spintec
SPIN IN ELECTRONICS

Highlights

2018

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cnrs advancing the frontiers

UNIVERSITÉ Grenoble Alpes

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FOREWORD

This booklet gathers a selection of scientific highlights of SPINTEC over the year 2018. Besides these, several cornerstones in the life of the laboratory shall be mentioned over the same period.

On the side of partnership we are happy of the success of the lab this year, being involved in five new ANR projects and several on waiting list; two European projects; the start of the European-scale Spintec-coordinated DARPA project on skyrmions; the involvement in the NEED project from Univ. Grenoble Alpes, devoted to sustainable electronics. Spintec is also largely involved in the FETFLAG CSA project Nanoengineering, aiming at paving the way to a Flagship integrating spintronics as a key technology. Finally, we also started actively our official association with the IFW-Dresden under the auspices of CNRS and the Leibniz Society, with already two co-supervised PhD projects, several financial projects posted jointly, and common working projects held on both labs.

On the innovation side, the two most recent spin-off companies are being consolidated: HProbe is enlarging its portfolio of customers for electric probers under three-dimensional configurations of magnetic field, while Antaios is paving the way to exploit our IP for SOT-MRAM. On its side, Crocus technology is successfully turning to the market of magnetic sensors, now selling products to customers. Finally, several direct collaborations with new industrial partners are reaching an advanced stage of negotiation.

The year 2019 comes with exciting challenges, such as the creation of the large CEA Institute in Grenoble, bringing together forces on physics, chemistry and biology. In this Institute we will work jointly with our colleagues from Pheliqs and MEM laboratories, under the auspices of a newly-created Department for Nanophysics. 2019 also comes with the opportunity of regrouping almost all our activities in a single building, further fostering our collective strategy. We will also welcome our latest recruit Frederic Bonell, an experienced scientist in epitaxy, to contribute to the development of thin-film topological insulators and two-dimensional materials for spintronics.

We hope that you will enjoy browsing the following pages.

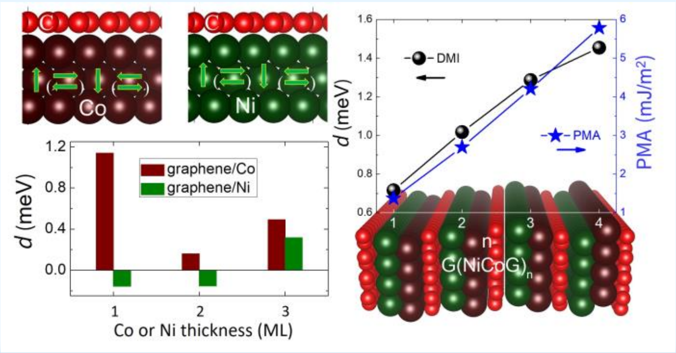
Lucian Prejbeanu, Executive Director

Olivier Fruchart, Deputy Director

Significant Dzyaloshinskii–Moriya interaction at graphene/ferromagnet interfaces due to the Rashba effect

Despite being a weak spin–orbit coupling material, graphene demonstrated to induce significant Dzyaloshinskii–Moriya interaction due to the Rashba effect leading to formation of chiral spin textures in adjacent ferromagnet (FM) at graphene/FM interfaces. First-principles calculations and experiments using spin-polarized electron microscopy show that this graphene-induced Dzyaloshinskii–Moriya interaction can have a similar magnitude to that at interfaces with heavy metals. This work paves a path towards two-dimensional-material-based spin orbitronics.

The possibility of utilizing the rich spin-dependent properties of graphene has attracted much attention in the pursuit of spintronics advances. The promise of high-speed and low-energy-consumption devices motivates the search for layered structures that stabilize chiral spin textures such as topologically protected skyrmions. Whereas chiral magnetism induced by the interfacial DMI has become an important topic, the DMI at interfaces with graphene was not expected to be significant because, according to the Fert–Levy model, the DMI scales with spin-orbit coupling (SOC) in the material contacting the ferromagnetic metal layer and graphene lacks strong SOC. At the same time, recent observations of enhanced PMA at graphene/FM interfaces suggested that they are unusual: if graphene enhances the PMA at interfaces in the absence of strong SOC, then it is interesting to ask if graphene has similarly strong effects on the DMI, helping thereby to promote this and other two-dimensional (2D) materials for spin orbitronics. This idea was tested in this work by exploring the interfaces of graphene with cobalt and nickel, where these two ferromagnetic metal elements are chosen for their small lattice mismatch and strong interaction with graphene.



Crystal and spin configurations of graphene-coated Co and Ni films used for DMI calculations and total DMI coefficient as a function of ferromagnetic metal film thickness for graphene/Co (brown) and graphene/Ni (green) slabs (left panel).
DMI and PMA for multilayers of graphene/[Co/Ni/graphene]n as a function of the junction number n (right panel).

Spintec's theory group in collaboration with colleagues in France, USA and Brazil discovered both from first-principles calculations and from magnetic imaging experiments that a graphene/ferromagnetic metal interface generates significant DMI. The calculated DMI constants the largest DMI can reach up to 1.14 meV per atom for a graphene-coated single atomic layer of Co (see left panel in Fig. above). Experimental measurements of DMI in graphene/Co by means of SPLEEM confirmed these findings. Furthermore, $[Co/Ni/graphene]_n$ heterostructures allowing simultaneous enhancement of the DMI and PMA were proposed (right panel in Fig. above). All these findings demonstrate that the graphene-induced DMI should be sufficient to stabilize magnetic chiral spin textures such as skyrmions in ultrathin ferromagnetic metal films attached to graphene.

Team: Theory and Simulation

Collaboration: CNRS/Thales (France); LBNL (USA); UC Davis (USA); CDTN (Brazil); UFMG (Brazil)

Funding: EU Horizon 2020 grant no. 696656 (GRAPHENE FLAGSHIP); ANR ULTRASKY; ANR SOSPIN

Further reading: *Significant Dzyaloshinskii–Moriya interaction at graphene–ferromagnet interfaces due to the Rashba effect*, H. X. Yang, G. Chen, A. A. C. Cotta, A. T. N'Diaye, S. A. Nikolaev, E. A. Soares, W. A. A. Macedo, K. Liu, A. K. Schmid, A. Fert & M. Chshiev,
Nat. Mater. 17, 605 (2018). DOI: *10.1038/s41563-018-0079-4*

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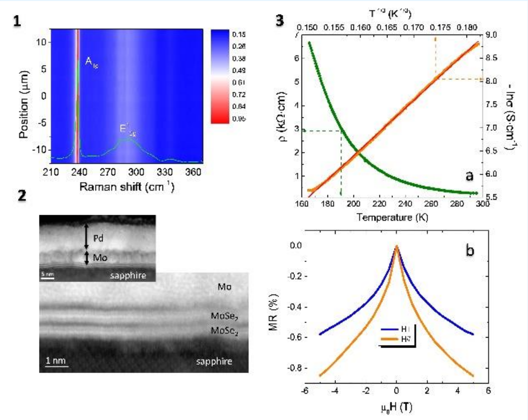
Millimeter-scale layered MoSe2 grown on sapphire and evidence for negative magnetoresistance

We have fabricated large-scale two-dimensional transition metal dichalcogenide (2D TMD) MoSe2, a promising candidate for electronics, valley-spintronics and optoelectronics, on insulating sapphire and have investigated its structural and transport properties. We have shown that the layered MoSe2 exhibits characteristics of a stoichiometric 2H-phase, a van der Waals epitaxy regarding the substrate and we have evidenced a hopping character for charge transport and an increase of conductivity of the layer under an application of magnetic field.

The fast rise of semiconducting 2D TMD urges to look for artificial synthesis methods in order to achieve a large-scale and uniform 2D layers. So far, most of device demonstrations based on layered TMDs were obtained with exfoliated flakes which cannot be transferred to large-scale design and implementation into functional devices.



1 : Raman mapping of one monolayer MoSe2 along one direction x (y) showing microscopic homogeneity of the layer. 2 : Cross sectional STEM image showing the van der Waals gap and interfaces between MoSe2, sapphire and metallic electrodes. 3 : resistivity versus temperature with the fit (3a) and the negative MR measured at 250 K with in-plane and out-of-plane applied magnetic fields (3b).

We have reported an alternative approach to fabricate $MoSe_2$ layers down to one monolayer on sapphire substrates by using molecular beam epitaxy (MBE). Weak interactions between the substrate and the epilayer were expected, resulting in van der Waals epitaxy. The MBE technique allowed us to obtain millimetre-scale $MoSe_2$ layers with a controllable thickness. The structural properties, identical to the bulk, the homogeneity of the layer were characterized using X-ray diffraction, Raman and photoemission (XPS) spectroscopies, scanning transmission electron microscopy (STEM). Contacting 2D layers with metallic electrodes remains a crucial challenge for the exploration of new physics in the TMDs. In our article, we have also addressed this issue by showing a good electrical contact between ultrathin layered $MoSe_2$ and Pd/Mo stacks, which were successfully fabricated *in-situ* under UHV conditions. Thereby we have pointed out a variable hopping character of the charge carrier conductivity in the layered $MoSe_2$. More interestingly, a magnetic field-dependent transport was investigated and a decrease in resistivity was observed for the first time in a MBE-TMD, stressing a fascinating feature of the charge transport in this system under the application of a magnetic field. The transport characteristics such as localization length, hopping length were considered for the discussion of the negative magnetoresistance. This negative magnetoresistance observed at millimeter-scale is similar to that observed recently at room temperature in WS_2 flakes, highlighting the fact that the underlying physical mechanism is intrinsic to these two-dimensional materials and occurs at very short scale.

Team: 2D Spintronics

Further reading: *Millimeter-scale layered MoSe2 grown on sapphire and evidence for negative magnetoresistance*, M.T. Dau, C. Vergnaud, A. Marty, F. Rortais, C. Beigné, H. Boukari, E. Bellet-Amalric, V. Guigoz, O. Renault, C. Alvarez, H. Okuno, P. Pochet, M. Jamet, Appl. Phys. Lett. 110, 011909 (2017), DOI: *10.1063/1.4973519*

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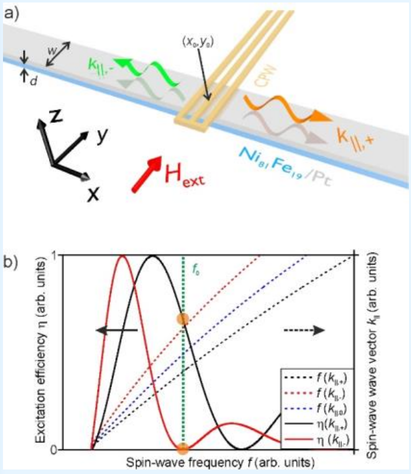
Unidirectional spin-wave emitters utilizing interfacial Dzyaloshinskii-Moriya interaction

We have created an analytical model of spin waves in microscopic spin-wave waveguides in the presence of interfacial Dzyaloshinskii-Moriya interaction. By comparing to micromagnetic simulations, we have demonstrated that spatially periodic excitation sources can be used to create a uni-directional spin-wave-emission source whose properties can be predicted by our model.

Since miniaturization of CMOS devices becomes increasingly difficult due to fundamental limitations and the increase of leakage currents, large research efforts are devoted to find alternative concepts that allow for a larger data-density and lower power consumption than conventional semiconductor approaches. Spin waves have been identified as a potential technology that can outperform CMOS in complex logic applications, profiting from the fact that spin waves enable wave computing on the nano-scale. These waves are the low energy excitation of a magnetic material, resulting from a small, local distortion of the magnetic order. Once excited, for example by a local magnetic field, they can convey their information along the magnetic material in form of their amplitude and phase. Submicrometer wavelengths in the GHz to THz frequency range, their easy integration on a chip and their compatibility with non-volatile magnetic memories make them an interesting alternative to other wave-based quasi-particle approaches, such as photonics.

In our work, we study the impact of interfacial Dzyaloshinskii-Moriya interaction, an asymmetric exchange interaction that can be present in ultrathin layer systems with an asymmetric stacking order, on the spin-wave excitation and propagation in microscopic spin-wave waveguides by an analytical model and micromagnetic simulations. We identify the impact of the Dzyaloshinskii-Moriya interaction on the spin-wave frequency, lifetime and the ellipticity of the magnetization precession, as well as on the excitation of spin waves by periodic excitation sources. Such sources, like microscopic coplanar waveguides, provide a certain wave-vector spectrum for the spin-wave excitation, which is determined by their dimensions. Together with the lifting of the degeneracy of the dispersion of spin waves propagating in opposite directions, this allows for a controlled spin-wave emission in a desired direction. Our model allows predicting the size of the microscopic spin-wave excitation source in order to achieve optimum emission conditions at a desired spin-wave wavelength and frequency.



