spintec
SPIN IN ELECTRONICS

Highlights

2023

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FOREWORD

This booklet gathers a selection of scientific highlights of SPINTEC over 2023. Besides these, we mention below a few cornerstones in the life of the laboratory, along with the prospects for SPINTEC in 2024.

2023 was a year full of events!

The scientific highlights in this booklet provide an insight in our key publications, signature for our mission to advance knowledge. In parallel to these, we maintained our high level of production of intellectual property, signature for our mission to contribute to innovation. Both missions have been supported this year by new funded projects, as well as new industrial partnerships (IDEMA, Hprobe, Crocus Technology). Several scientific highlights are described in this booklet covering various aspects of the research done in the lab. You can find details about how to use vibrating magnetic microparticles to stimulate insulin secretion, a new type of magnetic sensor based on a regular spin transfer torque MRAM cell or a very sensitive senor based on a high gain flux concentrator, a new all-optical mechanism for ultrafast magnetic memories, the non-volatile electric control of spin-orbit torques in an electron gas with promises on applications and exploited by the future start-up Nellow that won recently the 1st prize at the HEC Challenge+ Forum, how to build a spiking neuron based on magnetic tunnel junction, a voltage controlled magnetic anisotropy cell for cryo-electronics.

We want to emphasize also that our colleague Philippe Sabon received the CNRS 2023 collective crystal award for the Repotech project; the EIC acceleration funding obtained by the start-up Golana Computing, established this year by Mihai Miron, Gilles Gaudin and Miguel Rubio-Roy; and the key involvement of SPINTEC in the France 2030 PEPR exploratory and acceleration programs: one exploratory PEPR SPIN that we are co-leading, and in 3 acceleration PEPR: electronics, IA and quantum. Moreover Crocus Technology, a former start-up from SPINTEC, was acquired in 2023 for $420 million by Allegro MicroSystems, a global leader in power and sensing semiconductor technology for motion control and energy efficient systems. Crocus brings to Allegro unique technology and products well suited to serve high-growth applications in e-mobility, clean energy and automation, supported by more than 200 patents.

Contractual resources at SPINTEC reached 5 M€ in 2023, providing us with a healthy financial situation. New strategic and game-changing partnerships started, which allow us to strengthen our actions and expand our network. We are involved in two successful national initiatives of Excellence EquipEx, the 2D-MAG and NanoFutur projects. These will allow us to setup platforms for the synthesis of spintronic stacks, from the emerging 2D epitaxial materials to an industry-ready pilot line. Several innovation-oriented grants will also contribute to support the rise of new memory and logic actions, making use of spin-orbit torques and ferroelectric/magnetic architectures. Five new ANR projects were selected this year and we extended and expanded our partnership with IFW Dresden and York University in the framework of a CNRS International research partnership. SPINTEC is partner of the Infrachip European project

We keep welcoming new collaborators, to achieve our missions. CNRS assistant engineer Clément de Barbarin, Asli Denninger Consigney as project manager for the PEPR SPIN and Louis Desplat as CNRS scientist joined the lab in 2023.

The laboratory days held in Sassenage in September were an opportunity to discuss collectively the scientific and organizational challenges for the years to come, and sustain our collective life. Human is indeed the most valuable wealth of a research lab, and as such we are proud of our 11 PhD graduations and the 2 habilitation defenses (Olivier Boulle and Hélène Béa).

2024 is coming with new challenges!

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

2024 is an important year for the laboratory's development, with significant projects: the institutional kick-off of PEPR SPIN on January 29; scientific brainstorming days on February 12 and 13; the completion of the expansion and thermal shielding of our building, allowing the relocation of all colleagues in in single building, the installation of the SINGULUS deposition machine as part of the spintronic pilot line to produce complex stacks and state-of-the-art tunnel junctions, as well as the 2D epitaxy cluster to . Materials are indeed key in spintronics, and we are setting-up these two platforms with an ambition for international networking and visibility. Many other events and success are probably to come.

We will sustain our efforts to bring the innovative potential of spintronics better recognized, within SpintronicFactory, the European Magnetism Association and the IEEE Mag Soc, as well as through the scientific higher-education schools we are organizing: ESONN, InMRAM, ESM and QEM.

