Highlights

2022

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FOREWORD

This booklet gathers a selection of scientific highlights of SPINTEC in 2022.

2022 marked the celebration of the 20th anniversary of our laboratory. We organized on May 10th a special day retracing some of the key breakthroughs of the lab since its creation, ranging from fundamental discoveries to technologically-oriented demonstrations. The morning was focused on the history and current aspects of SPINTEC, with testimonials from former directors and current and former members of the team. The afternoon was devoted to the launch of an alumni network, open to doctoral and post-doctoral students, and to visits in the labs.

In 2022, new strategic partnerships were started, which will contribute to strengthen our actions and extend our network. We are involved in two successful national EquipEx Excellence initiatives, the 2D-MAG and NanoFutur projects. These projects will enable the establishment of platforms for the synthesis of spintronic stacks, from emerging 2D epitaxial materials to an industry-ready pilot line. We are also conducting two new bilateral projects with the United States and Germany on artificial intelligence topics. Several innovation-focused grants will also help support the rise of new memory and logic actions, using spin-orbit torques and ferroelectric/magnetic architectures. Finally, the year was marked by the laboratory's very strong involvement in several PEPR-type actions (national flagship projects on equipment and targeted scientific actions), with the success of crucial importance for the entire spintronics community of the SPIN exploratory PEPR, as well as the laboratory's significant participation in targeted projects of electronic, artificial intelligence and quantum PEPRs.

In 2022, several new employees joined the lab, aiming at reinforcing actions and critical expertise in the deployment of SPINTEC strategy. Isabelle de MORAES, engineer at the CEA, joined the epitaxy platform for materials and 2D spintronics stacks. Eyub YILDIZ, as CNRS assistant engineer, joined the laboratory in early July, enabling us to strengthen our instrumental development efforts in the context of a sharp expansion of our equipment fleet with funding from the SPIN exploratory PEPR and electronic acceleration PEPR. Finally, Johanna FISCHER joined the laboratory in December as researcher, after being selected for this year's CNRS research scientist national competition. Her arrival will allow us to expand our actions on magnetic sensors to in new directions in the years to come.

We now look confidently to 2023, identifying several challenges. On the science side, we will mainly implement the first steps of our two national EquipEx projects, involving the acquisition of new equipment, its connection and its benchmarking and we will contribute to the first steps of the national PEPR projects. On the organizational side and following the detailed assessment of our carbon footprint in 2021 and 2022, we will for the first time put in place incentive actions to reduce it and monitor it over the long term. This allows us to project ourselves collectively towards new strategic priorities for the years to come.

Lucian Prejbeanu, Executive Director / Olivier Fruchart, Deputy Director

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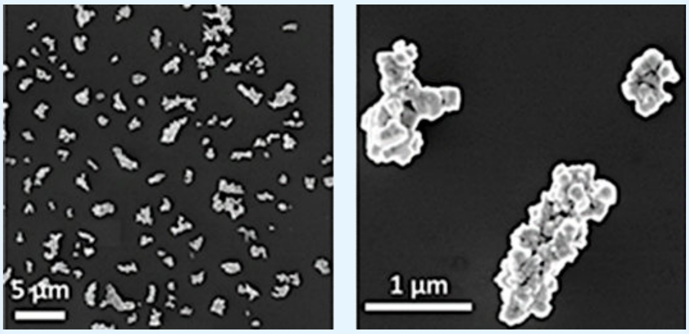
Directors of publication: Lucian Prejbeanu, Executive Director – Olivier Fruchart, Deputy Director

Biocompatible magnetic microparticles for cancer cells destruction

We present a new type of biocompatible surface-functionalized magnetic microparticles for cancer cells destruction. The magnetite particles, covered with polyethylene glycol molecules, are shown to favor cell-death via apoptosis when set into vibrations by an alternating magnetic field.

The use of magnetic particles for biomedical applications opens interesting perspectives. One of these is the destruction of cancer cells induced by the magnetic vibration of micro particles. However, despite excellent results obtained with in vitro cell cultures, in vivo studies have so far been disappointing. Two elements have been identified to explain this failure: the poor dispersion of the particles into tumoral tissue, and the reduction in the particles endocytosis which, contrary to in vitro, accumulate in the extracellular matrix.



Ball-milled magnetite particles

A team from SPINTEC, in collaboration with researchers from IRIG/SyMMES, has recently developed a new type of surface-functionalized magnetic microparticles for the destruction of cancer cells. These particles have been designed to overcome these shortcomings. They are anisotropic magnetite grains obtained by powder ball-milling. Ball-milling allows mass production of particles, with average size around one micrometer. This size is such that the vibration of the particles upon application of an oscillating magnetic field generates forces up to 10 nN, which is in the desired range to induce physiological stress to the cells. The particles also exhibit good dispersion properties in solution, which is attributed to their closed-flux magnetic structure at rest. After synthesis, the particles are functionalized by surface grafting of polyethylene glycol (PEG) molecules of different lengths. The goal of PEGylation is to ensure better dispersion within the cells, which has already been observed in other studies, and to modify the particle-cell interactions, by modulating the transmitted mechanical force.

The new particles were tested by assessing their ability to induce cell death with glioblastoma cancer cells. We first observed that, as expected, PEGylated particles evenly disperse among cells and undergo endocytosis. After subjecting the particles-loaded cells to a rotating magnetic field, the measurement of the metabolic activity and of the membrane integrity indicated that PEGylated particles do induce a decrease in cell viability - although at a lower pace than bare particles - and a higher ratio of apoptotic cells relative to the number of necrotic cells. Most interestingly, we observed that a low magnetic field frequency (down to 2 Hz) significantly enhances the occurrence of apoptosis.

These results highlight a difference in the cell death mechanism according to the type of particles - bare versus PEGylated - and the conditions of the mechanical stimulation. We attribute this to the damping of the vibration from the PEG chains, which opens promising perspectives for the future development of cancer-treatment strategies.

Teams: Health and Biology, Instrumentation

Collaborations: Marie Carrière and Yanxia Hou-Broutin (IRIG/SyMMES)

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

Further reading: *Magneto-mechanical treatment of human glioblastoma cells with engineered iron oxide powder microparticles for triggering apoptosis,* C. Thébault, M. Marmiesse, C. Naud, K. Pernet-Gallay, E. Billiet, H. Joisten, B. Dieny, M. Carrière, Y. Hou and R. Morel, Nanoscale Adv. 3, 6213 (2021).
Open acess: hal-03375349

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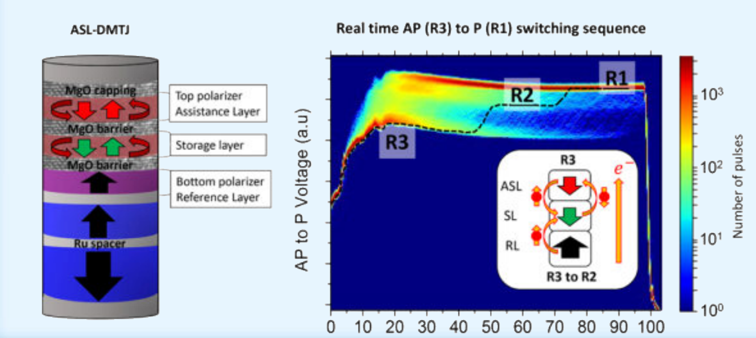
Designing magnetic memories with improved retention and writability

Magnetic Random Access Memory recently started to be commercialized by all main microelectronics factories. In MRAM, the information is coded via parallel or antiparallel magnetic configurations to represent ones and zeroes. The technology is intrinsically nonvolatile, meaning it can keep information without being electrically powered. However, non-volatility often comes with a trade-off between the information retention and the ease of writing. A higher energy barrier between parallel and anti-parallel states results in more stability and retention but more difficult switching and writing. In this work, we succeeded to improve both aspects by adding to the widely used magnetic stack an extra assistance layer.