(a) The microscopic spin-wave waveguide, here assumed to be made from a thin layer of permalloy (Py, Ni81Fe19) in contact with Pt, and the coplanar waveguide (CPW) acting as spin-wave excitation source. (b) The uni-directional emission: the interfacial Dzyaloshinskii-Moriya interaction splits the spin-wave dispersion (dashed lines) of waves running to the left and waves running to the right. In combination with the periodicity of the excitation spectrum (solid lines), this can be used to achieve an efficient spin-wave emission in only one propagation direction at a desired operation frequency (dashed vertical line).

Team: Spin Orbitronics

Collaboration: Fachbereich Physik and Landesforschungszentrum OPTIMAS, Technische Universit¨at Kaiserslautern, 67663 Kaiserslautern, Germany

Funding: European Commission under the Seventh Framework Programme (Grants No. 318144 and No. 2012-322369), Deutsche Forschungsgemeinschaft (SFB/TRR 173 Spin + X), Nachwuchsring of the TU Kaiserslautern

Further reading: *Creation of unidirectional spin-wave emitters by utilizing interfacial Dzyaloshinskii-Moriya interaction*, T. Brächer, O. Boulle, G. Gaudin, and P. Pirro, Phys. Rev. B 95, 064429 (2017), DOI: *10.1103/PhysRevB.95.064429*

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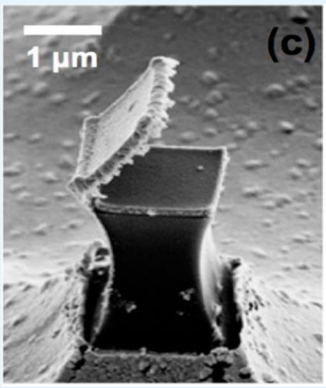
Nanotweezers and their remote actuation by magnetic fields

We have developed arrays of innovative magnetic nanotweezers or "nanojaws" on silicon wafers, by a top-down approach using the fabrication techniques of microelectronics.



SEM images of magnetic nanotweezers, with magnetic jaws of permalloy and gold nanohinge. (a) Opened tweezer at applied magnetic field (b) Closed tweezer at zero field. (c-d) Local magnetic field produced by a NdFeBr microsphere, actuating a tweezer.

The mechanical manipulation of micro- and nanometric objects relies on constantly evolving techniques, which are of great interest to the life sciences and biotechnologies. Numerous biomedical studies, either fundamental or applied to medical diagnosis and treatment, are concerned with the application of locally controlled forces to seize and capture microscopic biological samples. For example, to take a sample of biological tissue for biopsy; catch bacteria; pinch cancer cells to destroy or analyze them; sample viruses, biomolecules or DNA strands, and so on.

Many among all the devices for micromanipulation are using magnetic particles, whose advantage is the ability to be remotely actuated by the application of an external magnetic field. Some current macroscopic systems perform the function of magnetic clamps, for example to study DNA elasticity by pulling the strand by means of a grafted magnetic particle. This type of method is however limited to single sample manipulations.

Our study, published recently in Scientific Report, presents the first realization of arrays of a new type of magnetic nano-tweezers remotely actuated by an applied magnetic field. A top-down approach has been developed to produce at once millions of sub-micrometric clamps. The clamps are formed of two anisotropic magnetic particles connected by a hinge of nanometric thickness (Fig.). Their operating principle rests on the balance between the interaction with the applied field, the magnetostatic interaction between the two magnetic jaws (attractive in zero field - repulsive in sufficiently large field), and the restoring force exerted by the hinge. The correct operation of these clamps has been demonstrated in a SEM with a local magnetic field created in situ by a permanent magnet microsphere. The clamps studied up to now were still attached to the substrate, although the manufacturing process makes it possible to envisage their dispersion and use when released in a liquid. Designed to pinch objects with sizes comparable to their own, nano-tweezers could then act collectively on biological samples or other types of micro-nanometric elements.

The fabrication process has been developed at PTA (Plate-forme Technologique Amont).

Team: Health and Biology

Funding: Nano-Shark P2N ANR project (ANR-11-NANO-001)

Further reading: *Fabrication of nano-tweezers and their remote actuation by magnetic fields*, C. Iss, G. Ortiz, A. Truong, Y. Hou, T. Livache, R. Calemczuk, P. Sabon, E. Gautier, S. Auffret, L. D. Buda-Prejbeanu, N. Strelkov, H. Joisten and B. Dieny, Scientific Rep. 7, 451 (2017). DOI: *10.1038/s41598-017-00537-6*

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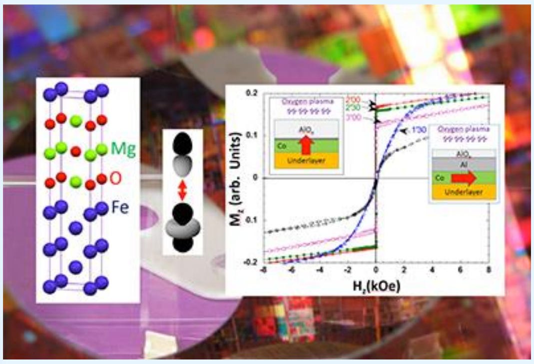
Perpendicular magnetic anisotropy at transition metal/oxide interfaces and applications

A comprehensive review on advances on PMA at transition metal/oxide interfaces in a view of spintronics applications has been published in the Reviews of Modern Physics.

Spin electronics is a rapidly expanding field stimulated by a strong synergy between breakthrough basic research discoveries and industrial applications in the fields of magnetic recording, magnetic field sensors, nonvolatile memories [magnetic random access memories (MRAM) and especially spin-transfer-torque MRAM (STT-MRAM)]. In addition to the discovery of several physical phenomena (giant magnetoresistance, tunnel magnetoresistance, spin-transfer torque, spin-orbit torque, spin Hall effect, spin Seebeck effect, etc.), outstanding progress has been made on the growth and nanopatterning of magnetic multilayered films and nanostructures in which these phenomena are observed. Magnetic anisotropy is usually observed in materials that have large spin-orbit interactions. However, in 2002 perpendicular magnetic anisotropy (PMA) was discovered to exist at magnetic metal/oxide interfaces [for instance Co(Fe)/alumina]. Surprisingly, this PMA is observed in systems where spin-orbit interactions are quite weak, but its amplitude is remarkably large—comparable to that measured at Co/Pt interfaces, a reference for large interfacial anisotropy (anisotropy~1.4 erg/cm2=1.4 mJ/m2). Actually, this PMA was found to be very common at magnetic metal/oxide interfaces since it has been observed with a large variety of amorphous or crystalline oxides, including AlOx, MgO, TaOx, HfOx, etc. This PMA is thought to be the result of electronic hybridization between the oxygen and the magnetic transition metal orbit across the interface, a hypothesis supported by *ab initio* calculations. Interest in this phenomenon was sparked in 2010 when it was demonstrated that the PMA at magnetic transition metal/oxide interfaces could be used to build out-of-plane magnetized magnetic tunnel junctions for STT-MRAM cells. In these systems, the PMA at the CoFeB/MgO interface can be used to simultaneously obtain good memory retention, thanks to the large PMA amplitude, and a low write current, thanks to a relatively weak Gilbert damping. These two requirements for memories tend to be difficult to reconcile since they rely on the same spin-orbit coupling. PMA-based approaches have now become ubiquitous in the designs for perpendicular STT-MRAM, and major microelectronics companies are actively working on their development with the first goal of addressing embedded FLASH and static random access memory-type of applications. Scalability of STT-MRAM devices based on this interfacial PMA is expected to soon exceed the 20-nm nodes. Several very active new fields of research also rely on interfacial PMA at magnetic metal/oxide interfaces, including spin-orbit torques associated with Rashba or spin Hall effects, record high speed domain wall propagation in buffer/magnetic metal/oxide-based magnetic wires, and voltage-based control of anisotropy. This review deals with PMA at magnetic metal/oxide interfaces from its discovery, by examining the diversity of systems in which it has been observed and the physicochemical methods through which the key roles played by the electronic hybridization at the metal/oxide interface were elucidated. The physical origins of the phenomenon are also covered and how these are supported by *ab initio* calculations is dealt with. Finally, some examples of applications of this interfacial PMA in STT-MRAM are listed along with the various emerging research topics taking advantage of this PMA.



Fe/MgO unit cell used for ab-initio calculation and Hysteresis loop showing the existence of PMA

Teams: Theory and Simulation, MRAM Memories

Further reading: *Perpendicular magnetic anisotropy at transition metal/oxide interfaces and applications*, B. Dieny and M. Chshiev, Rev. Mod. Phys. 89, 025008 (2017), DOI: *10.1103/RevModPhys.89.025008*

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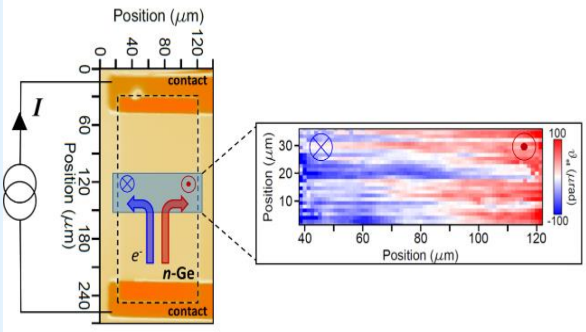
Spin-Hall Voltage over a Large Length Scale in Bulk Germanium

The spin Hall effect (SHE) could be used in semiconductor spintronics to generate spin currents where electrical spin injection is still challenging due to the impedance mismatch issue. The SHE was first observed by magneto-optical Kerr effect on a very short length scale in a semiconductor: GaAs. In this work, we use the same technique to image the spin accumulation in germanium produced by the SHE. Due to the long spin diffusion length in this material, we can observe the spin accumulation signal and its linear dependence over distances as large as 30 µm.

Germanium is one of the most appealing candidate for spintronic applications, thanks to its compatibility with the Si platform, the long electron spin lifetime and the optical properties matching the conventional telecommunication window. Electrical spin injection schemes have always been exploited to generate spin accumulations and pure spin currents in bulk Ge. Here, we use the spin-Hall effect, which is based on the spin-orbit coupling, to generate a uniform spin current into an epitaxial *n*-doped Ge channel. The electrically-induced spin accumulation, transverse to the injected charge current density, is equivalent to an effective magnetization that we detect using polar magneto-optical Kerr microscopy at low temperature.



Large length scale spin accumulation in Germanium by spin hall effect

We show that a large spin density up to 400 µm^3 can be achieved at the edges of the 100-µm-wide Ge channel for an applied electric field lower than 5 mV/µm. We find that the spin density linearly decreases toward the center of the Ge bar, due to the large spin diffusion length, and such a decay is much slower than the exponential one observed in III-V semiconductors like GaAs. It allows a very large spin accumulation over a length scale of tens of micrometers. We also characterize the electrically-induced spin voltage as a function of the applied bias and temperature, revealing that the spin-to-charge conversion in bulk Ge is preserved and measurable up to 120 K.

These results lay the foundation for multi-terminal spintronic devices, where different spin voltages can be exploited as inputs for magneto-logic gates on the same Ge platform.