We hope that you will enjoy browsing the following pages, gathering a selection of scientific highlights and cornerstones of SPINTEC over 2023.

Lucian Prejbeanu, Executive Director / Olivier Fruchart, Deputy Director

SPINTEC Highlights – December 2023 – Editor: Gregory Di Pendina

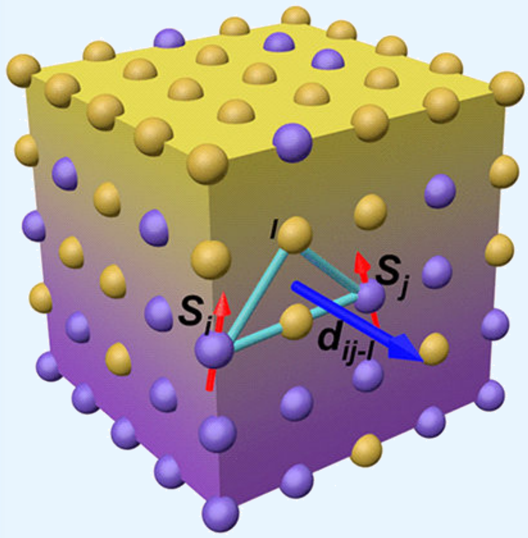
Directors of publication: Lucian Prejbeanu, Executive Director
Olivier Fruchart, Deputy Director
Hélène Béa, Associate professor HdR

CONTENTS

Gradient-induced Dzyaloshinskii–Moriya interaction

The Dzyaloshinskii–Moriya interaction (DMI) arising in the magnetic systems with broken inversion symmetry plays an essential role in topological spintronics. Using atomistic spin model simulations of an intriguing type of DMI emerging in the films with composition gradient (g-DMI), we demonstrated that both the strength and chirality of g-DMI can be controlled by the composition gradient even in the disordered system.

While it is usually believed that the disorders like the intermixing and dusting of elements at interfaces are detrimental to the interfacial DMI, there are a number of experiments showing of a significant DMI (termed g-DMI hereafter) in the amorphous thin films with a composition gradient breaking the inversion symmetry. For instance, the measured DMI values show a linear relation with the film thickness, signifying a bulk nature of g-DMI in the thin films. In addition, several experiments have suggested that the combination of g-DMI and spin–orbit torques (SOT) may lead to the current-induced magnetization switching in a single magnetic layer, although the microscopic mechanisms remain not well explored. To have an in-depth understanding of g-DMI, several fundamental questions remain to be cleared up: How is the g-DMI controlled by the composition gradient? What about the distribution of g-DMI over the thin film? How do the magnetic state and the spin dynamics get affected by the g-DMI?



Schematic representation of a thin film of alloy comprising magnetic (magenta) and non-magnetic (yellow) heavy atoms with a linear vertical compositional gradient. One of DMI vectors arising from interaction between spins mediated by neighboring heavy atom.

The aforementioned questions have been clarified using systematic and comprehensive theoretical analysis of the g-DMI based on the atomistic spin calculations. First, it turns out that in contrast to the interfacial DMI, the g-DMI can be engineered by the composition gradient without the demand of a high-quality interface for the enhancement of total DMI. Next, the linear composition gradient can lead to almost uniform distribution of g-DMI inside the bulk layers of thin film. Indeed, the layer-resolved analysis of g-DMI unveils the additive nature inside the bulk layers and clarifies the linear thickness dependence of g-DMI observed in experiments. Due to this additive nature of g-DMI, increasing the film thickness is beneficial to increase the total DMI. Furthermore, the g-DMI leads to topological magnetic structures such as spin spirals and skyrmions and the g-DMI driven field-free SOT switching, both of which are crucial toward the practical spintronic device applications. Compared to the interface DMI with its properties determined by constituent elements and ordering of the atoms at the interface, both the strength and chirality of g-DMI are continuously tunable by the composition gradient, thus being advantageous for practical applications. These results elucidate the underlying mechanisms of g-DMI, open up a new way to engineer the topological magnetic textures, and may lead to more exotic spin phenomena induced by the g-DMI in the future.