A Spin-Transfer-Torque MRAM cell consists of a magnetic tunnel junction, which essentially comprises two magnetic layers separated by a tunnel barrier. One of these layers (the REFerence layer: REF) has a fixed magnetization whereas the magnetization of the other (the Storage Layer : SL) can be switched to be set either parallel or antiparallel to that of the Reference layer. This magnetization switching is achieved by sending pulses of current through the tunnel junction, taking advantage of the magnetic torque that results from the exchange interactions between the spin-polarized tunneling electrons and those responsible for the Storage layer magnetization (so-called spin-transfer torque). In conventional STT-MRAM, the SL magnetization is only submitted to the spin-transfer torque originating from the REF. In the present study, a third magnetic layer called "assistance layer" (ASL) was added above the SL (see Figure) to create a second spin-transfer torque contribution on the free layer. The ASL magnetization can also be switched thanks to the spin transfer torque from the SL. The properties of this ASL have been carefully tuned so that during the write pulse, the spin-transfer torque from the ASL on the SL magnetization adds up with that from the Reference layer to enable switching of the SL magnetization at lower current. Besides, the interactions between the storage layer and ASL were adjusted so that the ASL magnetization always ends up parallel to that of the storage layer in standby, thus increasing the thermal stability of the SL magnetization. As a result, both the memory retention and writability were improved.

The team conducted real-time measurements of the device resistance and demonstrated that the layers switch dynamically as expected. They aim to improve the constituent materials in the future to further improve the memory performance.



Left : Memory cell with the three main magnetic layers highlighted : Reference layer (Ref), storage layer (SL) and Assistance layer (ASL).
Right: Real time measurement of the device resistance during write pulse showing the initial state (characterized by resistance R3), an intermediate state in which REF and ASL are magnetized antiparallel yielding additive spin transfer torques on the SL magnetization (R2) and finally R1 in which the SL and ASL end up magnetized parallel.

Teams: MRAM, Theory and simulation, Material-Nanofabrication-Instrumentation

Funding: ERC MAGICAL n°669204

Further reading: *Real-time investigation of double magnetic tunnel junction with a switchable Assistance layer for high efficiency STT-MRAM*, D. Sanchez Hazen, B. M. da Silva Teixeira, D. Salomoni, S. Auffret, L. Vila, R. C. Sousa, I. L. Prejbeanu, L. D. Buda-Prejbeanu, and B. Dieny, APL Materials 10, 031104 (2022). *Open access: hal-03555700*

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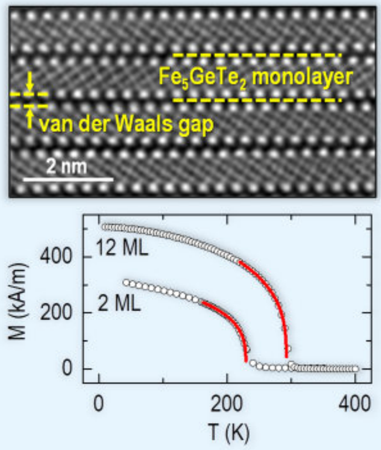
Large-scale epitaxy of the van der Waals room-temperature ferromagnet Fe_5GeTe_2

Van der Waals (vdW) layered magnets are promising materials to develop ultracompact and multifunctional spintronics devices. However, most of them are magnetic only at low temperature and are almost exclusively studied in the form of small flakes obtained by mechanical exfoliation. Here, we demonstrate the direct growth by molecular beam epitaxy of Fe_5GeTe_2, a room temperature vdW ferromagnet.

It has been known for a long time that magnetism vanishes when lowering the thickness of a material. The Mermin-Wagner theorem even states that long-range magnetic order cannot survive in a 2D isotropic system due to the competition with thermal fluctuations. For this reason, magnetic materials have long been missing in the family of 2D vdW crystals. It is only in 2017 that long-range magnetic order was reported in monolayer CrI_3 and bilayer $Cr_2Ge_2Te_6$, in which ferromagnetism is allowed by the presence of a magnetic anisotropy. The ultimately large surface-to-volume ratio of 2D magnets makes their magnetic properties very sensitive to external stimuli such as strain, light or electric fields. This characteristic can be used to create multifunctional and low power spintronics devices. However, most of 2D magnets possess a low Curie temperature (T_C) and are obtained by exfoliation of bulk crystals. Integrating them into practical multilayers requires higher T_C and scalable fabrication methods.



Electron microscopy image of epitaxial Fe5GeTe2, and temperature dependence of magnetization for a thick film and a bilayer.

We achieved the uniform growth of Fe_5GeTe_2 thin films on sapphire, on a centimeter-scale area, by molecular beam epitaxy. By employing a set of structural and chemical characterization techniques such as X-ray diffraction, Rutherford backscattering and scanning transmission electron microscopy, we could demonstrate the single-crystallinity of the films and the perfect control of the ternary composition. The magnetic properties were measured with SQUID and X-ray magnetic circular dichroism as a function of temperature and thickness of the layers. We found ferromagnetic ordering up to room temperature (293 K) in thick films and up to 229 K in bilayers, which is significantly higher than in other 2D magnets. A striking result is that ultrathin layers display ferromagnetism despite their very weak magnetocrystalline anisotropy. Actually, we found that the temperature evolution of magnetization does not follow the expected behavior for 2D spin systems. It is better described by 3D magnetic models, independently of the thickness. This unconventional behavior suggests that high temperature ferromagnetism in Fe_5GeTe_2 primarily originates from the 3D coordination between Fe atoms inside each vdW monolayer.

This work highlights the potential of molecular beam epitaxy as a key tool for the growth and tailoring of 2D magnets, and constitutes a stepping stone to their integration into large-area vdW multilayers for spintronics.

Team: 2D Spintronics, Theory and simulation, Spinorbitronics, Materials

Collaboration: IRIG/MEM, SOLEIL synchrotron

Funding: Minatec LABS N°2018 AURA P3, UGA IDEX EPI2D and IRS/EVASPIN, ANR-20-CE24-0015, ANR-18-CE24-0007, KAUST OSR-2018-CRG7-3717, DARPA TEE program MIPR# HR0011831554, Graphene Flagship EU H2020 881603, ANR-10-LABX-51-01

Further reading: *Large-scale epitaxy of two-dimensional van der Waals room-temperature ferromagnet Fe_5GeTe_2*, M. Ribeiro, G. Gentile, A. Marty, D. Dosenovic, H. Okuno, C. Vergnaud, J.-F. Jacquot, D. Jalabert, D. Longo, P. Ohresser, A. Hallal, M. Chshiev, O. Boulle, F. Bonell, M. Jamet, npj 2D Mater. Appl. 6, 10 (2022). *Open access: hal-03271458*

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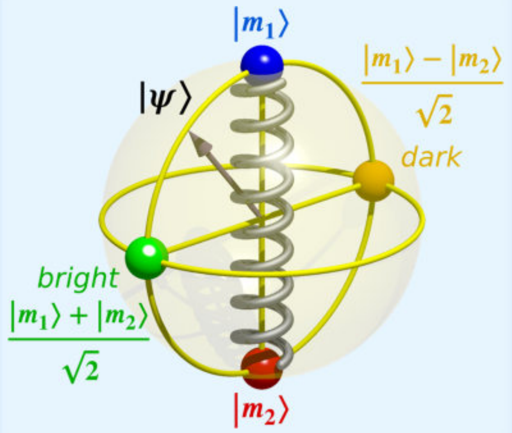
Bright and dark states of two distant macrospins strongly coupled by phonons

A new form of spintronic is emerging, exploiting electrical insulators. Recent spectroscopic studies performed at SPINTEC have revealed the coherent coupling that may establish between two distant macrospins separated by a non-magnetic dielectric spacer via circularly-polarized acoustic phonons that carry angular momentum information. This long-range effect represents an important progress in magnonics and spin wave computing.

Quantum processing requires the coherent transfer of state information between distant quantum bits. Transfer by direct coupling is limited to distances over which their wave functions overlap. Indirect coupling via a slowly-decaying third-party waveform—a tripartite hybridization with vanishing direct coupling elements—promises an enhancement of the maximum separation and thus of the size of quantum bit arrays. Here, we demonstrate control of the collective dynamics of two distant magnets mediated by the lattice vibrations, or phonons, in a monolithic device—an important step toward the development of integrated solutions.