Team: 2D Spintronics

Collaboration: C. Zucchetti, F. Bottegoni, S. Dal Conte, J. Frigerio, E. Carpene, G. Isella, F. Ciccacci, G. Cerullo, and M. Finazzi, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

Further reading: *Spin-Hall Voltage over a Large Length Scale in Bulk Germanium*, F. Bottegoni et al., Phys. Rev. Lett. 118, 167402 (2017). DOI: *10.1103/PhysRevLett.118.167402*

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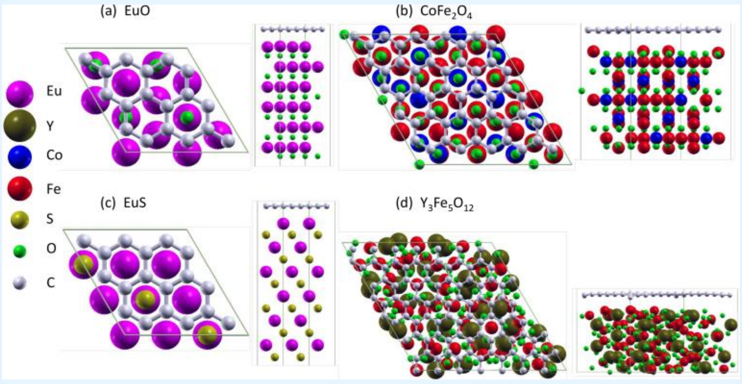
Tailoring magnetic insulator proximity effects in graphene: first-principles calculations

Advancing spintronic devices requires using novel 2D materials including graphene with featured properties. In particular, a significant effort has been focused on injecting spins and inducing magnetism in graphene giving rise to emerging field of graphene spintronics. It is demonstrated that robust spin polarization can be induced in graphene via proximity with magnetic insulators including yttrium iron garnet (YIG) and europium chalcogenides.

Graphene stands as a potential spin-channel material. There is, however, a fundamental challenge in the development of external ways to control the propagation of spin currents at room temperature, in view of designing novel spintronic devices. Since carbon is non-magnetic, a significant effort is focused on injecting spins and inducing magnetism in graphene. It can be induced and controlled using defects or by putting it at the interface with magnetic materials. The most promising is the use of magnetic insulators (MIs) as an alternative route to induce magnetism in graphene via the exchange-proximity interaction.



Side view and top view of the calculated crystalline structures for graphene on top of (a) EuO film (b) CoFe2O4(C) EuS (d) Y3Fe5O12

In this work, using first-principles calculations, the impact of the nature of the magnetic insulators on the magnetic proximity effect induced in graphene is elucidated. Four cases of different magnetic insulators were studied: europium oxide (EuO), europium sulfite (EuS), cobalt ferrite CoFe2O4 (CFO) as well as yttrium iron garnet $Y_3Fe_5O_{12}$ (YIG) [Fig. 1]. The proximity induced exchange-splitting parameters were obtained from the band structure of graphene calculated in each case. Electron doping occurs for all cases except the CFO where the Dirac point lies about 0.5 eV above the Fermi level. The magnetic proximity effect results in a large and robust to MI thickness variation exchange-splitting parameter of a few tens of meV. The presence of spin-dependent band gaps around Dirac point was found in all cases, except for CFO.

These findings pave the way towards possible engineering of graphene spin-gating by proximity effect especially in view of recent progress in experiments.

Team: Theory and Simulation

Collaboration: Institut Català de Nanociència i Nanotecnologia (ICN2)

Funding: the European Union’s Horizon 2020 research and innovation program GRAPHENE FLAGSHIP under grant agreement No. 696656

Further reading: *Tailoring magnetic insulator proximity effects in graphene: first-principles calculations*, Ali Hallal, Fatima Ibrahim, Hongxin Yang, Stephan Roche and Mairbek Chshiev, 2D Materials 4 (2), 025074 (2017). DOI: *10.1088/2053-1583/aa6663*

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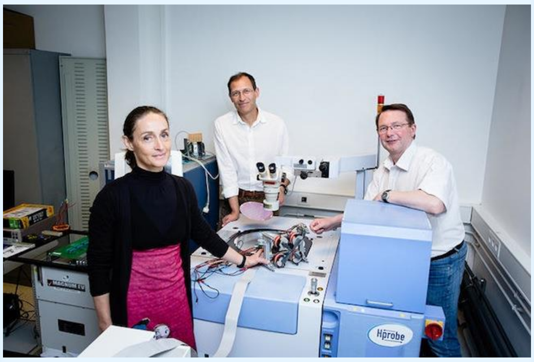
Jean-Pierre Nozières rewarded with the CNRS Innovation Medal 2017

Jean-Pierre Nozières, Spintec researcher in magnetic devices, is one of the winners of the Innovation Medal of the CNRS “cuvee” 2017 at 54 years old. Since 2011, this distinction has been awarded for outstanding scientific research leading to a remarkable innovation, whether in the technological, therapeutic or societal fields.

At the origin of more than twenty patented innovations, Jean-Pierre Nozières conducts research on magnetic components, from material to concepts, and over the last ten years, more particularly on MRAM (magnetic random access memories).

A physicist by training, co-founder in 2002 with Bernard Diény (CEA) of the SPINTEC - laboratory (joint unit in between CEA, CNRS and Grenoble-Alpes University), a laboratory he led for ten years, Jean-Pierre Nozières was, together with other colleagues from Spintec, at the origin of the creation of four start-ups in spintronics. The first, Crocus Technology, born in 2006, specializes in the industrialization of the MRAM technology developed at the Spintec laboratory. In 2014, Jean-Pierre Nozières launched eVaderis around the design of memory blocks and ultra-low-power circuits for the Internet of Things. Antaïos in 2016 develops the ultra-fast MRAM technology for computing processors, when HProbe in 2017 offers on-line control equipment for the manufacture of MRAMs.



From left to right: Isabelle Joumard (Spintec engineer), Jean-Pierre Nozières, Laurent Lebrun (HProbe co-founder).

Jean-Pierre Nozières had already received last July one of the five grand prizes of the 18th national contest for the creation of innovative technology companies i-LAB. At the origin of more than twenty patented innovations, Jean-Pierre Nozières conducts research on magnetic components, from material to concepts, and over the last ten years, more particularly on MRAM (magnetic random access memories).

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Jean-Pierre Nozières had already received last July one of the five grand prizes of the 18th national contest for the creation of innovative technology companies i-LAB.

Further reading: *https://lejournal.cnrs.fr/articles/medaille-de-linnovation-le-palmares-2017*

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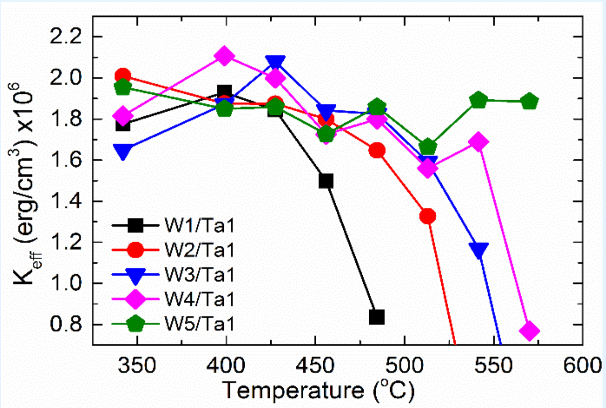
Significant improvement of magnetic and electrical properties of magnetic tunnel junctions by insertion in the stack of refractory metal laminations (tungsten)

Magnetic tunnel junctions are the basic elements of a new class of magnetic memory called MRAM (Magnetic Random Access Memory). These are about to enter in volume production at major microelectronics foundries (Samsung, TSMC, Global Foundries…). To move towards high density memory (several Gbit), short access time (sub 3ns), and elevated temperature of operation (150°C required for automotive applications), their magnetic and electrical properties must still be improved.



Perpendicular magnetic anisotropy (Keff) of FeCoB storage electrode of MTJ stacks with W lamination of various thicknesses inserted between the FeCoB electrode and the Ta cap layer as a function of annealing temperature.

In particular, the magnetic anisotropy of the magnetic electrodes which determines the memory retention must be increased as well as the tunnel magnetoresistance amplitude (TMR). The heart of a magnetic tunnel junction is a stack consisting of Buffer/FeCoB/MgO/FeCoB/Cap. The magnetic electrodes of FeCoB 1nm to 2nm thick are initially amorphous while the MgO tunnel barrier is polycrystalline. The buffer and protecting layer (Cap) are most often in tantalum (Ta). These stacks must be annealed after deposition in order to improve the crystallinity of the MgO barrier and provoke the crystallization of the FeCoB electrodes. This crystallization is required to obtain a large tunnel magnetoresistance (TMR). The higher the annealing temperature, the better the crystallization. However, the annealing temperature is usually limited to about 300°C by interdiffusion phenomena taking place in the metallic layers of the stack, in particular of Ta in FeCoB. It has discovered at SPINTEC that by introducing lamination of a refractory metal in the stack, in particular of tungsten whose melting temperature is 3422°C, the annealing temperature can be increased up to 570°C. The refractory metal mechanically stiffens the whole stack. The resulting tunnel magnetoresistance is increased by about 30%.

Team: MRAM Memories

Further reading: *Enhanced annealing stability and perpendicular magnetic anisotropy in perpendicular magnetic tunnel junctions using W layer*, Jyotirmoy Chatterjee, Ricardo C. Sousa, Nicolas Perrissin, Stéphane Auffret, Clarisse Ducruet, and Bernard Dieny, Appl. Phys. Lett. 110, 202401 (2017), DOI: *10.1063/1.4983159*

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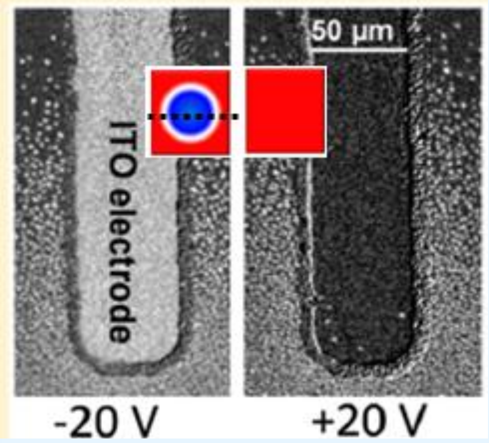
A skyrmion switch

Nanoscale magnetic skyrmions are good candidates for data manipulation and storage in spintronic applications (logic and/or memory). M. Schott et al. have recently shown that a gate voltage can nucleate or annihilate skyrmions. This proof of concept of a skyrmion switch paves the way towards skyrmion-based applications.

Skyrmions are chiral magnetic bubbles: their magnetic texture, or topology, is peculiar since magnetization follows a cycloid along a line across the skyrmion (see dotted line in inset of fig.1). Such topology results from the presence of an interfacial interaction called Dzyaloshinskii-Moriya interaction (DMI). It is due to the asymmetry of the heavy metal/ferromagnet/oxide trilayers studied here. This DMI makes the skyrmions stable, less sensitive to defects than usual domain walls and easily moveable by electrical current. They are currently very popular as they could be used as storage nanoscale data bits that could be very dense, with low power manipulation; they could also be used for magnetic logic with efficient operation. Their creation and erasing with simple, local and low power means are thus important milestones for applications. This study, published in Nanoletters, arises from the collaboration of teams from Néel Institute and Spintec Laboratory in Grenoble. In trilayers composed of a heavy metal (Platinum), an ultra-thin ferromagnet (Cobalt) and an insulating oxide (Alumina), they have shown that the size and density of magnetic skyrmions can be modulated by a gate voltage. Finally they have even managed to create and erase skyrmions with the voltage, thus demonstrating a skyrmion switch device operation. These measurements were done at room temperature with materials compatible with electronics. It thus leads to sizeable advances not only in understanding of these magnetic skyrmions but also for their future use in a device.



Kerr effect microscopy images showing evolution of skyrmions density (bright dots) under the electrode for negative (large density) and positive (very low density) applied voltages. (Inset) schematics of the electrically controlled skyrmion switch: presence (-20V) or absence (+20V) of skyrmion depending on the applied gate voltage. The magnetic texture of the skyrmion along the dotted line is peculiar.

In this study, the skyrmions are micron-sized. The next step will consist in studying smaller skyrmions, typically in the 10 nm range. In fact, smaller skyrmions would be more suited for application purposes, but they would also be more difficult to observe.

Team: Magnetic Sensors

Collaboration: Néel Institute, Univ. Grenoble Alpes / CNRS

Funding: French Research Agency via the project ANR ELECSPIN (ANR-16-CE24-0018)

Further reading: *The skyrmion switch: turning magnetic bubbles on and off with an electric field,* M. Schott et al. Nanoletters 17 (5), 3006 (2017). DOI: *10.1021/acs.nanolett.7b00328*

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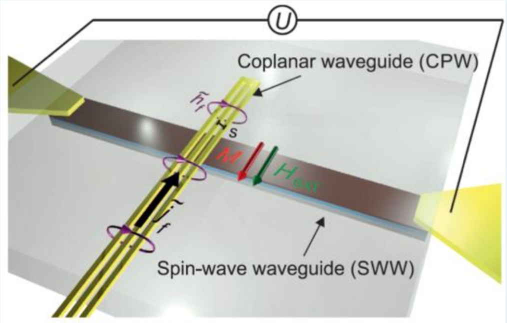
Detection of Short-Waved Spin Waves in Individual Microscopic Spin-Wave Waveguides Using the Inverse Spin Hall Effect

We report on the wave-vector independent detection of short-waved spin waves with wavelengths down to 150 nm by the inverse spin Hall effect in spin-wave waveguides made from CMOS-compatible sputtered Ta/CoFeB/MgO. These findings open up the path for miniaturized scalable interconnects between spin waves and CMOS, and the use of ultrathin films made from standard spintronic materials in magnonics.