Team: Theory / Simulation

Collaborations: Lab. Albert Fert, Palaiseau (France), NIMTE and Nanjing Univ. (China)

Funding: EU Graphene Flagship, MOST, Zhejiang PNSF, NNSFC & CAS (China)

Further reading: *Gradient-Induced Dzyaloshinskii–Moriya Interaction*, J. Liang, M. Chshiev, A. Fert and H.-X. Yang, Nanoletters, 22, 10128 (2022) *Open access: hal-03942584*

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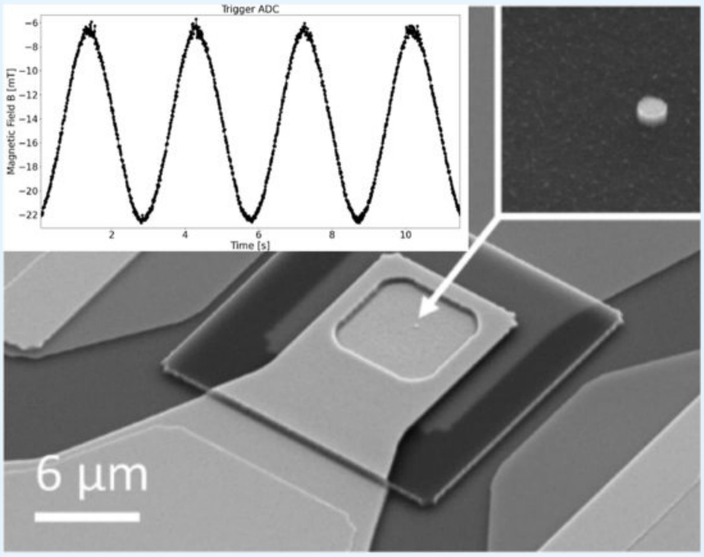
Spin transfer torque based magnetic sensor and signal conditioning electronics

We demonstrated experimentally a new working type of magnetic sensor based on the spin transfer torque, using 50-100 nm diameter perpendicular magnetic tunnel junctions, based on a magnetic field sensing principle patented by SPINTEC in 2002, also describing possible read-out methods and their associated signal conditioning electronics. Improvements over conventional magneto-resistive (MR) sensors are the wide magnetic field range with a signal detection independent of the range.

Conventional MR sensors detection principle consists of a tradeoff between signal amplitude and magnetic field range, i.e. high sensitivity sensors have a limited field range. The sensitivity is defined as the resistance change per unit of magnetic field, and the sensor range represents the region where linearity between field and resistance change can be maintained. The demonstrated spin transfer torque based sensor provides new detection principle, no longer limited by the accuracy of the resistance measurement. The resistance is measured to detect changes between the junction low and high resistance states, when subjected to a periodic sine or triangular applied voltage. The voltage at which the junction switches state is linearly dependent on the applied field.



Scanning electron microscopy image of perpendicular magnetic tunnel junction fabricated with 50 nm diameter (zoom in right insert). (left insert) Detected signal from magnetic field applied with 10 Hz.

Magnetic field detection was proven, by detecting the sensor switching voltage with two possible schemes, time to digital converter or pulse width modulation (PWM). The PWM method achieved lower noise and better resolution, while requiring a larger layout for the associated electronic circuit. The main advantages of the proposed sensor are the small size of the sensor itself, resulting in low power and smaller footprint of the conditioning electronics. The detection range can be wider that MR sensors, as directivity is no longer linked and limited by the field range. The sensor is also immune to the application of large fields, which cause irreversible damage to MR sensors. Since our sensor is closely related to STT magnetic memory (MRAM) cells, monolithic sensor integration with CMOS circuits and mass production can be realized in MRAM foundries with minimal changes. Present sensor performance is still not at the level of commercially available MR sensors, but simple improvements of the sensing element as well as conditioning electronics are being implemented to lower the noise level. The sensor could find applications in diverse domains from industrial applications to the medical field, embedded either in a single small chip or as an array of sensing units.