In our experiment, two thin ferromagnets sit on either side of a 0.5-mm-thick crystal and communicate with one another by acting as “speakers” and “microphones” for sound waves in the crystal. The system can be brought into tripartite hybridization by carefully tuning the two ferromagnetic resonance frequencies to an acoustic resonance of the whole crystal. There, the entire system of magnetization and lattice can oscillate only coherently. One can illustrate the appeal of our method at the hand of the Bloch sphere shown in the Figure, which spans the phase space of the bonding and anti-bonding states that is relevant for a large community.



Bloch sphere representation of the generic hybridization of |m₁> and |m₂>. The equatorial plane is reached when resonance of |m₁> and |m₂> are matched. It can evolve there to bright and dark states, which correspond to the extrema coupling to an inductive antenna.

Illumination of the bound and antibound magnetic states by an external microwave field leads to bright or dark collective modes depending on the sign of the indirect mutual coupling. The phononic system uniquely allows for switching its polarity by shifting parity of the phonon-mode index, which decides if the lattice displacement at the position of the two magnets is out of phase or in phase.

The long lifetimes of magnons and phonons inside insulating garnets are key to unveiling this remote strong coupling between macrospins at room temperature. At low temperatures, we envisage quantum information exchange and distant entanglement of magnons, phonons, and microwave photons. Our work marries the fields of magnonics and phononics, profiting from the best of both worlds.

Teams: Spin insulatronics, Topological spintronics

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

Funding: ANR-18-CE24-0021 Maestro; ANR-21-CE24-0031 Harmony; EU HORIZON-EIC-2021-PATHFINDEROPEN PALANTIRI-101046630

Further reading: *Bright and dark states of two distant macrospins strongly coupled by phonons*, K. An, R. Kohno, A. N. Litvinenko, R. L. Lopes Seeger, V. V. Naleto, L. Vila, G. de Loubens, J. Ben Youssef, N. Vukadinovic, G. E. Bauer, A. N. Slavin, V. S. Tiberkevich, O. Klein, Phys. Rev. X 12, 011060 (2022). *Open access: hal-03334687*

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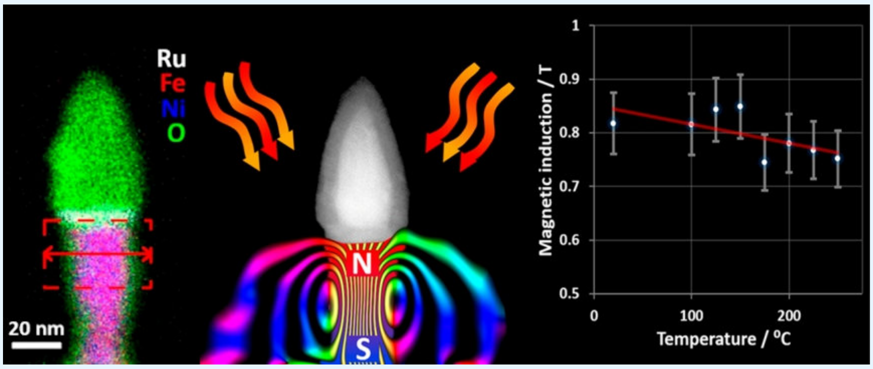
Perpendicular-shape-anisotropy MRAM do not fear temperature

Perpendicular-shape-anisotropy magnetic random-access memory (PSA MRAM) has been proposed to maintain the thermal stability of solid-state magnetic bits down to a few nanometers in diameter. Here we confirm directly with high-spatial resolution and high-sensitivity electron holography that magnetization is weakly affected by temperature, in contrast with the conventional ultrathin MRAM cells.

Magnetic random-access memory (MRAM) is an emerging class of solid-state memory. It is non-volatile, boasts orders of magnitude larger endurance than flash, and has a good compromise between write energy and time, typically a few nJ and a few ns. Based on these assets, MRAM is now used commercially in microcontrollers or as cache memory. Expanding the use of MRAM for the automotive industry or for high-density memories such as DRAM, requires to enhance their thermal stability down to advanced technological nodes. Standard MRAMs face their limits here, as their ultrathin storage layers are very sensitive to thermal energy, so that even at room temperature memory cells below 20nm in diameter lose long-term retention. In 2018 SPINTEC and Tohoku University proposed independently the concept of perpendicular-shape-anisotropy MRAM, in which the storage layer is a vertical nanopillar, enhancing its thermal stability via a dipolar shape effect and a large volume. While electric measurements have confirmed the ability to operate such sub-10nm MRAM cells, information on their enhanced thermal stability is only inferred indirectly.

Here, we have used off-axis electron holography to monitor the thermal dependence of the magnetization state and the spontaneous magnetization in a sub-20nm FeNi nanopillar, such as used for the storage layer in a PSA-MRAM cell. This technic is ideally suited for that purpose, combining high spatial resolution, direct and quantitative information about magnetization, and fully compatible with variable temperature. We showed that the magnetization state is very close to uniform, perpendicular and symmetric. Besides, we measured directly that magnetization is very weakly decaying with temperature, no more than in the bulk material, in sharp contrast with the ultrathin storage layers implemented in standard MRAM cells.



(left) Chemical map of a perpendicular-shape-anisotropy free layer (pink part) (center) Colored iso-phase lines in electron holography, indicative of magnetic induction lines. This highlights magnetization in the pillar, and the stray field outside (right) Minute decrease of magnetic induction with temperature.

Our results confirm the relevance of PSA MRAM for demanding applications, such as automotive or high-density memories. Our results have been made possible by combining several methodology developments, such as a specific preparation of lamella to reduce non-magnetic artefacts, registered acquisition of image stacks to improve signal-to-noise ratio, and disentangling magnetization from the demagnetizing and stray fields to provide accurate figures for magnetization. We believe that these developments will be useful for a variety of nanosized magnetic elements.

Teams: MRAM, Spin Textures, Instrumentation

Collaboration: CEA-LETI, PTA, PFNC

Funding: ERC Magical, ANR RTB

Further reading: *Quantitative Visualization of Thermally Enhanced Perpendicular Shape Anisotropy STT-MRAM Nanopillars*, T. P. Almeida et Al., Nano. Lett. 22, 4000 (2020). *Open access: hal-03553914v2*

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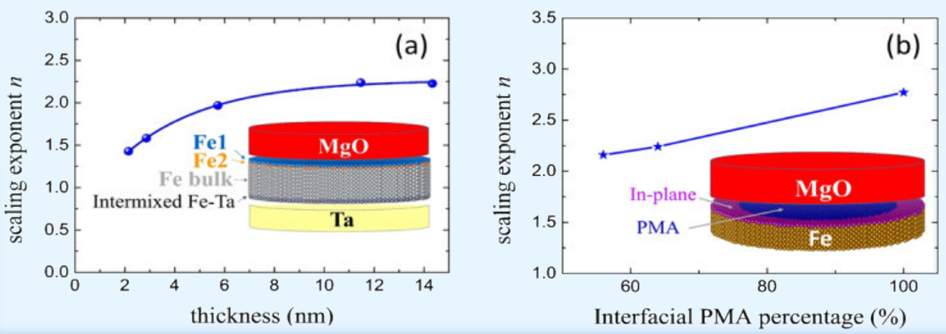
Unveiling temperature dependence mechanisms of perpendicular magnetic anisotropy at Fe/MgO interfaces.

A recent breakthrough in understanding the thermal effects on the magnetic properties of perpendicularly magnetized Fe/MgO interfaces is reported. It turns out that macroscopic mechanisms play a decisive role in determining the thermal stability of magnetization in such systems.

The perpendicular magnetic anisotropy (PMA) at magnetic transition metal/oxide interfaces(TM/Ox) is a key phenomenon in building out-of-plane-magnetized magnetic tunnel junctions for spin-transfer-torque magnetic random access memory (STT-MRAM). The PMA at those interfaces originates from strong hybridizations between the interfacial (Co)Fe-3d and the O-2p orbitals, combined with spin-orbit coupling. Interestingly, TM/Ox interfaces provide both low switching currents, owing to the relatively weak Gilbert damping, and high thermal stability thanks to their large PMA values. Since thermal effects become more critical with downscaling, understanding the temperature dependence of the magnetic properties, in particular the magnetization (*M*) and anisotropy energy (*K*), becomes crucial. The correlation between the temperature-dependent first order *K* and *M*, as described by Callen and Callen, follows a power scaling law: $K(T)/K(T=0)=[M(T)/M(T=0)]^3$. However, deviations from this law and in particular $n < 3$ scaling exponents have been reported experimentally.

