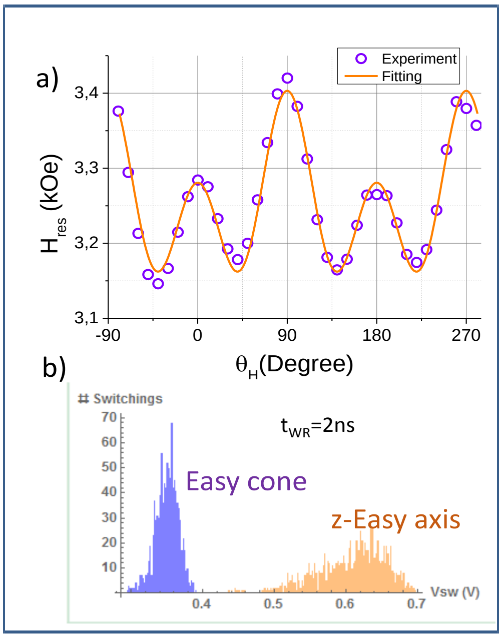
Further reading: *Highly efficient and tunable spin-to-charge conversion through Rashba coupling at oxide interfaces*, E. Lesne, Yu Fu, S. Oyarzún, J. C. Rojas-Sánchez, D. C. Vaz, H. Naganuma, G. Sicoli, J.-P. Attane, M. Jamet, E. Jacquet, M. George, A. Barthelemy, H. Jaffres, A. Fert, M. Bibes, L. Vila, Nature Mater. 15, 1261 (2016). DOI: 10.1038/nmat4726

@ Laurent.Vila@cea.fr
Matthieu.Jamet@cea.fr
Jean-Philippe.Attane@cea.fr

## Misalign to write faster

**The writing in conventional magnetic memories based on magnetic tunnel junctions (STT-MRAM) is intrinsically stochastic: a large amplitude thermal fluctuation is required to trigger the switching of the storage layer magnetization. SPINTEC has shown that this stochasticity can be almost completely suppressed by inducing an oblique anisotropy (easy-cone anisotropy) in the storage layer. This greatly increases the writing speed in the memory.**

In magnetic memories (MRAM), the information is encoded via the relative orientation of the magnetizations of two ferromagnetic layers: a storage layer (STO) of switchable magnetization and a reference layer (REF) of fixed magnetization (« 0 »=parallel alignment=low resistance state; « 1 »=antiparallel alignment=high resistance state). These magnetizations are oriented normal to the plane of the layer. During write, the STO magnetization is switched by the Spin Transfer Torque (STT) phenomenon due to the exchange interactions between the tunneling electrons injected in STO (spin-polarized along the REF magnetization) and those responsible for the STO magnetization. When the magnetizations of STO and REF are strictly parallel or antiparallel, this torque is zero. A slight angle between the two magnetizations is required to trigger the STO magnetization reversal. In STT-MRAM, this initial angle is provided by magnetic thermal fluctuations. This yields stochasticity in the switching. Consequently, it is necessary to increase the write pulse duration and/or its amplitude to reach sufficiently low write error rates (for instance $10^{-11}$). This is detrimental for the realization of short access time memory such as SRAM-like used for Cache applications.




*a) Ferromagnetic resonance field versus angle between applied field and normal to the layers. The variation indicates the presence of second order (uniaxial) and fourth order (quadratic) anisotropy terms. b) distribution of STO magnetization switching events showing a narrower distribution at lower switching voltage Vsw in presence of an easy cone anisotropy than with a uniaxial perpendicular anisotropy.*

In this study, we have shown that this problem can be circumvented by inducing an easy-cone anisotropy in STO [1]. This means that, at equilibrium, the STO magnetization, instead of being aligned along the normal to the plane of the layer, lies along any direction on a cone of axis normal to the plane. In contrast, the REF is designed to keep its perpendicular anisotropy. Thanks to this easy cone anisotropy, the STO and REF magnetizations always keep a relative angle so that upon write, the STO magnetization reversal can be triggered at the very onset of the write current pulse. Such easy cone anisotropy has been evidenced at the lab. It results from higher order anisotropy terms which could be revealed by ferromagnetic resonance experiments. This quadratic anisotropy itself results from spatial fluctuations of uniaxial anisotropy which can be induced during deposition and annealing of the magnetic tunnel junction stacks. Thanks to this easy cone anisotropy, the writing is much more reproducible and can be faster and/or realized at lower write voltage thereby reducing the write energy consumption.