Team: MRAM

Collaborations: University of Applied Sciences Northwestern Switzerland (Switzerland), ICube Strasbourg, (France)

Funding: Swiss Nanoscience Institute (n°A16.10), ERC MAGALIGN (n°963895)

Further reading: *Conditioning Circuits for Nanoscale Perpendicular Spin Transfer Torque Magnetic Tunnel Junctions as Magnetic Sensors*, H. Nicolas, R. C. Sousa, A. Mora-Hernández, I.L. Prejbeanu, L. Hebrard, J.B. Kammerer and J. Pascal. IEEE Sensors Journal, 23, 5670, (2023).
Open access: hal-04029607

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Non-volatile electric control of spin-orbit torques in an electron gas

Spin-orbit torques (SOTs) have the potential to manipulate magnetization using in-plane current, for which two-dimensional electron gases (2DEGs) provide a highly efficient spin-to-charge current interconversion. Here, we report the non-volatile electric-field control of SOTs in an oxide-based Rashba-Edelstein 2DEG.

We recently reported a significant progress in the path towards a next generation of memory devices with greater energy efficiency. The non-volatility is a key ingredient to optimize the power consumption of memory and logic devices.

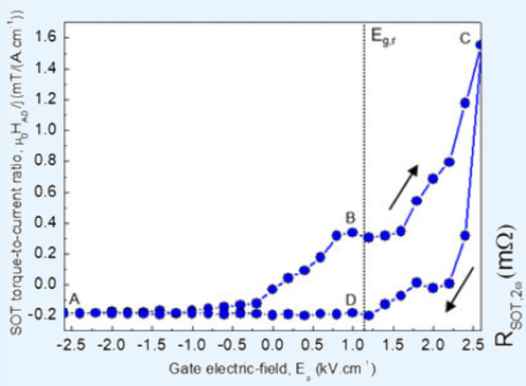
Here, we show a breakthrough in modulating the spintronics properties of a two-dimensional electron gas (2DEG) using an electric field. We used Ta/CoFeB/MgO stacks on (001)-oriented $SrTiO_3$ substrates, which offer key advantages for integration into magnetic tunnel junctions with high tunnel magnetoresistance.

To characterize the magnetic and electrical properties of the 2DEG, we injected an input current in a Hall cross, and measured the longitudinal and transverse Hall resistances as a function of the magnetic field. The sheet resistance of the device decreases by 380% as the temperature reduces, which is characteristic of 2DEG conduction.

Furthermore, the 2DEG conductivity can be modulated using an electric field applied across the $SrTiO_3$ substrate, with two switchable and remanent high and low-resistivity states of the device, with a resistance contrast of 1064% (615% at remanence).

Using harmonic Hall voltage measurements methods, we then measured the spin-orbit torques in the Hall cross, and found that the SOT effective fields are different for high and low-resistivity states. We explore the modulation of the spin-orbit torques (SOTs), showing that the SOT hysteresis results from two factors: the hysteretic modulation of the 2DEG resistivity, and the variation of the conversion with the 2DEG Fermi level position.

This non-volatile electric control of the SOTs in 2DEGs has the potential to create a new generation of spin-orbit torque devices, with the experimental finding of a reproducible inversion of the SOT torque signs, and of a control of the SOTs that could be used to build reconfigurable SOT-MRAMs, and manipulate skyrmions, domain walls, or magnons.



Gate electric-field dependence of the spin-orbit torques (more precisely of the anti-damping-like effective field $\mu_0 H_{AD}$), demonstrating the non-volatile electric-field control of the spin-orbit torques.

Team: Topological Spintronics

Collaboration: Lab. Albert Fert, Palaiseau (France)

Funding: ANR Contrabass (ANR-20-CE24-0023), Institut Universitaire de France, ERC Fresco (101001995), Marie Skłodowska-Curie ITN Spear (n°955671)

Further reading: *Non-volatile electric control of spin-orbit torques in an oxide two-dimensional electron gas*, C. Grezes, A. Kandazoglou, M. Cosset-Cheneau, L. M. Vicente Arche, P. Noël, P. Sgarro, S. Auffret, K. Garello, M. Bibes, L. Vila & J.P. Attané. Nature Communications 14, 2590 (2023).