The miniaturization of CMOS devices becomes increasingly difficult due to fundamental limitations and the increase of leakage currents. Large research efforts are devoted to find alternative concepts that allow for a larger data-density and lower power consumption than conventional semiconductor approaches. Spin waves have been identified as a potential technology that can complement and outperform CMOS in complex logic applications, as they enable wave computing on the nanoscale. The practical application of spin waves, however, requires the demonstration of scalable, CMOS compatible spin-wave detection schemes in material systems compatible with standard spintronics as well as semiconductor circuitry.

$Ta/Co_8Fe_{72}B_{20}/MgO$, typically used in STT-MRAM are patterned as rectangular SWWs. The SWWs are connected to leads at their edges, which allow for the detection of the rectified voltage arising from the propagating spin waves, using the inverse spin Hall effect (iSHE). On top of the SWWs, CPWs of different sizes have been structured to create a dynamic Oersted field which excites propagating spin waves with different and well-defined finite wave vectors in the SWW with in-plane anisotropy.

We show that down to wavelengths of $\lambda \approx 150$ nm the detection by the iSHE is independent of the spin-wave wavelength. By performing additional measurements using microfocused Brillouin light scattering spectroscopy, we show that the excitation is indeed local and, consequently, the iSHE allows for the detection of localized spin-wave dynamics. Thus, the iSHE can be used to detect information transport by short-waved spin waves.



Ta/CoFeB/MgO trilayer patterned into a spin-wave waveguide (SWW) with leads to measure the voltage drop along the SWW. On top of an insulating Al_2O_3 layer, a nanometric, shorted coplanar waveguides (CPWs) with wire spacing s acts as spin-wave excitation source.

In addition, we have demonstrated that despite the presence of interfacial damping, the spin-wave lifetime in Ta/CoFeB/MgO is comparable to the one in thicker films of commonly used magnonic materials such as $Ni_{81}Fe_{19}$. This is attributed to the large perpendicular magnetic anisotropy, which also results in a strongly preferred emission direction by the CPW. The additional large reported current-induced spin orbit torques in this material system, render it a highly promising system for magnonic applications.

These findings open up the path for miniaturized scalable interconnects between spin waves and CMOS and the use of ultrathin films made from standard spintronic materials in magnonics.

Teams: Spin Orbitronics, Microwave Devices

Collaboration: Technishe Universität Kaiserslautern, Germany

Funding: CNES, the Deutsche Forschungsgemeinschaft: DFG-GSC266, DFG-Project B01 SFB/TRR 173 Spin+X, EC FP7-spOt project (318144), Nachwuchsring of the TU Kaiserslautern

Further reading: *Detection of Short-Waved Spin Waves in Individual Microscopic Spin-Wave Waveguides Using the Inverse Spin Hall Effect*, T. Brächer, M. Fabre, T. Meyer, T. Fischer, S. Auffret, O. Boulle, U. Ebels, P. Pirro, G. Gaudin, Nano Lett. **17**, 7234 (2017). DOI: *10.1021/acs.nanolett.7b02458*

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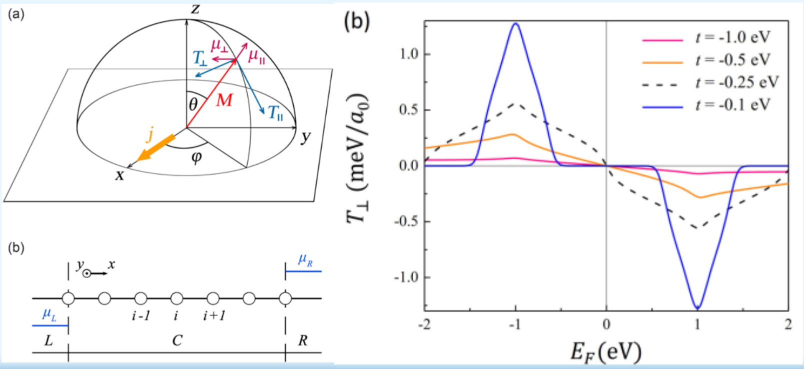
Intrinsic spin-orbit torque in a single-domain nanomagnet

Theoretical studies of the intrinsic spin-orbit torque (SOT) in a single-domain ferromagnetic layer with Rashba spin-orbit coupling (SOC) has been performed. It was found that in the case of a small electric field, the intrinsic SOT to first order in SOC has only the field-like torque symmetry and can be interpreted as the longitudinal spin current induced by the charge current and Rashba field. Numerical and analytical results suggest that the different sign of SOT in identical ferromagnets with different supporting layers, e.g., Co/Pt and Co/Ta, can be attributed to electrostatic doping of the ferromagnetic layer by the support.

Spin-orbit torque has been attracting a tremendous interest since it allows to manipulate the magnetization direction in a ferromagnetic layer without the presence of a second polarizing ferromagnet. In this work, the intrinsic SOT has been investigated arising from the band structure alone for a ferromagnetic layer with Rashba spin-orbit coupling. A ballistic transport formalism based on the Keldysh non-equilibrium Green's function (NEGF) method and a single-orbital tight-binding (TB) Hamiltonian model. To gain insights into the physical picture, an analytic expression for SOT to first order in SOC was derived and used to analyze the SOT dependence on the band-structure parameters and applied voltage.

Analytical and numerical results studies allowed to conclude that in the limit of large samples, to first order in SOC the SOT has the field-like torque (FLT) symmetry and is proportional to the longitudinal component of the spin current, while the damping-like torque (DLT) component arises for finite-size systems due to the bias-induced voltage drop. It was found that the SOT efficiency decreases with bandwidth and that the magnitude and sign of the band contributions to SOT depend on the band spin component and occupation. This makes it possible to change the overall sign of SOT by electrostatic doping.



Schematic views of the two-dimensional ferromagnetic layer and of two-probe setup consisting of the scattering region (left panel).

FLT dependence on the position of Fermi level (right).

These findings could help explaining experimental observations of the opposite signs of SOT in Co/Pt and Co/Ta layers in terms of hole and electron doping of the Co layer from the supporting Pt or Ta layers, respectively, and may be useful for selecting specific material combinations with optimal properties.

Team: Theory and Simulation

Collaboration: Western Digital Corporation, San Jose, CA, USA; Univ. of Puerto Rico, San Juan, PR, USA

Funding: "Emergence et partenariat stratégique" program of Univ. Grenoble Alpes.

Further reading: *Intrinsic spin-orbit torque in a single-domain nanomagnet*, A. Kalitsov, S. A. Nikolaev, J. Velev, M. Chshiev, and O. Mryasov, Phys. Rev. B 96, 214430 (2017). DOI: *10.1103/PhysRevB.96.214430*

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Sub-10nm thermally stable Perpendicular Shape Anisotropy magnetic memory

Abstract. A new concept of thermally stable and electrically switchable Spin Transfer Torque Magnetic Random Access Memory (STT-MRAM) scalable to diameter down to 4nm was proposed and demonstrated. By dramatically increasing the thickness of the storage layer, a bulk magnetic anisotropy perpendicular to the plane of the layers can be induced which dramatically improves the memory properties, in particular its retention down to 4nm diameter with no penalty on the write current.

Among the various technologies of non-volatile memories, STT-MRAM gathers a unique combination of assets: non-volatility, write speed (3-30ns), density (4Gbit demonstrated by Hynix/Toshiba), low consumption (a few tens of fJ/write), and very importantly an extremely long write endurance (>10^{13}cycles). Conventional STT-MRAM are based on out-of-plane magnetized magnetic tunnel junctions (MTJs) in which the storage layer magnetization is pulled out-of-plane thanks to a perpendicular anisotropy originating from the interface between the oxide barrier and the magnetic electrodes. This phenomenon was discovered at SPINTEC in 2002 and reviewed in Rev. Mod. Phys. 89, 025008 (2017). In conventional STT-MRAM, this interfacial anisotropy is large enough to insure thermal stability of the storage layer magnetization down to diameter of the order of 20nm. To increase the STT-MRAM downsize scalability, a novel type of MRAM with much thicker storage was developed at SPINTEC. By drastically increasing the thickness of the storage layer to values comparable to its diameter, a perpendicular shape anisotropy (PSA) is induced in the storage layer which comes on top of the previously mentioned interfacial anisotropy with no penalty on the switching current. As a result, the perpendicular anisotropy is greatly reinforced enabling to maintain magnetic thermal stability (i.e. good memory retention) down to 4nm diameter. The name PSA-STT-MRAM was coined to designate this memory.

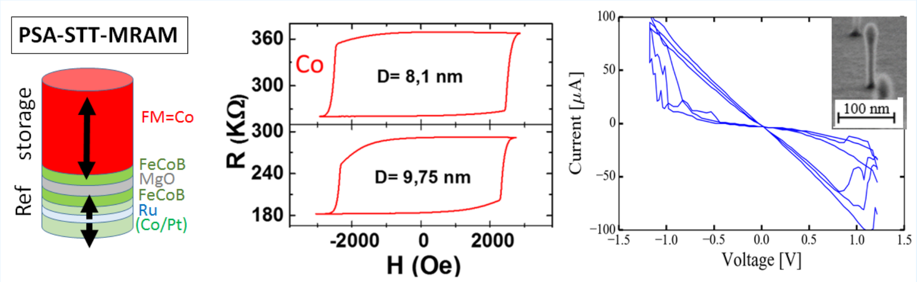

Illustration of the PSA-STT-MRAM concept. R(H) loops showing large coercitivity at 300K even for pillars 8.1nm in diameter. Illustration of spin transfer torque switching in a pillar 12nm in diameter.

In addition to their excellent and tunable thermal stability at sub-10nm diameter, PSA-STT-MRAM have additional advantages: bulk and interfacial properties of the storage layer can be separately optimized. For instance, low Gilbert damping material can be used in the bulk of the storage layer to reduce the write current without compromising on the tunnel magnetoresistance amplitude. Furthermore, because the storage layer is thick, the thermal variation of its magnetic properties is much closer to that of the corresponding bulk material and therefore much less temperature dependent than when very thin storage layer are used. As a result, PSA-STT-MRAM can more easily be designed to operate on a wide range of temperature than conventional STT-MRAM which is very important for automotive and industrial applications or to fulfill solder reflow compliance.

Teams: MRAM Memories, Theory and Simulation

Funding: ERC MAGICAL n°669204

Further reading: *A highly thermally stable sub-20 nm magnetic random-access memory based on perpendicular shape anisotropy*, N. Perrissin, S. Lequeux, N. Strelkov, A.Chavent, L. Vila, L. Buda-Prejbeanu, S. Auffret, R.C. Sousa, I.L. Prejbeanu, B. Dieny. Nanoscale,10, 12187-12195(2018). DOI: *10.1039/C8NR01365A*

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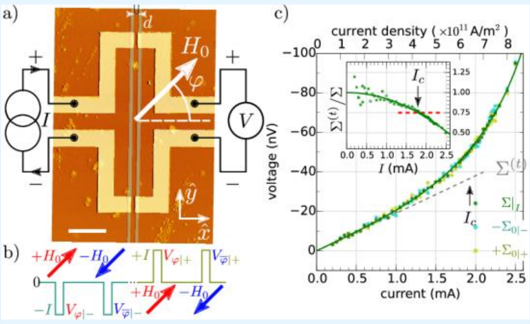
Nonlinear properties of pure spin conductors

We have recently reported that pure spin conductors could behave as nonlinear component in the high power regime, hereby opening up considerably the realm of functions realizable with magnetic materials. An additional feature is that these are continuously tunable by an external magnetic field.