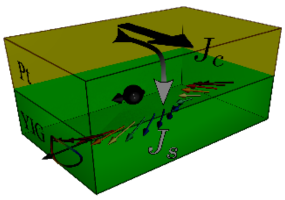
Further reading: *Second order anisotropy contribution in perpendicular magnetic tunnel junctions*, A. A. Timopheev, R. Sousa, M. Chshiev, H. T. Nguyen, B. Dieny, Sci. Rep. 6, 26877 (2016).
DOI: 10.1038/srep26877

@ Bernard.Dieny@cea.fr

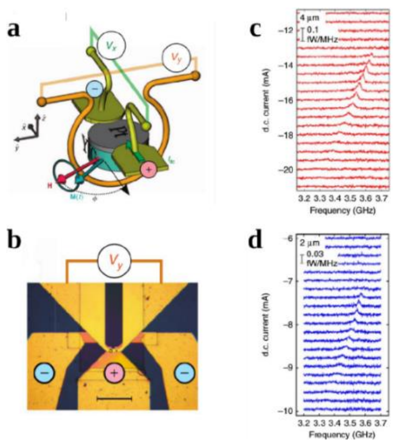
## Of spin super-conduction spin in electric insulators

**Magnonic is an emerging research field, which aims at exploiting pure spin transport in magnetic materials. The elementary excitations are the propagating spin-waves, also called magnon, which are bosonic quasiparticles. The advantages over conventional electronic devices are a significant reduction in energy consumption thanks to the absence of Joule heating, as well as new features taking advantage of the wave-particle duality. Magnetic materials could be electrical insulators, knowing that their dynamical characteristics are usually much better than their metal counterparts. Among all magnetic insulators, yttrium iron garnet (YIG or Y3Fe5O12) holds a special place for having the lowest known damping factor in nature.**

An inherent problem of using a magnetic insulator, is that the inter-conversion of the magnetic signal into an electrical signal (or vise-versa) at the inlet or outlet of the device. Until recently this interconversion was provided by microwave antennas put on the top surface of the material and inductively coupled to the magnetization dynamics. However, this method is not very sensitive and it requires the use of large volumes which prevents extreme miniaturization of devices. This situation has changed radically since the discovery of the spin Hall effect, which capitalizes on the deflection of the electron trajectory according to their spin orientation. When a charge current (Jc) is flowing in a normal metal of strong spin-orbit coupling such as platinum (Pt) it converts into a pure spin current (Js), propagating in the perpendicular direction, where the conversion efficiency is set by the spin Hall angle. If the latter can be transmitted through the interface then it can in principle provides the inter-conversion sought. It turns out that the experimental confirmation of the existence of a spin transfer at the insulator/metal interface has been the subject of a controversy in the community for the past 5 years. The striking signature of the spin transfer process would be the emission of microwave radiation when the system is pumped out of equilibrium by a d.c. current. Since the spin transfer torque on the magnetization is collinear to the damping torque, an instability threshold occurs when the natural damping is fully compensated by the external flow of angular momentum, leading to spin-wave amplification through stimulated emission. Using analogy to light, the effect was called spin-wave amplification by stimulated emission of radiation (SWASER). In a recent paper submitted to Nature Communications [1], we showed for the first time it was possible to induce self-oscillation YIG while flowing a direct electrical current in an adjacent layer of Pt above a critical threshold. To observe this effect, two features were important in order to minimize the amplitude of the threshold current. First it is necessary to use ultra-thin film of YIG of the highest quality, which must then lithographically patterned into micron-size disks in order to lift the degeneracy between normal modes. Direct observation of an RF signal emitted spontaneously will allow better understanding of the spin transfer processes at the interface, but it will possibly open the way to new magnonic functions exploiting the electronic control of magnetic relaxation.




Schematic illustration of the Spin Hall effect showing the inter-conversion of a charge current in Pt, $J_c$, into a pure spin current $J_s$ entering in the YIG.




*(a) Schematic diagram and (b) microscopic image of the device used to study spin transfer effects in two YIG|Pt microdiscs of respectively 2 and 4µm in diameter. (c) and (d) For each of the disks, measurement with a spectrum analyzer of the fluctuations Vy when z DC current flows between the two contacts Vx. An RF signal appears above a critical current of about -13,5mA and -7,4mA respectively for each disk.*

<u>Further reading</u>: *Generation of coherent spin-wave modes in Yttrium Iron Garnet microdiscs by spin-orbit torque*, M. Collet, X. de Milly, O. d'Allivy Kelly, V.V. Naletov, R. Bernard, P. Bortolotti, J. Ben Youssef, V.E. Demidov, S.O. Demokritov, J.L. Prieto, M. Mun oz, V. Cros, A. Anane, G. de Loubens & O. Klein, Nature Comm. 7, 10377(2016). DOI: 10.1038/ncomms10377