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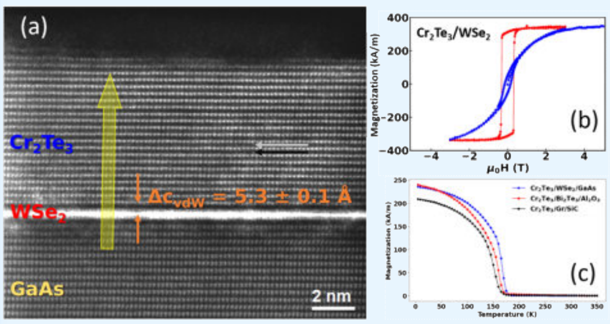
Epitaxial van der Waals heterostructures of Cr_2Te_3 on 2D material

For the future integration of 2D materials in spintronic devices (sensors, memories…), the ability to grow van der Waals (vdW) heterostructures combining 2D magnets, high mobility, high spin-orbit coupling (SOC) or topological materials on large areas constitutes a real challenge today. Here, by using molecular beam epitaxy in the van der Waals regime, we could grow high crystalline quality vdW heterostructures with sharp interfaces and well defined magnetic and magnetotransport properties in agreement with *ab initio* calculations.



(a) Transmission electron microscopy image in cross section showing the Cr_2Te_3 / WSe_2 (1ML) / GaAs van der Waals heterostructure. (b) Out-of-plane (red) and in-plane (blue) hysteresis curves recorded by SQUID showing the strong PMA. (c) Remanence curves of the three vdW heterostructures.

Achieving large-scale growth of two-dimensional (2D) ferromagnetic materials with high Curie temperature (T_C) and perpendicular magnetic anisotropy (PMA) is highly desirable for the development of ultra-compact magnetic sensors and magnetic memories. In this context, van der Waals (vdW) Cr_2Te_3 appears as a promising candidate. Bulk Cr_2Te_3 exhibits strong PMA and a T_C of 180 K. Moreover, both PMA and T_C might be adjusted in ultrathin films down to the monolayer by engineering composition, strain, or applying an electric field.

In this work, we demonstrate the molecular beam epitaxy (MBE) growth of vdW heterostructures of five-monolayer quasi-freestanding Cr_2Te_3 on three classes of 2D materials: graphene (high mobility semimetal), WSe_2 (high SOC semiconductor) and Bi_2Te_3 (topological insulator).

By combining structural and chemical analysis down to the atomic level with *ab initio* calculations, we confirm the single crystalline character of Cr_2Te_3 films on the 2D materials with sharp vdW interfaces (Fig. (a)). They all exhibit PMA (Fig. (b)) and T_C close to the bulk Cr_2Te_3 value of 180 K (Fig. (c)). *Ab initio* calculations confirm this PMA and show how its strength depends on strain. Finally, from Hall measurements, we revealed a strong anomalous Hall effect, which changes sign at a given temperature. We theoretically explain this effect by a sign change of the Berry phase close to the Fermi level. This transition temperature depends on the 2D material in proximity, notably as a consequence of charge transfer.

MBE-grown Cr_2Te_3/2D material bilayers constitute model systems for the further development of spintronic devices combining PMA, large spin-orbit coupling and sharp vdW interface.

Teams: 2D Spintronics, Theory / Simulation

Collaborations: IRIG-MEM/PHELIQS/SYMMES, Institut Néel, Grenoble (France), C2N, Palaiseau (France), SOLEIL, St-Aubin (France)

Funding: ESR/EQUIPEX 2D-MAG (ANR-21-ESRE-0025), EU Graphene Flagship

Further reading: *Epitaxial van der Waals heterostructures of Cr_2Te_3 on 2D materials*, Q. Guillet, L. Vojacek, D. Dosenovic, F. Ibrahim, H. Boukari, J. Li, F. Choueikani, P. Ohresser, A. Ouerghi, F. Mesple, V. Renard, J.F. Jacquot, D. Jalabert, H. Okuno, M. Chshiev, C. Vergnaud, F. Bonell, A. Marty and M. Jamet, Physical Review Materials 7, 054005 (2023). *Open access: hal-04017966*