The recent demonstrations that spin-orbit torques (SOTs) allow one to generate and detect pure spin currents transfers to an adjacent layer has radically changed our grasp about material compatibility with spintronics. In particular, it has triggered a renewed interest in magnetic insulators, which are much better spin conductors than metals. A large effort has concentrated so far on yttrium iron garnet (YIG), which is famous for having the lowest known magnetic damping parameter. The typical experiment is a non-local transport measurement between two parallel Pt wires deposited on top of YIG as illustrated in FIG.1.



a) Top view of a lateral device. Two Pt wires (grey lines) are aligned along the ŷ-direction and placed at a distance d=1.2µm apart on top of a 18 nm thick YIG film (scale bar is 5 µm). The non-local conductance I-V (injector-detector) is measured using current pulses while rotating the magnetic H_0 field in-plane.

In a recent joint paper publication, we have reported measurement of the non-local spin conductance of YIG films when the driving current is varied in a wide magnitude range creating, first, a quasi-equilibrium transport regime and, then, driving the system to a strongly out-of-equilibrium state. The lateral device is biased by an in-plane magnetic field set at a variable azimuthal angleφ. We sort the nonlocal voltages according to their symmetry with respect to the magnetization direction. At low current, the spin transfer signal, Σ_0, follows first a linear behavior which is believed to be dominated by thermal magnons' transport. The interesting novel feature is the fact that the signal, Σ_0, deviates from a purely linear transport behavior at large current above, I_c. Quite remarkably the deviation from the linear conductance occurs very gradually and approximately follows a quadratic behavior (see insert). We have also found that at high current, the spin conductance is dominated by magnetostatic magnons, which are low-damping non-equilibrium magnons thermalized near the spectral bottom by magnon-magnon interaction, with consequent a sensitivity to the applied magnetic field. These findings are not only important from the fundamental point of view, but might be also useful for future applications. Although transport of thermal magnons is difficult to control due to their relatively high energies, the crossover to a subthermal spin conduction regime allows the development of controllable spin conductors by relatively weak magnetic fields. From a fundamental point of view, these studies of magnon transport in YIG by means of the direct and inverse spin Hall effects are also very interesting as they provide new means to alter strongly the energy distribution of magnons up to thermal energies, where the interplay between these nonequilibrium populations is expected to lead to new collective quantum phenomena at room temperature.

Teams: Microwave Devices, Spin Orbitronics

Collaboration: SPEC - CEA-Saclay - CNRS and Unité Mixte de Physique CNRS-Thales, Université Paris-Saclay, Gif-sur-Yvette, France ; LabSTICC, CNRS, Université de Bretagne Occidentale, Brest, France ;

Further reading: *N. Thiéry et al., Nonlinear spin conductance of yttrium iron garnet thin films driven by large spin-orbit torque, Phys. Rev. B 97, 060409 (2018). N. Thiéry et al., Electrical properties of epitaxial yttrium iron garnet ultrathin films at high temperatures, Phys. Rev. B 97, 064422 (2018).* DOI: *10.1103/PhysRevB.97.060409* | *10.1103/PhysRevB.97.064422*

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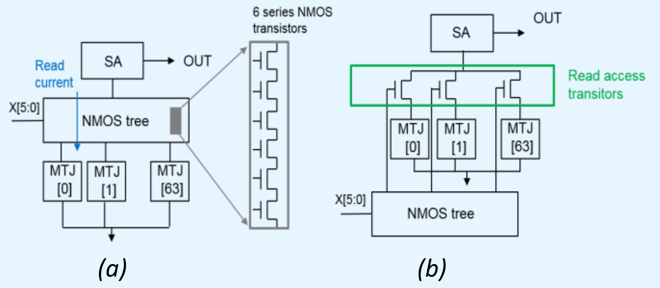
High speed and low area look-up table design based on MRAM memory

Continual growth in the size and functionality of FPGA over few years leads to an increasing interest in their use for high speed applications. However, the memory access speed limits the execution speed. The great amount of data affects the whole function. This work introduces a novel high speed and low-area efficiency MRAM based non-volatile Look-Up Table (nvLUT).

In opposition to ASIC, Application Specific Integrated Circuit optimized for a dedicated function, Field Programmable Gate Array (FPGA) is a key device to quickly realize prototyping systems. Their specifications and functions are directly programmable by users. Look-Up Table is the elementary cell of FPGA where data is usually stored into volatile memory cell, typically SRAM cells. Thanks to its non-volatility, the use of Magnetic Tunnel Junction (MTJ) could solve the power dissipation problem that is facing SRAM memories used for FPGA. It also makes the LUT much more energy efficient.



(a) General architecture of 6 inputs nvLUT where NMOS tree in series with MTJ. Read current passes through NMOS tree and MTJ selected flowing to the ground.
(b) Proposed architecture where NMOS tree and MTJ are separated. Read current passes through only one transistor and selected MTJ.

The number of input variables in LUT have a direct impact of the functional performance. In general, a larger number of inputs of the LUT is necessary because it gives the LUT the ability to realize and perform more complex logic functions. This leads also to a global area reduction. N-input LUT requires N-NMOS transistors connected serially. It forms this way a CMOS logic tree. Thus, during reading, high resistance becomes critical because the read current is limited due to series-NMOS transistors tree. Additionally, the propagation delay of output logic circuit is also dependent of inputs and becomes increasingly important when the number of inputs increases. The larger the number of inputs is, the slower the reading is. Finally, the number of input is limited because of functional reasons. To solve this set of issues, we proposed a new nvLUT architecture. It separates the CMOS logic tree from the reading path. Therefore, the propagation delay no more depends of the number of inputs and is constant. Thus, the reading current do not vary when the number of input variables in increased. It results a good delay of propagation whatever the nvLUT complexity.

In the case of an 8 input non-volatile Look-Up Table, our proposed circuit ensures a sufficient reading current. It offers a short delay whatever the number of inputs. This innovation offers a 55% sense delay reduction, 47% number of MTJ reduction, 46% power-delay product reduction. It also offer a wider possible input number. This architecture designed on a 130nm hybrid CMOS / MRAM process is presently under nano-fabrication. We expect to perform the tests in the coming months.

Teams: Spintronics IC Design, MRAM Memories

Funding: CEA LETI, Minatec campus

Further reading: *High Speed and High-Area Efficiency Non-Volatile Look-Up Table Design Based on Magnetic Tunnel Junction*, Rana Alhalabi, Gregory Di Pendina, Ioan-lucian Prejbeanu and Etienne Nowak, 17th Non-Volatile Memory Technology Symposium (NVMTS), 2017, DOI: *10.1109/NVMTS.2017.8171280*

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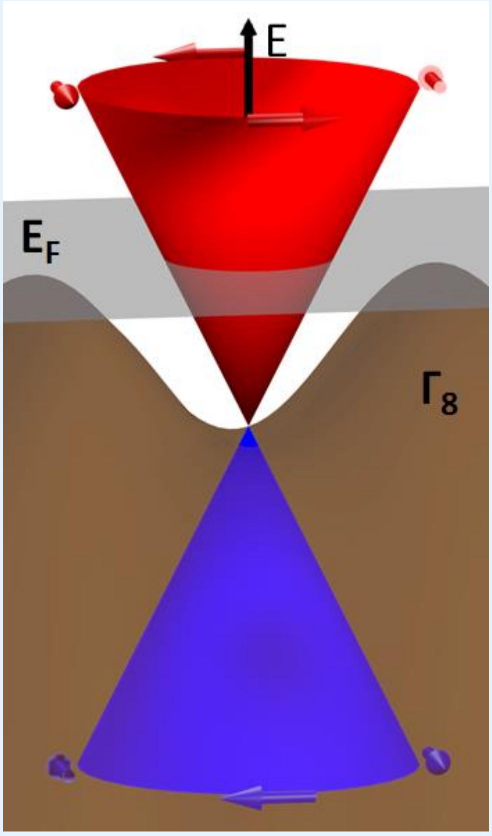
Highly Efficient Spin-to-Charge Current Conversion in Strained HgTe Surface States Protected by a HgCdTe Layer

We report the observation of spin-to-charge current conversion in strained mercury telluride at room temperature, using spin pumping experiments. We show that a HgCdTe barrier can be used to protect the HgTe from direct contact with the ferromagnet, leading to very high conversion rates.

Conventional spintronics is based upon the use of magnetic materials to manipulate spin currents. Such a manipulation can be achieved by harnessing the spin-orbit coupling in nonmagnetic materials. It has also been recently demonstrated that higher conversion rates can be obtained by using two-dimensional electron gas with high spin-orbit coupling, in topological insulator surfaces. As a consequence, the use of topological insulators is generating a growing attention in spintronics.



Schematic representation of the band structure of strained HgTe, with the Dirac dispersion cone of the surface states, and the bulk Γ_8 band. The arrows represent the helical spin configuration.

The main interest of TIs lies in their surface states, which possess a linear Dirac-like energy dispersion, and in the perpendicular locking between spin and momentum. A flow of electric current in the two-dimensional electron gas gives rise to a perpendicular spin accumulation, this effect being known as the Edelstein effect, while the reverse spin-to-charge conversion phenomenon is known as the inverse Edelstein effect.

We demonstrate a very efficient spin-to-charge current conversion at room temperature in strained HgTe. We also show that a HgCdTe barrier can be used to protect the HgTe surface states from direct contact with the ferromagnet, leading to an enhancement of the conversion efficiency.

We then show that the dependence of the conversion with the HgTe thickness differs from the usual dependence observed in spin Hall materials. These dependences, associated with the temperature dependence of the resistivity, suggest that the high conversion rate can be attributed to the spin momentum locking at the surface states of HgTe.

These results underline the necessity to add an interlayer between the topological insulator and ferromagnetic metal to obtain high conversion efficiencies, and show that insulating layers are good candidates to protect the TI surface states. The HgTe thickness dependence of the conversion rate is strongly different from SHE materials, suggesting that several mechanisms, such as hybridization, might play a key role.

Team: Spin Orbitronics

Collaboration: DOPT-Leti, Institut Néel

Funding: ANR Toprise (ANR-16-CE24-0017) and Laboratoire d’excellence LANEF (ANR-10-LABX51-01)

Further reading: Highly Efficient Spin-to-Charge Current Conversion in Strained HgTe Surface States Protected by a HgCdTe Layer, P. Noel, C. Thomas, Y. Fu, L. Vila, B. Haas, P-H. Jouneau, S. Gambarelli, T. Meunier, P. Ballet, and J. P. Attané, Phys. Rev. Lett. 120, 167201 (2018). DOI: *10.1103/PhysRevLett.120.167201*

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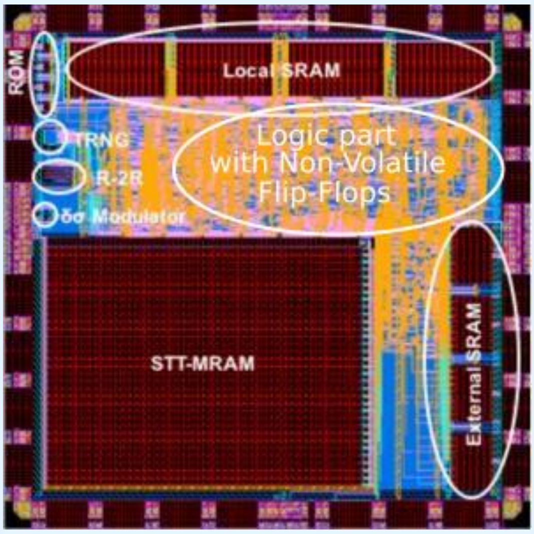
The EU GREAT Project delivered its 2nd tape-out demonstrator

A full hybrid magnetic/CMOS System on Chip (SoC), embedding analog and digital functions based on spintronics devices on the same die, has been designed and sent to manufacturing. It is the first demonstrator of such a circuit worldwide.

Spintronics, which aims at using magnetic devices beside standard CMOS transistors, has been intensively studied for several years as a solution to contribute to push forward the incoming limits in microelectronics scaling. It is now seen as one of the most promising emerging non-volatile technologies and is on the way to becoming a mainstream technology for most of the microelectronics players. A specificity of this technology is that magnetic devices (MTJs for Magnetic Tunnel Junctions) allow performing analog functions, like sensing or RF communication in addition to the standard memory function. Being able to integrate all these functions in a same die (SoC for System on Chip) would allow drastically simplifying the process (reducing the cost) and reducing the power consumption. This is particularly interesting for IoT (Internet of Things) applications, were smart communicating objects has to operate in energy constraint environments, at very low-cost.