Using a multi-scale approach, researchers at SPINTEC in collaboration with Western Digital elucidated the correlation mechanisms between the temperature dependence of magnetic anisotropy and that of magnetization in Fe/MgO structures. In an ideal interface, first-principles calculations of the layer-resolved magnetic anisotropy, magnetic moments, and exchange constants, show an enhancement of the values at the interface compared to bulk. Those intrinsic parameters provide a more accurate description of the temperature dependence of the magnetic properties in the atomistic model. The temperature-dependence of the total and layer-resolved anisotropy were shown to follow the Callen and Callen scaling power law and thus intrinsic properties cannot explain deviations from this law. By modelling realistic samples, we attribute the deviations observed experimentally to two macroscopic mechanisms: the presence of a magnetic dead layer or the spatial fluctuations of the interfacial PMA.



The correlation between the temperature-dependent magnetic anisotropy and magnetization, described by the scaling exponent n, is revealed for (a) dead-layer including, and (b) inhomogeneous Fe/MgO samples.

Those results are anticipated to help in understanding the thermal stability of the storage layer magnetization, which is a key parameter for the memory retention in STT-MRAM applications.

Team: Theory and simulation

Collaboration: Western Digital Technologies, USA.

Funding: Advanced Storage Research Consortium (ASRC) and ERC MAGICAL No. 669204.

Further reading: *Unveiling temperature dependence mechanisms of perpendicular magnetic anisotropy at Fe/MgO interfaces*, F. Ibrahim, A. Hallal, A. Kalitsov, D. Stewart, B. Dieny, M. Chshiev, Phys. Rev. Applied 17, 054041 (2022). *Open access: arxiv.org/abs/2011.02220*

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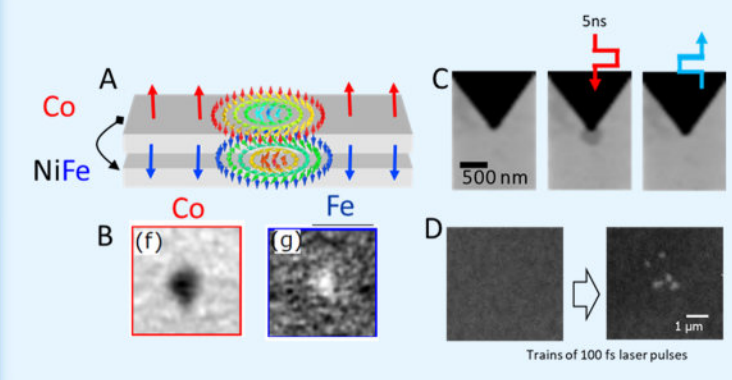
Observation of skyrmions in synthetic antiferromagnetic and their nucleation using current and light

Skyrmions in synthetic antiferromagnets are appealing for use in future memory and computing devices, combining small size and fast motion, but creating, stabilizing, and observing them remains a challenge. Here, we demonstrate the stabilization and current and light induced nucleation of skyrmions in a synthetic antiferromagnet, observing the magnetization texture in each layer using X-ray magnetic microscopy.

Magnetic skyrmions are currently fascinating many research groups in the world, as they could offer a new way to store and process information in our computers. These nanoscale magnetic textures are composed of elementary nanomagnets that wind up to form a stable spiral structure, like a well-tighten node. Skyrmions can be manipulated by very low electrical currents, which opens a path for their use as information carriers in computing devices. Several groundbreaking memory and logic devices have thus been proposed, that promise very large information density and low power consumption.

These devices are based on the manipulation of trains of skyrmions in magnetic tracks by electrical current. However, these applications still remained distant as the finite magnetic moment of the magnetic skyrmions limit their minimal size and leads to a deviation of the skyrmion motion toward the edge of the track, where they can annihilate. Coupling two skyrmions antiferromagnetically, as in synthetic antiferromagnets (SAF) (see Figure A), allows to lift these limitations, promising ultra-small and ultra-fast skyrmions.



A Skyrmions in SAF are composed of antiferromagnetically-coupled skyrmions in two ferromagnetic layers (here Co and NiFe). B STXM image of skyrmions in the Co layer and in the NiFe layer. The opposite contrast demonstrates the antiferromagnetic alignment of the skyrmion magnetization in each layer. C Skyrmion nucleation and annihilation by local current injection observed by XMCD-PEEM. The black triangle are gold electrodes patterned on top of the SAF track. D Nucleation of skyrmions by ultra fast laser pulses observed by XMCD-PEEM

In this work, we engineered synthetic antiferromagnetic layers in order to stabilize skyrmions at room temperature, and demonstrated the antiferromagnetic alignment of the skyrmion magnetic texture in each layer using X-ray magnetic microscopy (Figure B). Writing information in devices also requires the controlled creation and suppression of the skyrmions using external stimuli. This was demonstrated using local current injection (Figure C) as well as using ultra-fast (100 fs) laser excitation (Figure 1D). The next step is to study the dynamics of the SAF skyrmions induced by electrical current and demonstrate their expected fast motion (>1km/s).

Teams: Spinorbitronics, Theory and simulation,

Collaboration: NIST Boulder, Institut Néel, Université Paris 13, Synchrotrons Bessy, Soleil, SLS, Alba

Funding: DARPA, ANR Skylogic

Further reading: Skyrmions in synthetic antiferromagnets and their nucleation via electrical current and ultra-fast laser illumination, Juge, R. *et al.* Nat Commun 13, 4807 (2022). *Open access: hal-03752807*

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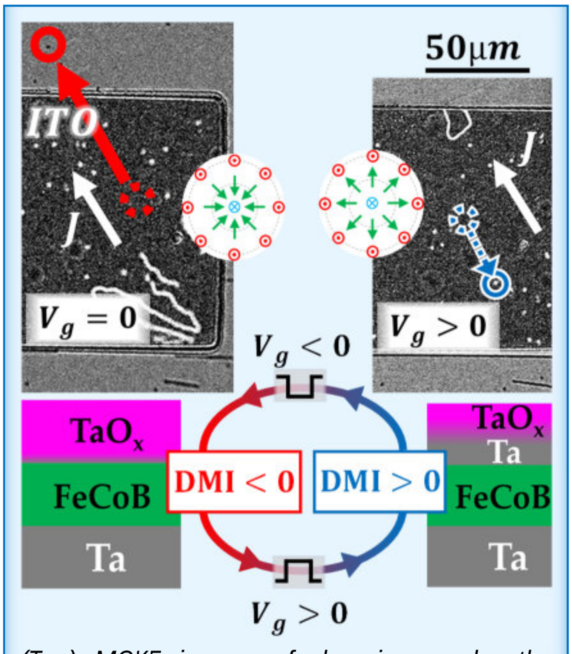
Controlling skyrmion chirality with a gate voltage

Magnetic skyrmions are localized chiral spin textures, which offer great promise to store and process information at the nanoscale. The unique sense of rotation of their surrounding domain wall, called chirality, results from the so-called Dzyaloshinskii–Moriya Interaction. We managed to drive the inversion of the skyrmion chirality by applying a gate voltage, thus opening the possibility to individually and locally manipulate skyrmions for complex computing.

Skyrmions are circular magnetic domains encircled with a single-chirality domain wall. They attract much interest since it is possible to shift them (undistorted) under an electric current, with great efficiency and in a direction that depends on their chirality. These nanoscale data bits are hence attractive for spintronic applications and are envisioned for dense data storage, efficient logic or neuromorphic computing.

The sign of the Dzyaloshinskii–Moriya Interaction (DMI) determines the chirality of the skyrmion. In ultrathin trilayers composed of a heavy metal, a ferromagnet and an oxide, DMI has an interfacial origin related to the symmetry breaking at interfaces. We had previously shown that the application of a gate voltage on the structure can modify the DMI amplitude. In the present work, we have demonstrated the first local and low-power reversal of skyrmion chirality related to the sign inversion of DMI under gate voltage. Such reversal induces an inversion of the current induced motion of the skymions under the gate electrode.