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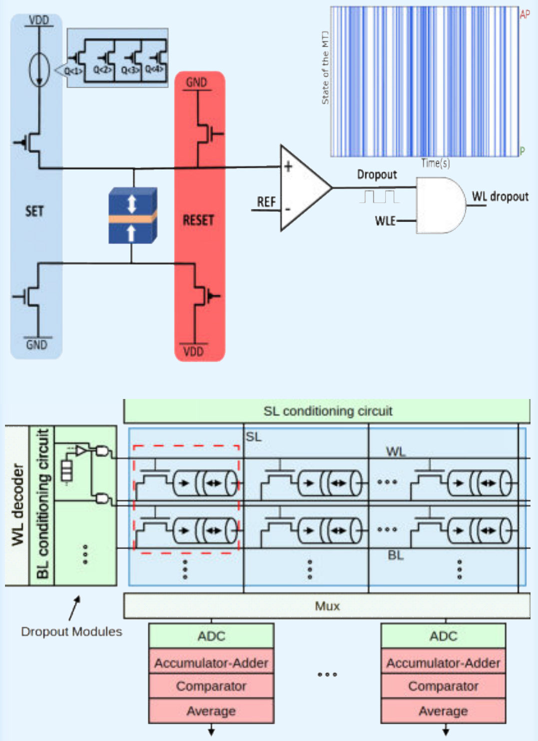
SpinDrop: dropout-based bayesian binary neural networks with STT-MRAM

Bayesian neural networks (BayNN) using Dropout-based approximation provides a systematic approach for estimating the uncertainty of predictions. Despite such merit, they are not suitable for implementation in an embedded device and in most cases cannot meet high-performance demands for certain applications. We show that computation in-memory (CiM) architecture with spintronics emerging non-volatile memories (NVMs) is a great candidate for high-performance and low-power acceleration BayNNs in hardware.

Neural Networks (NNs) are in the center of modern computing thanks to their ability to solve complex and difficult tasks in numerous application domains, including autonomous driving and medical applications. Nevertheless, their predictions can be incorrect if the input sample is outside of the training distribution or affected by noise. Consequently, quantifying the uncertainty of the NN prediction allows the system to make more insightful decisions by avoiding blind predictions. Therefore, uncertainty quantification is crucial for a variety of applications, including safety-critical applications.

We propose for the first time a Bayesian Binary Neural Network (BayBNN) using spintronic-based Dropout as a Gaussian approximation and develop a complete solution and flow spanning from the training algorithm to the circuit-level hardware implementation. We propose a hardware-based Dropout method and present its hardware implementation using spintronic devices, specifically Spin transfer torque (STT) magnetic tunnel junctions. We demonstrate the concept of Bayesian Binary Neural Networks through holistic, extensive analysis from device and circuit level evaluations up to the algorithmic level. We show that the proposed approach can be used to detect out-of-distribution and noisy data, being robust against variability issues of the Dropout generation mechanism.



Spindrop Module Schematic and Inference architecture for Bayesian Binary Neural Network

Our proposed approach embraces the randomness of the STT-spintronic-based CiM architecture, considering it as a feature instead of as an issue. For this purpose, the stochastic and deterministic aspects of STT-Magnetic random access memories (MRAM) have been combined in a crossbar array-based architecture. Moreover, at the architecture level, we show that it does not imply changes in the bit-cell design, leading to the re-utilization of the bit-cell array designed for classic MRAM memory or for classic Binary NN. The results show up to 100% detection capabilities for out-of-distribution data, and up to 15% improvement in accuracy for poisoned data. Furthermore, our results show the high resilience of the proposed concept to process and thermal variations.