Layout of the second demonstrator of the GREAT project, currently in manufacturing phase

In 2015, the EU launched the GREAT project (for heteroGeneous integRated magnetic tEchnology using multifonctionnal stAndardized sTack), with an aim to co-integrate multiple functions like sensors, RF receivers and logic/memory together within CMOS by adapting MTJs to a single baseline technology (MSS for Multifunctional Standardized Stack) in the same SoC. The main objectives of the project are to develop the MSS devices, co-integrate them with standard CMOS in a full hybrid process, design elementary functions based on this MSS and integrate them in a full SoC to run a pertinent application and evaluate the gain compared to standard approaches.

A first demonstrator delivered in 2017, embedded mainly test structures and elementary logic circuits. Partners announced that the second demonstrator is now under manufacturing using the hybrid CMOS/MSS technology of TowerJazz. The project partners designed in particular an ultra-low power “normally off” microcontroller, based on a 32-bit non-volatile processor core with several features. A non-volatile flip flop, a non-volatile controller with Instant on-off capabilities using efficient wake-up and backup recovery operations thanks to the non-volatility are part of this SoC. Moreover, an SRAM and MSS-based memories, secure block based on the MSS stack (cryptographic keys generation) and a set of Analog IP block were integrated to this ASIC.

The next phase of the project will consist in testing the demonstrator and in characterizing the hybrid CMOS/MSS process. Results are expected by the second quarter of 2019.

Team : Spintronics IC Design

Collaboration: Karlsruhe Institute of Technology (KIT), Laboratoire d'Informatique, de Robotique et de Microélectronique de Montpellier (LIRMM), Universitatea Transilvania din Brasov (UTBV), Technische Universität Dresde (TUD), Singulus Technologies AG, Tower Jazz, eVaderis and Toplink Innovation

Funding: from (H2020-ICT-2015) under grant agreement No.687973 (GREAT).

Further reading: Tahoori, M., Nair, S. M., Bishnoi, R., Senni, S., Mohdad, J., et al. (2017, July). *GREAT: heteroGeneous integRated magnetic tEchnology using multifunctional standardized sTack*. In VLSI (ISVLSI), 2017 IEEE Computer Society Annual Symposium on (pp. 344-349). IEEE.

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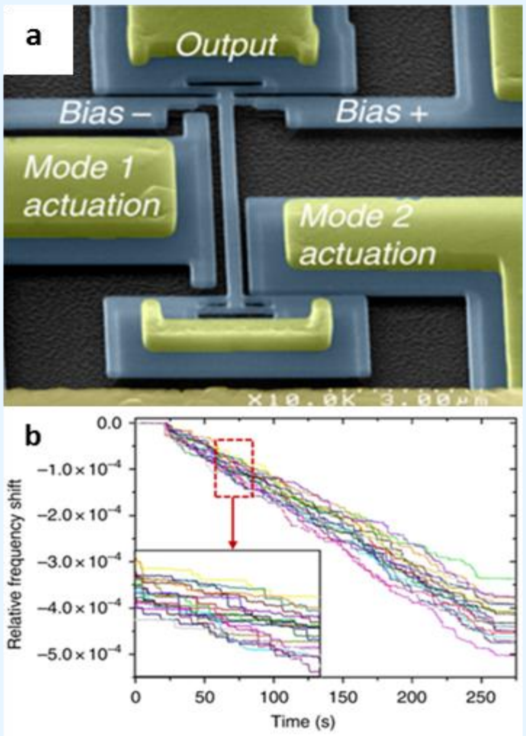
Single-particle mass spectrometry with nanomechanical resonators

Mass spectrometry (MS) is an essential tool in a broad variety of fields, with good efficiency up to the kDa mass range (~10^{-21} g). We demonstrate here Nano-electro-mechanical systems mass spectroscopy (NEMS-MS) with arrays of individually addressed nanomechanical resonators, allowing for measurements in the MDa (~10^{-18} g) to GDa (~10^{-15} g) mass range.

One of the main challenges to perform practical NEMS-MS analysis stems from the size mismatch between the analyzed beam and the small nanomechanical detector area. To overcome this limitation arrays of 20 individually addressed nanomechanical resonators were designed, with each resonators designed with a distinct resonance frequency that allows them to be individually addressed. Using such arrays, mass spectra of nanoparticles have been recorded with excellent speed due to a significantly enhanced capture cross-section compared to individual resonators.



a) Doubly-clamped nanomechanical resonator with electrodes for mode 1 and mode 2 actuation; b) Mode 1 relative frequency time traces for an array of NEMS exposed to a flux of 7.2 nm Ta nanoclusters. Inset: Zoom-in with frequency jumps associated with single-particle deposition.

Monocrystalline silicon resonators were fabricated from SOI wafers with very large scale integration processes. The resonators are electrostatically actuated and use a differential piezoresistive readout. Particles landing on a resonator add to its total mass and cause its resonance frequency to downshift. As these frequency shifts also depend on the landing position on the resonator's surface, the frequencies of two resonance modes are monitored simultaneously to resolve the mass and position of the deposited particle. The device testing was made by comparing real-time measurements of the size distribution of Ta clusters made by gas-phase condensation, using simultaneously NEMS-MS and Time of Flight Mass Spectroscopy, on a setup installed at INAC/Spintec. The NEMS-MS provides an accurate spectrum of the cluster populations over a large mass range (530–2400 kDa).

This study is a part of a multidisciplinary project including i) the development of a setup coupling NEMS to a Surface Acoustic Wave Nebulization system, which will enable the analysis of large biomolecules and macromolecular systems that are too big to be reliably measured by conventional mass spectrometry, and ii) the development of new devices using nanoresonators with optical transduction, in order to improve the readout efficiency for very large and dense arrays.

Team: Health and Biology

Collaboration: CEA-LETI, CEA-BIG, INSERM, California Institute of Technology, Indian Institute of Science

Funding: LETI Carnot Institute NEMS-MS project, ERC Enlightened project (616251) and Marie-Curie Eurotalents incoming (M.S.) fellowship

Further reading: *Single-particle mass spectrometry with arrays of frequency-addressed nanomechanical resonators,* E. Sage, M. Sansa, S. Fostner, M. Defoort, M. Gély, A. K. Naik, R. Morel, L. Duraffourg, M. L. Roukes, T. Alava, G. Jourdan, E. Colinet, C. Masselon, A. Brenac, and S. Hentz, Nat. Commun. 9, 3283 (2018). DOI: *10.1038/s41467-018-05783-4*

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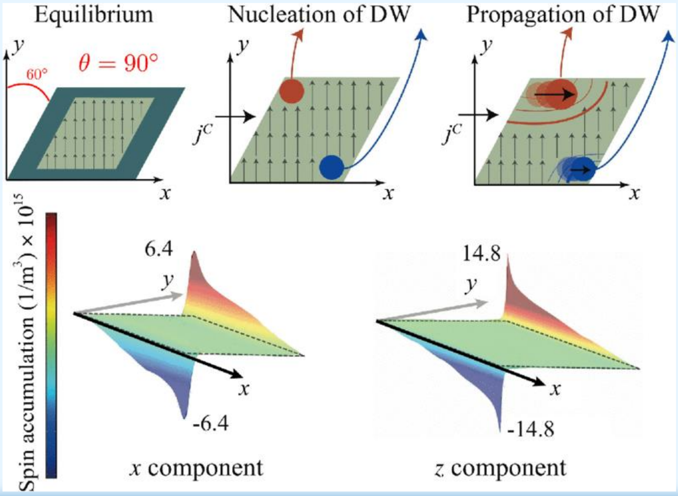
Spin Hall and Spin Swapping Torques in Diffusive Ferromagnets

A complete set of the generalized drift-diffusion equations for a coupled charge and spin dynamics in ferromagnets in the presence of extrinsic spin-orbit coupling is derived from the quantum kinetic approach, covering major transport phenomena, such as the spin and anomalous Hall effects, spin swapping, spin precession, and relaxation processes. It is argued that the spin swapping effect in ferromagnets is enhanced due to spin polarization, while the overall spin texture induced by the interplay of spin-orbital and spin precession effects displays a complex spatial dependence that can be exploited to generate torques and nucleate or propagate domain walls in centrosymmetric geometries without the use of external polarizers, as opposed to the conventional understanding of spin-orbit mediated torques.

Spin-orbit torques generated in a single ferromagnetic layer are of great importance in enabling electrical control of the magnetization without the use of external polarizers, and they offer many promising advantages compared to spin-transfer torques, such as high scalability and stability. Thus, finding novel routes to excite magnetization dynamics by means of spin-orbit torques is essential for realizing high-performance spintronic devices. Recently, a new mechanism referred to as spin swapping, which converts a primary spin current into a secondary spin current with interchanged spin and flow directions was proposed to exist in normal metals and semiconductors in the presence of spin-orbit coupled impurities.

Spintec Theory team in collaboration with colleagues at KAUST has clarified the nature of the extrinsic spin Hall and spin swapping effects in diffusive ferromagnets, and demonstrated that these effects can offer potential advantages in contrast to non-centrosymmetric magnetic multilayers involving heavy metals. They first derived a set of coupled spin-charge diffusive equations was derived by using the non-equilibrium Green's function formalism and taking into account scattering off the impurity induced SOC potential. Next, the interplay between spin-orbital and spin precession effects has been investigated in order to demonstrate current-driven manipulation of the magnetization in centrosymmetric magnets. This follows from distorted spin accumulation profiles built up, for instance, in samples with a diamond-shaped geometry shown in figure above giving rise to nonzero local spin-orbit torques.



Spin accumulation profiles (bottom-left and bottom-right panels) as calculated for the diamond-shaped geometry. The top panels describe the idea of nucleation and propagation of reversed magnetic domains. Red and blue circles correspond to the spin-up and spin-down components of the spin accumulation, respectively; black arrows show the magnetization pointed along the y axis.

Team: Theory and Simulation

Collaboration: KAUST (Saudi Arabia);

Funding: “Emergence et partenariat stratégique” program at the Univ. Grenoble Alpes

Further reading: *Spin Hall and Spin Swapping Torques in Diffusive Ferromagnets*, Christian Ortiz Pauyac, Mairbek Chshiev, Aurelien Manchon, and Sergey A. Nikolaev, Phys. Rev. Lett. 120, 176802 (2018). DOI: *10.1103/PhysRevLett.120.176802*

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Mihai MIRON rewarded with the yearly junior prize of IMT French Academy of Sciences

Mihai Miron, junior CNRS scientist working at SPINTEC, was awarded the yearly junior prize of IMT (Institut Mines-Télécom) – French Academy of Sciences. This prize is meant as a recognition for a major contribution to innovation in one of these fields: sciences and technology of numerical revolution in industry, science and technology of energy transition, environmental engineering.

Mihai MIRON

In the global context of information technology, playing a key role in our society however associated with significant and ever rising energy consumption, a promising way to improve the energy efficiency and performance is the integration of non-volatile random access memories. Spin Transfer Torque Magnetic Random Access Memory (STT-MRAM) has been identified by the ITRS semiconductor roadmap consortium as the most credible candidate. Ioan-Mihai MIRON, from the team Spin Orbitronics, has discovered a new physical phenomenon allowing to switch magnetization of a storage layer by means of in-plane electric current. Contrasting with standard STT where electric current flows perpendicular to the layers and their interfaces, he showed that it is possible to reverse the magnetization through an in-plane current, by transferring angular momentum directly from the crystal lattice at the interface between the magnetic storage layer and a heavy-metal underlayer. This is the now-called Spin-Orbit torque effect (SOT), which only occurs in magnetic materials or stacks that lack structural inversion symmetry and that have strong spin orbit coupling.

Spin-orbit torques allow faster switching (sub-nanosecond) with a lower current density than STT, and thus a lower energy consumption. Also, it releases constraints on material endurance issues as the high write current does not flow through the storage layer. These assets qualify SOT-MRAM as an ideal candidate for replacement of current SRAM in cache levels.