(Top) MOKE images of skyrmions under the transparent electrode (ITO, in black) showing the motion of skyrmions along the current J under no gate voltage (left) or against it under positive gate voltage V_g (right). Schematics illustrate their structure. (Bottom) Illustration of the effect of the gate voltage on the oxygen content at the ferromagnet/oxide interface.

In more details, this study was performed in Ta/FeCoB/TaOx ultrathin trilayers. In order to infer the sign of DMI under a gate voltage, we observed the current-induced motion of skyrmions under a transparent gate using polar magneto-optical Kerr-effect (MOKE) microscopy. Brillouin Light spectroscopy (BLS) measurements confirmed the inversion of DMI sign, which is attributed to oxygen ion migration under the gate.

Using micromagnetic simulations, we confirmed that the inversion of skyrmion chirality is possible without losing the skyrmions stability. Further material optimization would enable the inversion of the chirality of a unique stable skyrmion locally, envisioning an implementation in logic gates or neuromorphic computing.

Teams: Magnetic sensors, Spin-orbitronics, Materials, Instrumentation

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

Funding: French ANR (ELECSPIN, ADMIS), Nanosciences Foundation, DARPA, Institut Universitaire de France (IUF)

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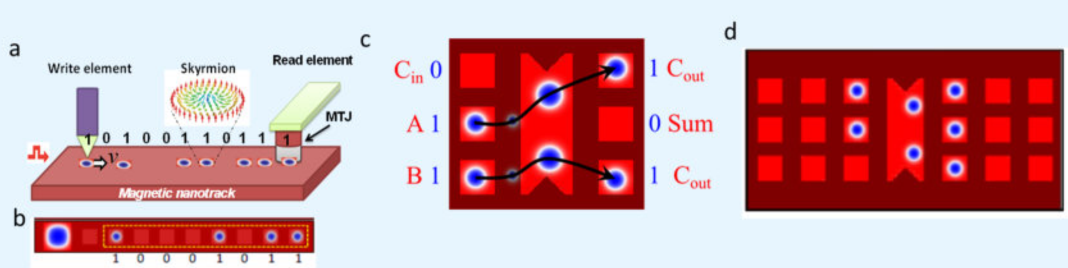
Computing and storing data at the nanoscale using magnetic skyrmions

Magnetic skyrmions are appealing for use in logic and memory devices, combining small size and fast motion. Here, we propose to exploit skyrmion interactions to perform both logic and memory operations at the nanoscale. Our concept opens a path for novel devices, which intrinsically merge high-density non-volatile data storage with computing capabilities.

Magnetic skyrmions are currently fascinating many research groups in the world, as they could offer a new way to store and process information in our computers. These nanoscale magnetic textures are composed of elementary nanomagnets that wind up to form a stable spiral structure, like a well tighten node. Skyrmions can be manipulated by very low electrical currents, which opens a path for their use as information carriers in computing devices. Several groundbreaking memory and logic devices have been proposed, that promise large information density and low power consumption. A prime example is the racetrack memory where trains of skyrmions in a track are moved toward the read and write elements using current pulses (see Figure a). Here the information is encoded in the position of the skyrmion in the train, where for instance, the presence of one skyrmion means 1, while no skyrmion means 0. However, this device is prone to errors: if one skyrmion goes faster or slower than the others or gets stuck by some defects in the materials, it may move forward or backward in the train, and change the information encoded.

To solve this issue, we proposed to define boxes in the track, in which the skyrmions get trapped on purpose (Figure b). This is performed by locally modifying the magnetic properties of the material (here magnetic anisotropy), using light ion irradiation for instance, here with He+. Simulations show that the skyrmions are indeed stable in the box and can be moved synchronously and reliably between the boxes using current pulses. More complex shapes can also be defined to perform logic operations. For instance, in the device shown in figure c, a larger box is defined where the skyrmions interact: the natural repulsion between the skyrmions in the box leads to a deviation of their trajectory and allows to perform a full adder operation. These gates can be cascaded to perform simple logic operations such as AND, OR, NOT, NAND, XOR, and NXOR. Both racetrack memory device and logic gates can also be combined (see Figure 1d) such that memory and logic operations are performed at the same place.

The integration of such a device in computers would allow a dramatic decrease of their power consumption, since it would save the high energy cost and time required to move data between the memory and computing units.



a. Schematic representation of the racetrack memory. b. Simulation of a racetrack device where skyrmions are stored into boxes (region of lower magnetic anisotropy). c. Simulation of a magnetic full adder. d. Device combining racetrack and logic devices.

Teams: Spinorbitronics, Theory and simulation, Artificial Intelligence

Funding: DARPA

Further reading: *Robust and Programmable Logic-In-Memory Devices Exploiting Skyrmion Confinement and Channeling Using Local Energy Barriers*, N. Sisodia, J. Pelloux-Prayer, L. Buda-Prejbeanu, L. Anghel, G. Gaudin, O. Boulle, Phys. Rev. Appl., 18, 014025 (2022). *Open access: hal-03740728v1*

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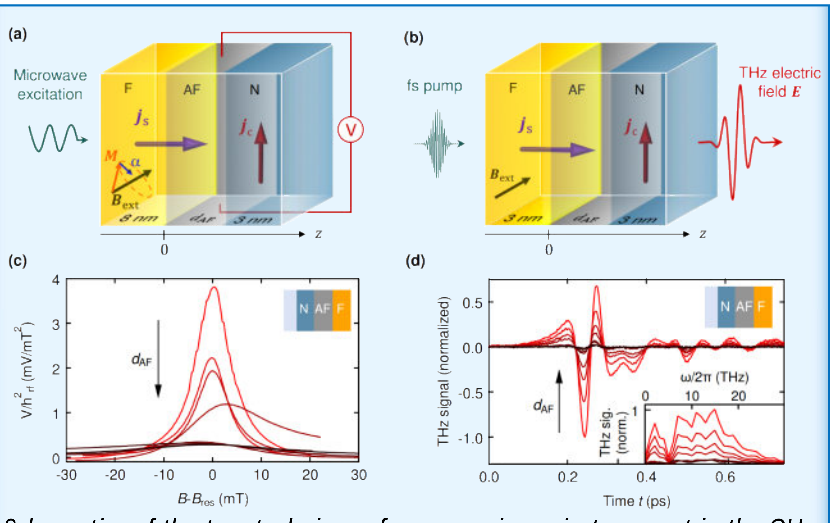
Spin-transport in antiferromagnets from the GHz to THz regime

Control over spin transport in antiferromagnetic systems is essential for future spintronic applications with operational speeds extending to ultrafast time scales. A consortium of physicists at SPINTEC, JGU Berlin and Charles University Prague established the essential role of interfaces for spin current injection and spin current-to-charge current conversion, from the gigahertz (GHz) diffusive to the terahertz (THz) ballistic regime. This work therefore opens the door for optimization of the spin control at ultrafast time scales.

The physics of antiferromagnetic materials is very rich, sometimes unique and unexpected compared to their ferromagnetic counterparts. New types of effects allowed in antiferromagnetic materials include for example: ultrafast dynamics, pseudospin magnonics, staggered topology, self-compensating skyrmions, and compatibility with superconductivity.

As antiferromagnetic materials possess two or more magnetic sublattices, coupled by an exchange field which can be as strong as a few thousands of Teslas, they can host ultrafast THz dynamics, and eventually carry spin-information suitable for data encoding.



Schematics of the two techniques for measuring spin-transport in the GHz and THz regime, and corresponding raw signals.

Control over spin transport in antiferromagnetic systems is therefore essential for future spintronic applications with operational speeds extending to ultrafast time scales. Here, we study the transition from the GHz to THz regime of spin transport and spin-to-charge current conversion in the prototypical antiferromagnet IrMn by employing spin pumping and THz spectroscopy techniques. We have shown that the ultrafast spin injection and conversion in IrMn are operative up to ~30 THz and currently limited by the pump pulse duration and detection bandwidth. The upper bound of the spin-to-charge conversion efficiency in IrMn, amounts to roughly 10% of the conversion in Pt. The direct comparison of the THz to GHz regimes revealed that the characteristic length of the spin transport is four times larger at GHz frequencies, ~2 nm. As the underlying mechanism, we suggest a dominating ballistic electron transport in the THz regime, compared to an electronic diffusive transport in the GHz regime mixed with an eventual magnonic contribution. We also showed that contributions of the interfaces to the spin-to-charge current conversion can be significant and even can dominate the other conversion processes in the THz regime, thus making it useful in optimizing and engineering the ultrafast spintronic functionalities in antiferromagnets.