@ Olivier.Klein@cea.fr

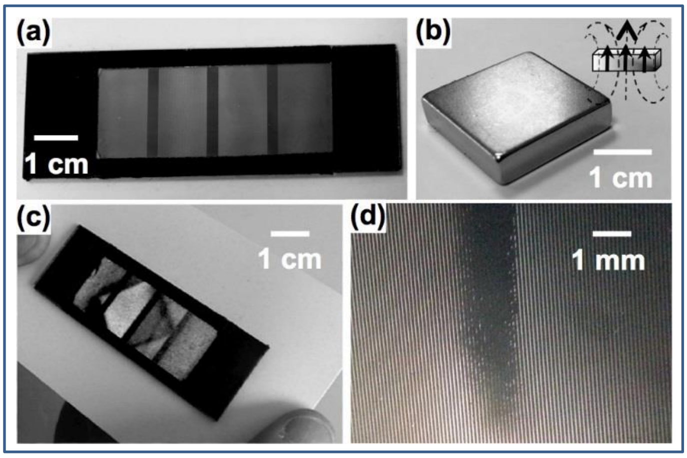
## Magneto-optical micromechanical systems for magnetic field mapping

**Magnetic field mapping techniques have continuously been developed due to the necessity for determining the spatial components of local magnetic fields in many industrial applications and fundamental research. Several factors are considered for sensors such as spatial resolution, sensitivity, linear response, required proximity to the sample, as well as the ability to filter noise and to measure without bringing in any perturbations to the sample.**

The existing techniques usually combine several of the desired features and in many cases they are found to be complementary. A well-established tool for obtaining the spatial distribution of magnetic fields is the magneto-optical imaging (MOI) method, which makes use of so-called MOI films such as ferrite garnet films and nanoparticle films. A MOI film placed on a magnetized surface will have its magnetic domain structure reorganized in accordance with the local intensity of the magnetization or stray field produced by the analyzed material. However, the method is non-quantitative and depositing a MOI film is an invasive process that leaves traces after removal. Other field mapping techniques are based on scanning, such as superconducting quantum interference device (SQUID), Hall bar, magnetic force, and scanning magnetoresistive microscopy. Despite being highly sensitive, scanning techniques are slow and each of them has its own drawback. For instance, SQUID microscopy operates at low temperatures, and magnetoresistive sensors operate with dc currents, thus possibly introducing heat and magnetic fields that can alter the sample.

In the paper we published recently in Scientific Reports, we report magnetic field mapping by use of a structure based on organized arrays of close-packed mobile magnetic elements. Each element is a magnetic cantilever with microscopic length and nanometer scale thickness. When placed in proximity to magnetized materials, the cantilevers are deflected depending on the intensity and direction of the stray fields. Due to a local change of reflectivity induced by the stray field, the field lines generate a contrast, which is even visible to the naked eye on the surface of the mapping device. The paper also demonstrates that the magnitude of a uniform magnetic field can be quantitatively determined by using a method based on coherent light diffraction. The sensitivity and the resolution of the device can be adapted by tuning the dimensions of the cantilevers and the number of cantilever in the arrays. Such magneto-optical surface offers the advantage of being a passive and easy-to-use device, since neither power source nor sample preparation is required.

*(a) Test device made of four different arrays of cantilevers of different size. (b) The NdFeB permanent magnet is (c) placed under the test device, which is perfectly opaque. The field lines form contrasted regions, which remind of shape of the magnet. (d) Close-up view by optical microscopy of a contrasted area.*




Further reading: *Magneto-optical micromechanical systems for magnetic field mapping*, A. Truong, G. Ortiz, M. Morcrette, T. Dietsch, P. Sabon, I. Joumard, A. Marty, H. Joisten, B. Diény, Sci. Rep. 6, 31634 (2016). DOI: 10.1038/srep31634

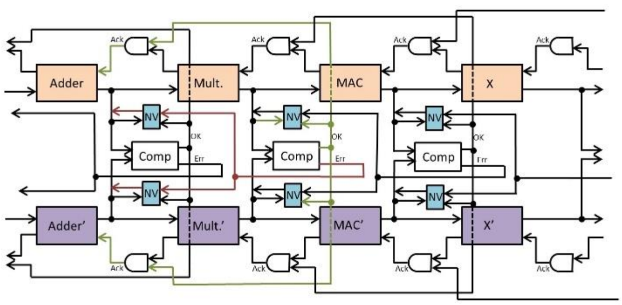

@ Bernard.Dieny@cea.fr
Helene.Joisten@cea.fr

## A Novel Asynchronous Radiation-Hard Error Correction Structure Based on MRAM

**Radiation robust circuit design for harsh environments like space is a big challenge for IC design and embedded systems. As circuits become more and more complex and CMOS processes get denser and smaller, their immunity towards particle strikes decreases drastically. Spintec proposed a novel integrated circuit structure that enable to increase to increase the robustness in space environment.**