Team: Spin Orbitronics

Further reading:

http://www.academie-sciences.fr/en/Prix-en-mathematiques-physique-mecanique-informatique-et-sciences-de-la-Terre-et-de-l-univers/prix-imt-academie-des-sciences.html

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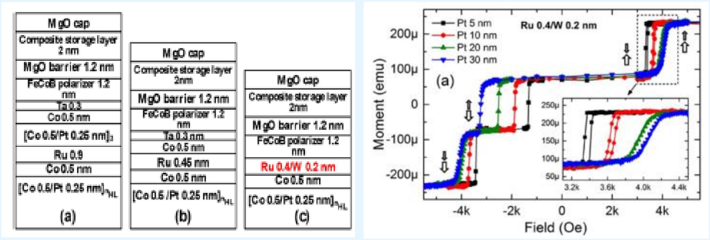
Novel multifunctional RKKY coupling layer for ultrathin perpendicular synthetic antiferromagnets

Abstract. A novel multi-functional antiferromagnetic coupling layer combining Ru and W is revealed to realize an extremely thin (3.8 nm), back-end-of-line compatible perpendicular synthetic antiferromagnetic layer, essential for spintronic memory and logic device applications. Two important advantages are provided by this ultrathin reference layer: the easing of the reference layer etching and the minimization of the dipolar field acting on the storage layer magnetization.

Perpendicular magnetic tunnel junction (pMTJ) stacks are the storage elements of STT-MRAM. Among the various technologies of non-volatile memories, STT-MRAM gathers a unique combination of assets: non-volatility, write speed (3–30 ns), density, low consumption (a few tens of fJ/write), and very importantly an extremely long write endurance (>10^{13}cycles). In order to fabricate a high density and high capacity memory array at advanced technology node (sub-20nm cell diameters), the stack must be as thin as possible, especially below the tunnel barrier. Indeed, for patterning the magnetic tunnel junction stacks, physical etching by ion beam (IBE) remains the preferred approach. However, this technique does not allow to reach very narrow pitch due to redeposition of non-volatile etch products at the side walls of the memory cells and shadowing efect when etching at large incidence angle. Reducing the thickness of the bottom part of the stack below the tunnel barrier is thereforevery advantageous to reduce the amount of redeposited species on the sidewalls of the MTJ. This increases the yield, the magnetoresistance amplitude, and decreases the dot-to-dot variability. Besides, the MTJ stack must endure a back end of line annealing at 400°C and exhibit a thermal stability factor between 60 and 100 depending on the memory capacity and acceptable error rate over the operating range of temperature. It must also have low Gilbert damping in the storage layer, a high spin transfer efficiency to minimize write current and a large tunnel magnetoresistance amplitude to maximize read speed. Conventional stacks comprise a relatively thick synthetic antiferromagnetic layer. In this paper, we report on an innovative way to achieve extremely thin, magnetically stable and thermally robust pSAF using a novel multi-functional anti-ferromagnetic (MF-AFC) coupling layer based on Ru/W bilayers. Apart from RKKY coupling the other functionalities are boron absorption from the FeCoB pinned layer, texture breaking and reduction of interdiffusion of Ru into FeCoB at high annealing temperature. Functional STT-MRAM cells were patterned, demonstrating the stability of the reference layer against applied write voltage pulses up to 1 V and exhibiting very low dipolar field on the storage layer (<200 Oe) for sub-20nm electrical diameters. This novel class of MF-AFC is promising for STT-MRAM, SOT-MRAM and logic application.



(a) A conventional thick pSAF using two sets of Co/Pt MLs, antiferromagnetically coupled by the Ru RKKY coupling layer. (b) A previously proposed thin-pSAF with Co/Pt MLs as a hard layer, antiferromagnetically coupled with Co/Texture breaking layer (Ta)/FeCoB polarizer layer by Ru. (c) A thin pSAF with multi-functional RKKY coupling layer (Ru/W). Right: magnetization reversal

Team: MRAM Memories

Funding: ERC MAGICAL n°669204

Further reading: *Novel multifunctional RKKY coupling layer for ultrathin perpendicular synthetic antiferromagnet*, Jyotirmoy Chatterjee, Stephane Auffret, Ricardo Sousa, Paulo Coelho, Ioan-Lucian Prejbeanu & Bernard Dieny. Scientific Rep. 8, 11724 (2018). DOI: 10.1038/s41598-018-29913-6

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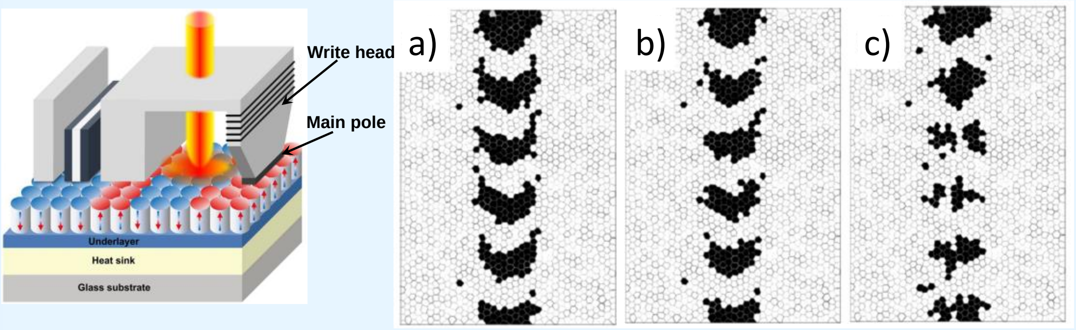
Impact of intergrain effective coupling due to huge thermal gradients in heat assisted magnetic recording

Heat assisted magnetic recording (HAMR) is a new hard disk drive (HDD) recording technology which uses a temporary near field heating of the media during write to increase hard disk drive storage density. It has been under development in HDD industry for more than 10 years. A phenomenon totally overlooked during the past development of this technology has been revealed in this study: The existence of effective coupling between grains in the recording media due to thermoemission of spin-polarized electrons. It has important consequences on recording performance.

In HAMR, extremely large thermal gradients are created in the recording media (up to 10K/nm) due to the combination of local heating achieved by a plasmonic antenna and media velocity as the hard disk rotates (20m/s). State of the art HAMR magnetic media consists of grains of FePt alloys exhibiting high perpendicular anisotropy separated by 1 to 2 nm thick carbon segregant. Next to the plasmonic antenna, the difference of temperature between two nanosized FePt grains in the media can reach 80K across the 1 to 2 nm thick grain boundary. This represents a gigantic local thermal gradient of 40 to 80K/nm across a carbon tunnel barrier. For comparison, in magnetic tunnel junctions, much weaker thermal gradients of the order of 1K/nm across the tunnel barrier were shown to cause an effective magnetic coupling due to thermoemission of spin-polarized electrons capable of inducing magnetization switching in the magnetic electrodes. Considering that the thermal gradients in HAMR are one to two orders of magnitude larger than those used in magnetic tunnel junctions, one may expect a strong impact from these thermal spin-transfer torques on magnetization switching dynamics in HAMR recording. This issue has been totally overlooked in the earlier development of HAMR technology. Our study carried out in collaboration between SPINTEC , Headway Technologies and NIMS Japan combined theory, experiments aiming at determining the polarization of tunneling electrons across the media grain boundaries and micromagnetic simulations of recording process taking into account these thermal gradients. It was shown that the magnetic coupling due to the huge thermal gradient in the media can have a detrimental impact on the recording performances by favoring antiparallel magnetic alignment between neighboring grains during the media cooling. Implications on recording media design were made in order to overcome the influence of these thermally induced coupling.



Schematic principle of Heat Assisted Magnetic Recording. Simulations illustrating the degradation of the written patterns on the magnetic media. Each bit of information (0 or 1) appears as a bunch of magnetic grains magnetized up (black) or down (white). The grain size is 8nm.

Team: Theory and Simulation

Funding: ERC MAGICAL n°669204

Further reading: Impact of Intergrain Spin-Transfer Torques Due to Huge Thermal Gradients in Heat-Assisted Magnetic Recording, Bernard Dieny, Mair Chshiev, Brian Charles, Nikita Strelkov, Alain Truong, Olivier Fruchart , Ali Hallal, Jian Wang, Yukiko K. Takahashi, Tomohito Mizuno, and Kazuhiro Hono, Advances in Magnetics, IEEE Trans.Mag. 2018; DOI: *10.1109/TMAG.2018.2863225*

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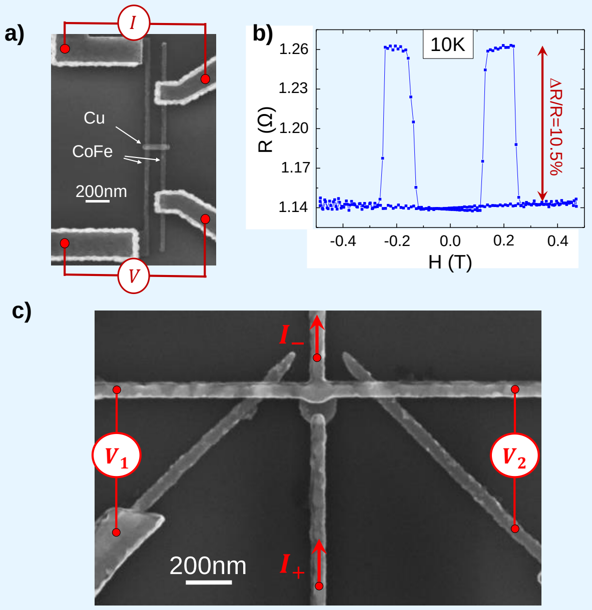
Giant magnetoresistance in lateral metallic nanostructures for spintronic applications

This study discuss the shift observed in spintronics from the current-perpendicular-to-plane geometry towards lateral geometries, illustrating the new opportunities offered by this configuration.

The possibility to combine ultrathin magnetic and non-magnetic layers allowed creating hetero-structures whose dimensions are smaller than the characteristic lengths of the spin-dependent transport. This has notably led to the discovery of the Giant Magnetoresistance (GMR), and to the development of transport experiments in the current-perpendicular to the plane (CPP) geometry.

Recent progresses in lithography techniques have enabled the creation of lateral nanodevices in which the lateral dimensions become smaller than physical lengths such as the spin diffusion length. Thus, the effects usually observed in current-perpendicular-to-the-plane configurations can be nowadays observed in lateral devices.



a) SEM image of a CoFe-based lateral spin valve, with the electrical setup for GMR measurements. b) Corresponding GMR measurement at 10K. a) SEM image of a setup allowing to detect the orientation of the magnetization direction of a CoFe nanodisk. The current is injected through the nanodisk, while two non-local detector are measuring the non-local spin signal V_1 *and* V_2.

Using CoFe-based all-metallic lateral spin valves, we show that giant magnetoresistance variations of more than 10% can be obtained (cf.fig. a and b), competitive with the current-perpendicular-to-plane giant magnetoresistance.

We also focus on the interest of being able to tailor freely the geometries. On the one hand, by tailoring the non-magnetic parts, we show that it is possible to enhance the spin signal of giant magnetoresistance structures. On the other hand, we show that tailoring the geometry of lateral structures allows creating a multilevel memory with high spin signals, by controlling the coercivity and shape anisotropy of the magnetic parts.

Furthermore, we studied a new device in which the magnetization direction of a nanodisk can be detected (cf. fig. c). We thus show that the ability to control the magnetic properties can be used to take advantage of all the spin degrees of freedom, which are usually occulted in current-perpendicular-to-plane devices.

Spin signals obtained in purely metallic nanostructures can thus compete with CPP GMR. Beyond that point, the flexibility of lateral structures, relatively to current-perpendicular-to-the-plane structures, can be combined to the use of spin-orbit effects to create and detect spin accumulations, and to the use of spin-transfer torques to switch magnetizations. It thus offers a new playground for the development of spintronic applications.

Teams: Spin Orbitronics, 2D Spintronics

Further reading: *Giant magnetoresistance in lateral metallic nanostructures for spintronic applications*, G. Zahnd, L. Vila, V.T. Pham, A. Marty, C. Beigné, C. Vergnaud and J. P. Attané, Scientific reports 7.1 9553 (2017). DOI: *10.1038/s41598-017-09086-4*

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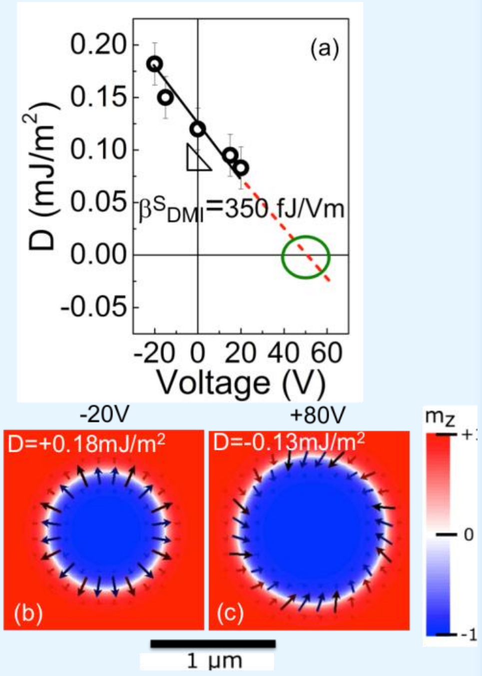
A Route towards Dynamic Control of Skyrmion Chirality

The very popular magnetic bubbles called skyrmions are promising for dense data storage, logic and neuromorphic applications thanks to the unique sense of rotation (chirality) of their surrounding domain wall. The so-called Dzyaloshinskii–Moriya Interaction (DMI) is crucial for their stability. Here, T. Srivastava et al. have shown that DMI can be dynamically and locally controlled with a gate voltage, thus paving the way towards a control of the skyrmion chirality.