Team: Antiferromagnetic spintronics, Materials

Collaboration: FHI Berlin (GE), Charles Univ. Prague (CZ), IRIG/SyMMES

Funding: ANR-15-CE24-0015-01, PE-18P31-ELSA

Further reading: *Impact of gigahertz and terahertz transport regimes on spin propagation and conversion in the antiferromagnet IrMn,* O. Gueckstock, R. L. Seeger, T. S. Seifert, S. Auffret, S. Gambarelli, J. N. Kirchhof, K. I. Bolotin, V. Baltz, T. Kampfrath, L. Nadvornik, Appl. Phys. Lett. **120**, 062408 (2022). *Open access: hal-03420656v2*

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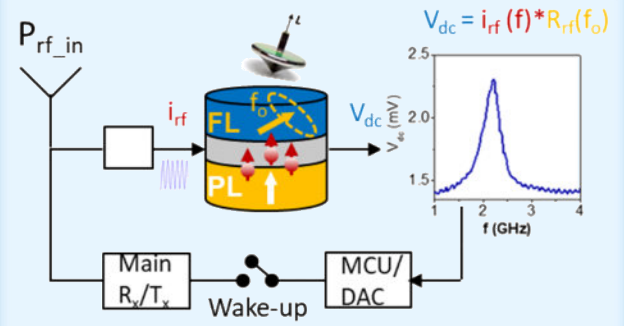
Waking-up wireless sensor nodes with perpendicular magnetic tunnel junctions

Spin-torque-nanodiodes based on magnetic tunnel junctions are promising candidates for RF energy harvesters and ultra-low power wake-up receivers with performances that are expected to surpass those of semiconductor diodes. Experiments on magnetic tunnel junctions with perpendicular magnetic anisotropy show how the performances can be optimized upon reducing the magnetic layer thickness and the device diameter.

Perpendicular magnetic tunnel junctions (pMTJs), whose free layer (FL) and polarizing layer (PL) are characterized by an interfacial perpendicular magnetic anisotropy (iPMA), are best known for their application as magnetic memories. SPINTEC demonstrated that these pMTJ devices show also good radio frequency (RF) functionalities, such as the generation of coherent microwave signals or the frequency selective conversion of an incoming microwave signal into a DC voltage signal Vdc (see Figure). The good RF-to-DC conversion efficiency of these devices makes them of interest for RF energy harvesters or wake-up receivers (see Figure) that are implemented in wireless sensor networks to improve their autonomy and energy consumption.



Principle of the RF-to-DC conversion: An incoming rf signal P_{rf_in} can induce, via the spin transfer torque, an oscillation of the magnetization, that results in oscillations of the magneto-resistance R_{rf}. At resonance, i.e. when the excitation frequency f is equal to an internal mode frequency f_o of the MTJ, the product $V_{dc}=i_{rf} \times R_{rf}$ contains a DC component that is large due to the large oscillation amplitude at resonance. This frequency selective RF-to-DC conversion is interest for the development of ultra-low power wake-up receivers, whose signal after demodulation is used to turn on the power hungry main Rx/Tx communication module when needed.

Here, we demonstrated how the conversion efficiency of pMTJs can be optimized via the tuning of the magnetic layer thickness *t* and the nanopillar diameter *D*, which determine the balance between the demagnetization and iPMA energies. Close to compensation, the amplitude of the resonance excitation and consequently the produced DC voltage Vdc is at its maximum. Furthermore, smaller diameters lead to higher current densities and through this to larger oscillation amplitudes. We have experimentally verified these size dependencies for pMTJs, demonstrating largest signal levels in the mV range for diameters as small as 50nm.

In addition, it was shown that the detection frequency of these pMTJs can be tuned over several Gigahertz, upon adding a small DC current (1mA or less). This is attributed to Joule heating that affects the iPMA energy constant. Finally, an amplitude-modulated incoming signal could be successfully demodulated. For wake-up receivers this means that the information encoded in the amplitude of the wake-up signal can be directly decoded by the pMTJ and that via a DC current it is possible to reprogram the frequency bandwidth of communication. These properties will be exploited within the European project Swan-on-chip.

Teams: RF devices, MRAM, Theory and simulation, Topological spintronics

Collaboration: Singulus, Thales TRT, G-INP/TIMA, INL

Funding: ANR SPINNET

Further reading: *Size-dependent enhancement of passive microwave rectification in magnetic tunnel junctions with perpendicular magnetic anisotropy*, A. Sidi El Valli, V. Iurchuk, G. Lezier, I. Bendjeddou, R. Lebrun, N. Lamard, A. Litvinenko, J. Langer, J. Wrona, L. Vila, R. Sousa, I. L. Prejbeanu, B. Dieny, U. Ebels, Appl. Phys. Lett. 120, 012406 (2022). *Open access: arXiv:2110.14501v1*

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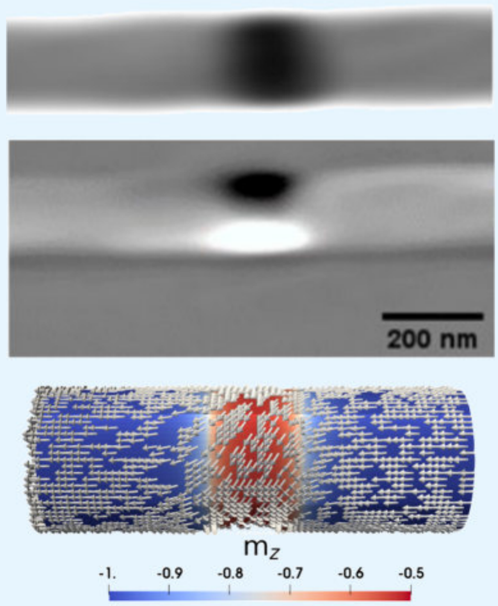
Micromagnetics of chemical modulations in cylindrical nanowires.

We combined chemical synthesis, magnetic microscopy and micromagnetic simulations to provide a comprehensive view of the micromagnetics of chemical modulations in cylindrical nanowires. This sets the ground for their use to investigate the specific aspects of domain-wall dynamics and spin waves in a curvilinear system.

Curvilinear and three-dimensional magnetism are a fast-developing field, considering the magnetic properties arising in systems with a three-dimensional shape and curved surfaces. A number specific effects have been predicted, such as effective anisotropy and Dzyaloshinskii-Moriya interactions, non-reciprocity of spin waves, interplay of chirality imposed by either shape or magnetization dynamics etc. Cylindrical nanowires are a textbook platform for exploring such physics, including spintronic effects when flowing a spin-polarized current through them. Introducing chemical modulations along such wires would provide an extra handle to control domain walls and spin waves in such investigations. Reports are emerging on the matter, however a general picture of the physics at play has not been drawn.

We considered nanowires of diameter ≈100 nm, consisting of longitudinally-magnetized segments of the soft-magnetic permalloy material, $Fe_{20}Ni_{80}$, separated by Fe-rich platelets of width a few tens of nanometers. These are grown by pulsed electroplating from a single bath in porous anodized alumina template. Following dissolution of the template, individual nanowires are contacted electrically on Si wafers to conduct electron transport and operando magnetic imaging. The latter revealed curling of magnetization around the axis at the modulations. This results from an attempt to screen magnetostatic charges arising at their interfaces due to the mismatch of magnetization. We described the situation analytically to derive scaling laws, which we refined with micromagnetic simulations, all consistent with the experimental findings. Curling increases with platelet thickness until reaching a plateau, when interfacial charges are screened. Curling, either clockwise or anticlockwise, can be controlled by the Œrsted field created by an electric current flowing in the wire. The current threshold is in the range 0.1-10x10^{12} A/m^2, following a reentrant behavior versus modulation width, reaching a maximum when the curling plateau is reached.



Structural (dark stands for high Fe content) and magnetic images of a modulation in a nanowire using transmission X-ray microscopy, along with a micromagnetic simulation of the same.