For critical applications (aviation and/or space), it would be desirable to provide a circuit that is rendered robust against the effects of radiation. Indeed, the presence of ionizing particles at high altitudes or in space can induce currents in integrated circuits that may be large enough to cause a flip in the binary state held by one or more gates. This may cause the circuit to malfunction, known as a single event upset (SEU). Furthermore, if SEUs occur at a relatively high rate, it may even be impossible for a processing operation to be completed before a reset is required. There is thus a need in the art for a circuit having relatively low surface area and power consumption, and that allows recovery following an SEU without requiring a reset.

The figure shows an error correcting asynchronous, or clock-less, structure. This structure is composed of a pipeline that comprises a series of asynchronous stages, such as an adder, a multiplier, a multiplier/accumulator and/or any asynchronous function. This pipeline is duplicated, the second series of stages (differentiated by an ’) being also the same operators. The second series of stages are functionally equivalent to the first and will generate identical output signals in the absence of error. There is a comparator coupled to the output data lines of each of the stages. Each comparator generates an error signal when a mismatch is detected between the data signals from corresponding pipeline stages. This error signal controls a mechanism that is inserted in the return acknowledgement signal of each stage. This mechanism, based on the error signal resulting from the comparison of the data signals from two stages, can activate or pause the propagation of the acknowledgement signal to the previous stage. If a mismatch occurs, the error signal from the comparator of that stage will block the acknowledgement signals going to the previous stage. By doing this, the previous stage continues to provide the same output and the stage concerned by the error can re perform its calculation, thus correcting the error. This is made possible by the delay insensitive properties of asynchronous communication protocol. The circuit can locally be paused waiting the dissipation of an error without affecting the global functionality of the system. This structure also integrates MRAM-based non-volatile storage circuits represented by NV. Each Magnetic Tunnel Junction (MTJ) storage circuit is configured to store the data signals at the output of the corresponding pipeline stage if the comparator of the stage does not indicate any error. However, if an error is detected by the comparator of a stage, the MTJ non-volatile storage circuit of the previous stage is adapted to output its stored value, which will overwrite the wrong value provided by that stage. This way the circuit is immune to any further SEU occurring in any stage. Finally, the MTJ non-volatile storage circuits permit the pipelines to be re initialized from a stored state following a reset or power down of the pipeline. This can be a further improvement in terms of power consumption. Such an ASIC using MRAM-based asynchronous design architectures enables to improve radiation robustness without really increasing the circuit area compared to the state of the art.




*MRAM-based asynchronous pipeline structure robust again particle strikes*

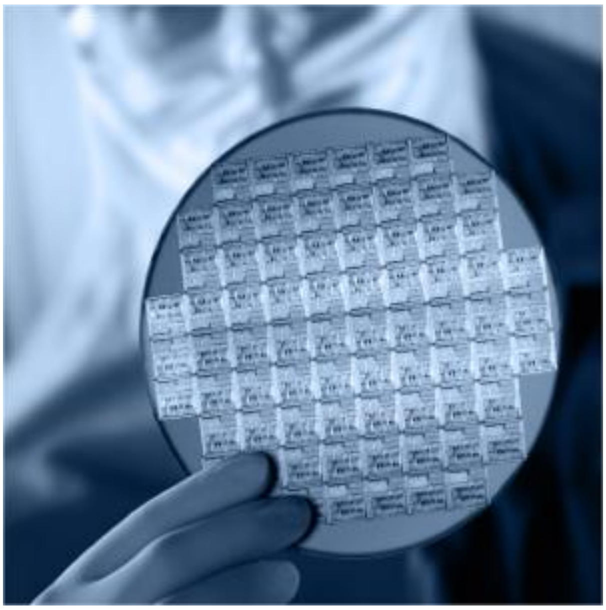
We would like to thank the CEA and CNES for their financial support for this Ph.D., as well as the LIRMM, LETI and CNRS for their implication.

Further reading: *An SEU tolerant MRAM based non-volatile asynchronous circuit design*, J. Lopes, G. Di Pendina, E. Beigne and L. Torres, 2016 16th European Conference on Radiation and Its Effects on Components and Systems (RADECS), Bremen, Germany. DOI: 10.1109/RADECS.2016.8093151

@ Gregory.DiPendina@cea.fr

# 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 devices 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. As such it is critical to be at the forefront of 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, 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.

# 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.

## SPINTRONIC 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 / 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

SPINTEC, CEA Grenoble, – 17 rue des Martyrs – GRENOBLE (France)
http://www.spintec.fr direction.spintec@cea.fr