(a) Evolution of DMI coefficient D under a gate voltage (black circles represent data points). Extrapolation (dashed line) to higher voltages is expected to lead to DMI sign reversal. (b) and (c) Micromagnetic simulations using experimental magnetic parameters (-20V) and extrapolated ones (+80V) leading to opposite chirality skyrmions.

The topology of skyrmions, these circular magnetic domains encircled with a single chirality domain wall, allows them to be shifted undistorted under an electric current with great efficiency. This behaviour makes them very attractive for spintronic applications where they could be used as nanoscale data bits for data storage, logic or more recent neuromorphic devices.

The Dzyaloshinskii–Moriya Interaction (DMI) determines the chirality of the skyrmion domain wall. In ultrathin trilayers composed of a heavy metal (HM), a ferromagnet (FM) and an oxide, DMI has an interfacial origin related to the asymmetry of the structure. The application of a gate voltage on the structure induces an electric field at the interface, hence modifying the DMI amplitude because of spin-orbit effect.

T. Srivastava et al. have shown the first demonstration of a large (130%) tuning of DMI with electric field (see Fig(a)). This study, published in Nanoletters, was performed in Ta/FeCoB/TaOx trilayers and results from the collaboration of teams from Spintec and Institut Néel in Grenoble and the Laboratoire des Sciences des Procédés et des Matériaux in Villetaneuse.

To directly access DMI variation under a gate voltage, they have used Brillouin Light Spectroscopy (BLS) through a transparent gate. By combining BLS and polar magneto-optical Kerr-effect microscopy, they further show a monotonic variation of DMI and skyrmion size with electric field with an unprecedented efficiency.

From the extrapolation of experimental data to higher voltages, they expect a sign reversal of DMI with electric field (see Fig (a)). The micromagnetic simulations performed for this study show that a change of sign would lead to a chirality switch (see Fig(b & c)). This local, dynamic and reversible manipulation of DMI establishes an additional degree of control to engineer programmable skyrmion-based memory or logic devices.

Teams: Sensors, Spin Orbitronics

Collaboration: Institut Néel, Laboratoire des Sciences des Procédés et des Matériaux,

Funding: French ANR (contract no. ELECSPIN ANR-16-CE24-0018), University Grenoble Alpes (project Automag2D), Nanosciences Foundation.

Further reading: *Large-Voltage Tuning of Dzyaloshinskii–Moriya Interactions: A Route toward Dynamic Control of Skyrmion Chirality*, T. Srivastava et al., Nanolett. 18, 4871 (2018). DOI: *10.1021/acs.nanolett.8b01502*

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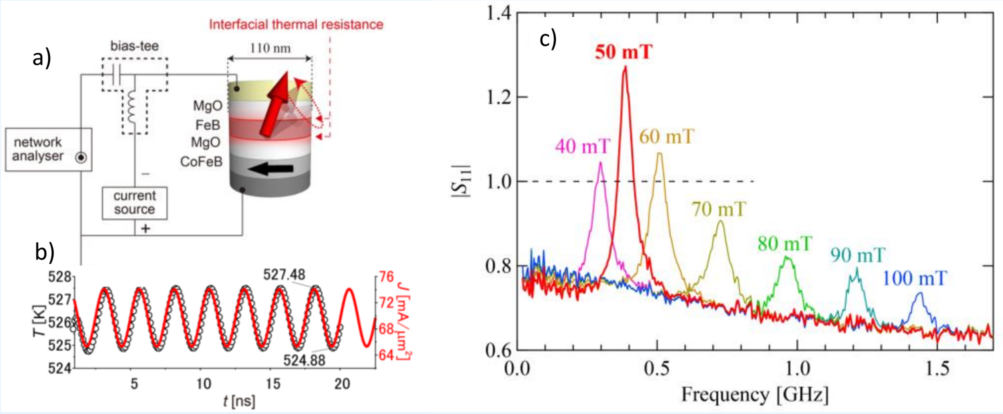
Efficient microwave amplification by heat modulation at GHz frequency in spintronics oscillators

Due to the nanometer size of magnetic tunnel junctions and high interfacial resistance of ultrathin MgO tunnel barriers, temperature modulation at GHz frequency can be achieved in these devices and efficiently use to amplify microwaves in spintronics oscillators.

Spintronics oscillators use two major phenomena discovered in spin-electronics: the tunnel magnetoresistance of magnetic tunnel junctions (MTJ) (i.e. the dependence of their electrical resistance on their magnetic configuration) and the spin transfer torque (i.e. the ability to modify the magnetic configuration by the current flowing through the magnetic tunnel junction). In this study, we demonstrated that a third phenomenon can be used to actually amplify a radiofrequency (RF) signal based on the RF temperature modulation of the MTJ. To achieve this, both a DC current and a weak RF current at a frequency close to the MTJ ferromagnetic frequency are sent through the tunnel junction. Due to the spin transfer phenomenon, the DC current triggers an oscillation of the magnetic configuration of the MTJ and the frequency of this oscillation locks at the frequency of the injected RF signal. Due to the tunnel magnetoresistance, the RF oscillation of the magnetic configuration yields a RF oscillation of the MTJ electrical resistance and correlatively a RF oscillation of the Joule heating dissipated in the junction. In this study, the MTJ was designed with double MgO tunnel barrier to increase the heat confinement between the two barriers. As a result, a RF modulation of the temperature of several degrees could be achieved in the heart of the tunnel junction. This temperature modulation yields a RF modulation of the magnetic anisotropy of the junction resulting in a significant enhancement and even amplification of the RF signal produced by the junction.

This work was performed in collaboration between Osaka Univ, AIST Japan, and SPINTEC.



a) Magnetic tunnel junction used for the experiments. It consists of a magnetically soft magnetic layer (FeB) sandwiched between two MgO tunnel barriers and a pinned reference magnetic layer (CoFeB) b) Simulations showing the temperature modulation at the heart of the tunnel junction i.e. at the FeB layer inserted between the two MgO barriers. c) microwave amplification coefficient (S_{11}). In the range of bias field between 40 and 60mT, it exceeds 1 showing RF amplification.

Team: Theory and Simulation

Further reading: *Microwave amplification in magnetic tunnel junction induced by heat-to-spin conversion at nano-scale,* Minori Goto, Yosuke Wakatake, Ugwumsinachi Kalu Oji, Shinji Miwa, Nikita Strelkov, Bernard Dieny, Hitoshi Kubota, Kay Yakushiji, Akio Fukushima, Shinji Yuasa, and Yoshishige Suzuki, Nature Nanotechnology (2018).

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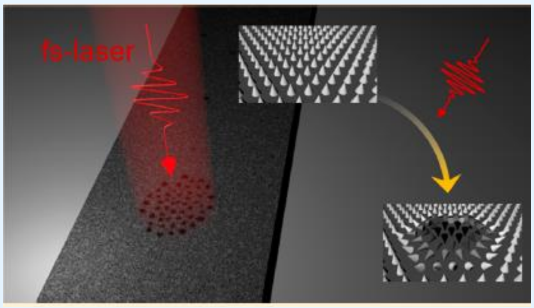
Creation of Magnetic Skyrmion Bubble Lattices by Ultrafast Laser in Ultrathin Films

Magnetic skyrmions are topologically nontrivial magnetic domains where the magnetization rotates in a fixed sense (chirality). They are usually created by magnetic fields or by non-homogeneous electric currents. Here S.G. Je et al. have shown that hexagonal skyrmion bubble lattices can be locally generated with ultrafast (30 fs) laser pulses. Their original optical approach to control skyrmions in commonly accessible materials paves the road towards the emerging skyrmion-based memory and synaptic devices.

Magnetic skyrmions are circular domain walls surrounded by a single chirality domain wall. This nontrivial topology implies that an energy barrier has to be overcome for their nucleation and annihilation. This same energy barrier allows their stabilization and makes them promising as dense information carriers in spintronic devices at the nanoscale. One of the major challenges for developing novel skyrmion-based memory, logic and neuromorphic devices is fast and controlled creation of magnetic skyrmions at ambient conditions.



Ultrashort laser impulsions generation of skyrmion lattice in a strip of ultrathin heavy metal/ferromagnet/oxide trilayer, measured by magneto-optic Faraday effect microscopy. The lateral size of the strip is 60 μm. (Insets: when illuminated, the uniform spins are transformed into skyrmions, topologically non-trivial swirling spin textures)

In this study published in Nanoletters, S.G. Je *et al*. have demonstrated, at room temperature, a controlled generation of skyrmion bubbles and hexagonal skyrmion bubble lattices from a ferromagnetic state by a single ultrafast (35 fs) laser pulse (see Figure).

This study, resulting from a collaboration between Spintec in Grenoble and Institut Jean Lamour in Nancy, was performed in Ta/FeCoB/TaOx ultrathin trilayers where the magnetic field alone does not lead to skyrmion bubble formation due to a high nucleation energy barrier. The measurements were performed by magneto-optic Faraday effect microscopy after the application of single ultra-short laser pulses. All light polarizations give similar effects, illustrating the importance of the local heating of the sample allowing to overcome the nucleation energy barrier.

The authors moreover show that the skyrmion bubble lattices possess enhanced immunity against magnetic field perturbations as compared to the isolated skyrmion bubbles, suggesting the promising prospects of skyrmion lattices for data storage. These results highlight the role of thermal effect in the creation of the skyrmion bubble lattice. It also offers an alternative way of ultrafast excitation and massive writing of clusters of skyrmions that decouples the writing operation from the skyrmion driving operation in the skyrmion-based shift register and that could be used in the emerging skyrmion-based synaptic devices.

Teams: Spin Orbitronics, Sensors

Collaboration: Institut Jean Lamour, Université de Lorraine, Nancy France

Funding: This work was supported by the ANR, by the Institut Carnot ICEEL for the project Optic-switch and Matelas, and by the French PIA project Lorraine Université d'Excellence.

Further reading: *Creation of Magnetic Skyrmion Bubble Lattices by Ultrafast Laser in Ultrathin Films,* S.-G. Je, P. Vallobra, T. Srivastava, J.-C. Rojas-Sánchez, T. H. Pham, M. Hehn, G. Malinowski, C. Baraduc, S. Auffret, G. Gaudin, S. Mangin, H. Béa and O. Boulle, Nanoletters (2018) DOI: *10.1021/acs.nanolett.8b03653*

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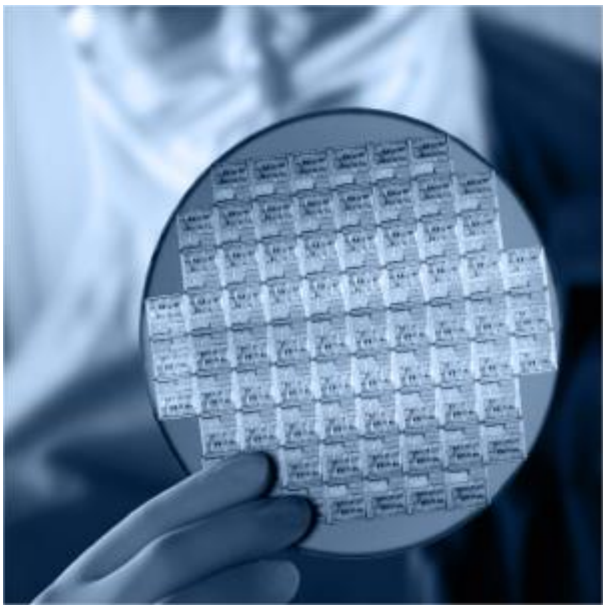
About SPINTEC

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 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 (January 2018)

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