This investigation is the first to provide a comprehensive overview of the micromagnetics of such chemical modulations. It has been made possible by combining advanced expertise in chemical synthesis, magnetic imaging, electric transport and micromagnetic modelling. We believe that this new knowledge will prove valuable when using such modulations to control the dynamics of domain walls of spin waves, either for the sake of fundamental spintronic physics or for device demonstrators. More generally, this demonstrates how chemical modulations may bring more richness to three-dimensional and curved systems.

Teams: Spin textures, Theory and simulation

Collaboration: IMDEA Madrid (Spain), Institut Néel (Grenoble), synchrotrons SOLEIL and ALBA

Funding: ANR Matemac-3D, Renatech, METSA

Further reading: *Micromagnetics of magnetic chemical modulations in soft-magnetic cylindrical nanowires*, L. Álvaro-Gómez et al., Phys. Rev. B 106, 054433 (2022). *Open access: hal-03668833*

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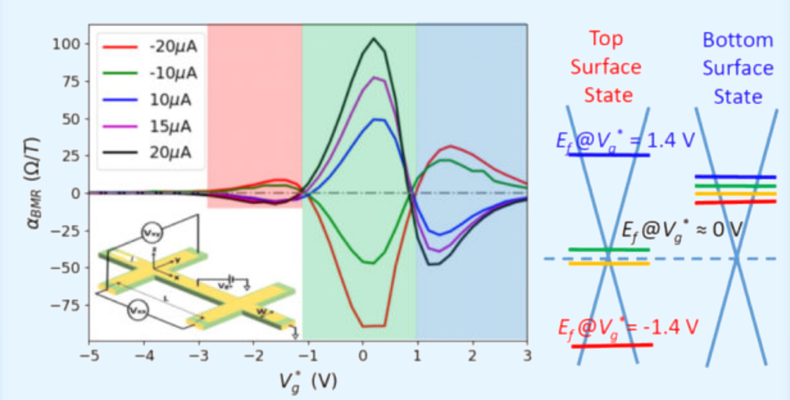
Bilinear magnetoresistance in the HgTe topological insulator

We report the observation of bilinear magnetoresistance (BMR) in strained HgTe, a prototypical TI. We show that both the amplitude and sign of this BMR can be tuned by controlling, with an electric gate, the relative proportions of the opposite contributions of the top and bottom surface states of the HgTe. This phenomenon, unique to TI, offers novel opportunities to tune their electrical response for spintronics.

Spin-orbit effects appearing in topological insulators (TI) and at Rashba interfaces are currently revolutionizing how we can manipulate spins. These have led to several newly-discovered effects, ranging from spin-charge interconversion and spin-orbit torques to novel magnetoresistance phenomena. In particular, a puzzling magnetoresistance has been evidenced, bilinear in electric and magnetic fields. Here, at magnetic fields of 1 T, the magnetoresistance that we observed in HgTe is of the order of 1 % and has a larger figure of merit than previously measured TIs. We propose a theoretical model giving a quantitative account of our experimental data. We show that both the amplitude and sign of this BMR can be tuned by controlling, with an electric gate, the relative proportions of the opposite contributions of opposite surfaces, according the Fermi level position respect to the Dirac point of both surfaces.



Left panel shows the evolution of the BMR parameter α_{BMR} at different current values, showing its linearity with the current intensity, altogether with a triple change of sign as a function of the gate voltage value. On the right the position of the Fermi level within the Dirac cone on the top and bottom surface states are depicted according to the colored region of the gate voltage value. The BMR of the two surface states are opposite due to their opposite chirality. The total BMR thus results in the competition of this two opposite contribution.

We carried out the magneto-transport measurements at low temperature (13 K) on a conventional Hall bar device. The magnetoresistance ($R - R_0$, where R_0 is the resistance at B = 0 T) for B aligned in-plane but transverse to the Hall bar (y-axis) follows a simple expression: $\alpha_{BMR} B_y + Q B_y^2$, which contains two contributions. The first one is odd and linear in field and corresponds to the BMR contribution. The second one is a quadratic contribution, even in field. For B applied along x or z, the magnetoresistance is mainly quadratic with field. Furthermore, the coefficient of the linear term (α_{BMR}) exhibits a linear dependence on current ($\alpha_{BMR} \propto$ I). The BMR is proportional to the current and magnetic field B along the y-axis, i.e. $\propto I B_y$, and vanishes for B along x- and z-axis. This results from the opening of the backscattering channel due to inhomogeneous spin momentum locking of the Fermi contours.

The demonstration of this bilinear magnetoresistance phenomenon in a cubic system rules out the spin warping origin previously put forward to explain these phenomena.

Team: Topological spintronics

Collaboration: LETI/Dopt, IRIG/Pheliqs, Néel Institute, Unité Mixte CNRS/Thalès

Funding: ANR Contrabass, SOspin, EU FET Proactiv Tocha, EU ITN SPEAR

Further reading: *Bilinear Magnetoresistance in HgTe Topological Insulator: Opposite Signs at Opposite Surfaces Demonstrated by Gate Control.* Y. Fu, J. Li, J. Papin, P. Noël, S. Teresi, M. Cosset-Chéneau, C. Grezes, T. Guillet, C. Thomas, Y.-M. Niquet, P. Ballet, T. Meunier, J.-P. Attané, A. Fert, and L. Vila, Nano Lett. 22, 7867 (2022). *Open access: hal-03326015*

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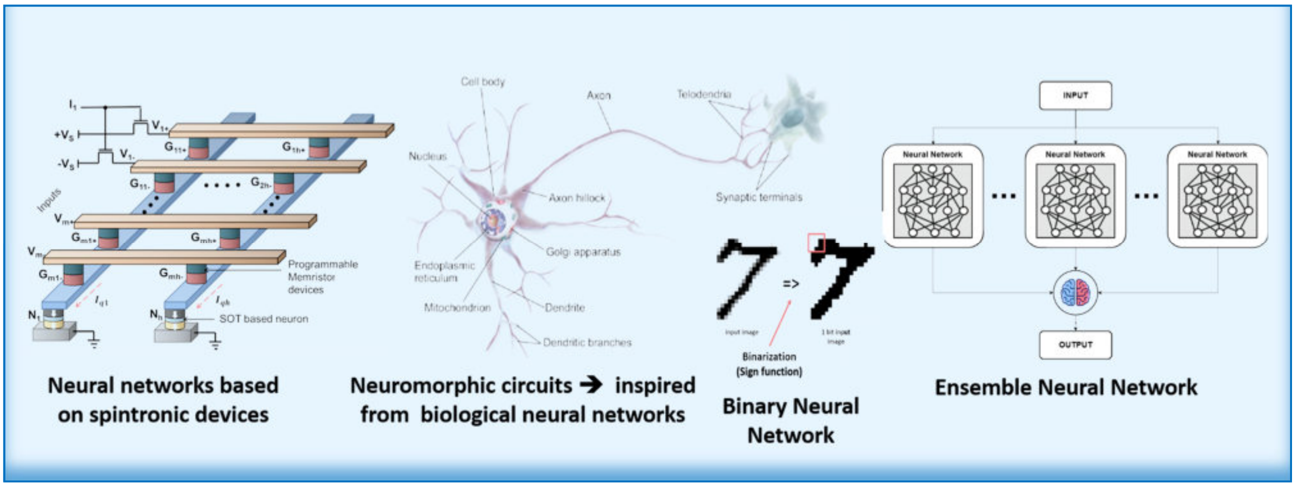
Spintronic Memristor based Binarized Ensemble Convolutional Neural Network

We investigated the use of spintronic devices to enable the implementation of a Binary Ensemble Convolutional Neural Network. A simulation flow has been setup and allowed to evaluate this disruptive combination. Very promising results have been obtained in terms of hardware optimization and power reduction.

The use of emerging technologies has been widely studied to efficiently implement Convolutional Neural Networks (CNN). Indeed, the standard Von-Neumann architecture does not give satisfactory results due to the memory access wall during inference. Crossbar array based on non-volatile resistive devices (memristors) allows performing In-Memory Computing (IMC), help mitigate this issue. Thanks to the resistive nature of devices, basic MAC operations required for CNN is done in analog manner, inside the data storage block.

However, the use of memristive devices suffers from limitations. The lack of maturity of these emerging technologies results in large process variations affecting the accuracy of the analog computation. Moreover, the binary nature of spintronic devices makes the implementation of multi levels synapses challenging. To mitigate these issues, we propose an architecture that combines two concepts. First, we use Ensemble Neural Network (ENN) paradigm that relies on the "wisdom of crowds" concept: we replace a large network with smaller and less accurate networks, trained with different samples of the same dataset. We prove that this is particularly well adapted to emerging technologies with possible large process variations. Second we use binary CNNs that can still provide a very fair accuracy, with an important simplification of the hardware.

The two combined concepts yield a Binary Ensemble CNN (BECNN) based on spintronic memristors. Here the Spin Orbit Torque Magnetic Tunnel Junctions (SOT MTJs) have been used as they offer much higher levels of resistance compared to other technologies. The evaluation of the architecture was performed on several datasets for image recognition. BECNN allows a reduction by 92% of the number of neurons and 95% for synapses respectively, for a similar accuracy. The architecture was implemented on several supports: FPGA, implementation showing already a reduction by 95% and 97% of the number of clock cycles and memory access. Further to that, IMC architecture with SOT crossbars allows a further reduction of the memory access by 95%. The SOT based crossbar array has been designed and validated at circuit level allowing a MAC operation with 3 orders of magnitude lower cost.



Teams: Spintronics IC design, Artificial Intelligence

Funding: MIAI @ Grenoble Alpes, ANR-19-P3IA-0003

Further reading: *Spintronic Memristor based Binarized Ensemble Convolutional Neural Network Architectures* , G. T. Tchendjou, K. Danouchi, G. Prenat and L. Anghel, IEEE Trans. Computer-Aided Design of Integrated Circuits and Systems, 2022, *Open Access: hal-03823906*

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SPINTEC research topics

SPIN ORBITRONICS

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

TOPOLOGICAL SPINTRONICS

The team aims at manipulating spins currents in nanostructures, in particular in quantum materials with Dirac fermions, such as topological insulators or Weyl semimetals, or at oxide interfaces. Some important aspects of future spintronics devices, such as the efficient spin-charge interconversion at interfaces or the ballistic transport of spin states for quantum interconnects, are studied by magneto-transport measurements.

2D SPINTRONICS

The team deals with spin-dependent phenomena in several important classes of materials: Si and Ge, which are the materials of today's microelectronics, and transition metal dichalcogenides and surfaces of topological insulators, which are emerging 2D materials with exceptional optical and spin-orbit properties. The team considers 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 aim at unraveling spin-dependent transport properties of antiferromagnets.

SPIN TEXTURES

The team considers novel spin textures, Bloch-point domain walls, tubular structures and magnetic skyrmions. This involves the three components of magnetization and their three-dimensional distributions, which may be topologically protected. The team designs the systems, images the spin textures with advanced techniques, and addresses these with spin-polarized current. The applied background are concepts for 3D magnetic memories and sensors.

SPIN INSULATRONICS

The team aims at understanding and controlling microwave oscillations of magnetization around its equilibrium, which are the natural dynamical response to external perturbations (*e.g.*, thermal fluctuations, microwave fields). This offers the promise for a new class of microwave devices based on magnetic insulators, benefiting from their small foot-print, their ability to be controlled electrically, and their integrability with CMOS technology to design local oscillators, microwave filters, detectors, and non-reciprocal devices.

MICROWAVE DEVICES

The teams aims at providing a fundamental understanding and control of the excitation, manipulation and detection of the linear and non-linear magnetization dynamics via spintronics phenomena occurring in magnetic nanostructures. Specific attention is given to identify potential microwave applications (oscillators, filters, detectors).

MAGNETIC SENSORS

The team activities cover up-stream research on the effect of gate voltage on interfacial magnetic properties, as well as sensor development (proof of concept) and expertise to support industrial R&D. This experimental research is essentially based on magnetic (VSM, MOKE) and electric (magnetotransport and noise) measurements.

MRAM MEMORIES

The team develops memory concepts with improved thermal stability, low power consumption and/or ultrafast writing. The targeted applications range from standalone to embedded memories, for various usages ranging from in-memory computing to artificial intelligence. Electric-field control of magnetization, possibly in combination with spin-charge interconversion, as well as optical switching of magnetization, are studied as further extension of spintronic memories beyond-CMOS technologies.

SPINTRONICS IC DESIGN

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

HEALTH AND BIOLOGY

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

ARTIFICIAL INTELLIGENCE

The team brings together various expertise of SPINTEC in spintronic devices: nanofabrication, characterization, circuit integration, architecture, and algorithm techniques, to implement hardware solutions for artificial intelligence (AI) and unconventional computing. Spintronic devices provide substantial opportunities to improve the energy efficiency of next-generation computing hardware. The team also takes advantage of brain-inspired computing models to deploy cutting-edge neuromorphic algorithms, closing the gap between current hardware AI implementations and exceptional brain computing ability.

THEORY AND SIMULATION

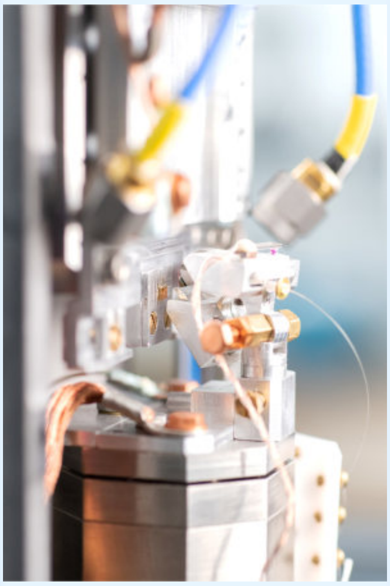
The team covers all aspects of fundamental and applied physics related to spin electronics by employing a wide range of theoretical approaches including ab initio, tight-binding, free electron and diffusive methods, combined with micromagnetic and atomistic simulation approaches. This allows explaining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

About SPINTEC

Positioned at the crossroad of science and technology, SPINTEC (SPINtronique et TEchnologie des Composants) is one of the leading spintronics research laboratories worldwide, ideally located on the *MINATEC* campus in Grenoble. The laboratory was created in 2002 and rapidly expanded to now exceed 100 persons of which 49 permanent staff and about 50 Ph.D. students, post-docs and international visitors. The scientific institutions taking part in the lab are: *CEA*, *CNRS*, and the *University of Grenoble Alpes* including the *Grenoble Institute of Technology*.

SPINTEC objective is to bridge fundamental research and innovative devices in the fast-growing field of spin electronics (spintronics). Indeed, the *international technology roadmap for semiconductors (ITRS)* now reckons that spintronic devices will play a major role in tomorrow's semiconductor chips, with high potential for stand-alone (e.g. DRAM) and embedded memories (SRAM etc.), magnetic field sensors, hardware components for artificial intelligence and bio-applications.

In this context, SPINTEC brings together top-level scientists and applicative engineers who work jointly to ensure that discoveries at the forefront of research are produced, and can be swiftly translated into technological proofs of concepts and functional devices. As such, the outcome of the laboratory is not only scientific publications and communications at international events, but also a coherent patents portfolio, implementation of relevant functional demonstrators, and partnerships for technology transfer. Our large scale provides a critical mass to master all required steps covering materials, nanofabrication, electrical and magnetic characterization, condensed-matter theory, simulation and the design of dedicated integrated circuits.



Sample stage of an NV-center microscope designed at SPINTEC

Whereas our fundamental research is mostly operated through collaborative grants with other research laboratories, applied research is often carried out in partnership with private actors. These can be large corporations (Applied Materials, Samsung, Seagate, INTEL), SME's (SNR, Singulus) or start-up companies spun-off from SPINTEC: *Crocus Technology* in 2006, *eVaderis* in 2014, *HProbe* in 2016, *Antaïos* in 2017, while the process for the creation of two more is ongoing.

SPINTEC plays also a major role in higher education in magnetism and nanotechnology, through chairing four highly visible international schools: the European School on Nanosciences and Nanotechnology ESONN, the European School on Magnetism ESM, the school on applied spintronics InMRAM, and the school on Quantitative Electron Microscopy QEM.

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