Teams: Spintronics IC Design, Artificial Intelligence

Collaboration: KIT, Karlsruhe (Germany)

Funding: ANR-DFG NEUSPIN (ANR-21-FAI1-0008), ANR-19-PI3IA-0

Further reading: *SpinDrop: Dropout-Based Bayesian Binary Neural Networks With Spintronic Implementationr*, S. Ahmed, K. Danouchi, M. Hefenbrock, G. Prenat, L. Anghel and M. B. Tahoori, IEEE Journal on Emerging and Selected Topics in Circuits and Systems, 13, 150 (2023).
Open access: arXiv 2306.10185
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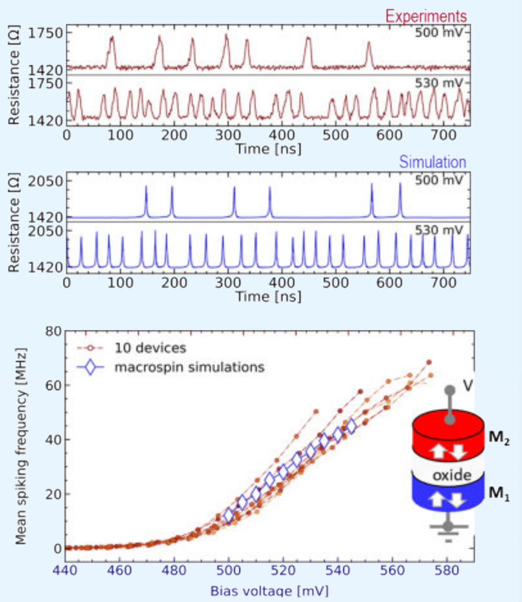
Spiking neuron based on magnetic tunnel junction with dual free layer

We demonstrated that a perpendicular magnetic tunnel junction (MTJ) is capable of emulating an artificial spiked neuron. The magnetic stack was designed so that the MTJ has two free layers, whose magnetization can be driven in a windmill-like dynamic by the spin transfer torque. The output-spiking rate is tunable by the DC bias voltage. This compact, field-free operating device is a practical solution for the development of spiking neural networks.



Experimental and simulated time traces of the resistance of a p-MTJ under bias voltages of 500 and 530 mV. The mean spiking rate vs bias voltage. Schematics of the pMTJ pillar.

Our goal is to develop a compact spintronic device able to generate an output signal with spikes upon injecting a DC current and thus mimicking a neuron function. The structure of our magnetic tunnel junction consists of two thin ferromagnetic layers with switchable magnetization oriented out-of-plane (OOP) owing to the perpendicular anisotropy induced at the interface with the Mg oxide spacer layer separating them (see schematics in the figure). Depending on the relative orientation of the magnetization of the two ferromagnetic layers (M_1 and M_2), the junction resistance changes due to different tunneling probabilities of spin up and spin down electrons across the barrier. The properties of the complete stack are designed so that the two magnetic layers have similar thermal stability, so that both of their magnetizations can be reversed by spin-transfer torque (STT). Under suitable conditions of applied voltage (V) and magnetic field, the magnetization of both layers switches continuously, creating an oscillation between anti-parallel (AP) and parallel (P) resistance states. Each transition between the AP and P states is associated with a sharp variation in resistance, similar to a spike.

Time-resolved resistance measurements performed on individual nanopillars with lateral size ~ 80 nm unveil a windmill dynamic state (see figure), in which there is a sequential and perpetual switching of the two magnetic layers. The DC bias voltage is used as a parameter to control the magnetization dynamics, generating signals similar to a firing event in biologically inspired neurons. The bias voltage can be adjusted to regulate the spiking rate, which can reach up to tens of MHz, as demonstrated by both experiments and simulations.

Our proof-of-concept device works at reasonable bias voltage and zero applied field, and these two features are relevant for large-scale integration. The small energy consumption of the device (4–16 pJ/spike) and its scalability are important benefits for embedded applications. The windmill-like dynamics have straightforward applications in brain-inspired computing, stochastic computing, in-memory computing, and sensors.

Teams: Theory / Simulation, MRAM

Collaboration: Lab. Albert Fert, Palaiseau (France)

Funding: ANR Spinspike (ANR-20-CE24-0002)

Further reading: *Spiking dynamics in dual free layer perpendicular magnetic tunnel junctions,* L. Farcis, B. M. S. Teixeira, Ph.Talatchian, D. Salomoni, U. Ebels, S. Auffret, B. Dieny, F. A. Mizrahi, J. Grollier, R. C. Sousa, and L. D. Buda-Prejbeanu, Nanoletters 23, 7869 (2023). *Open access: arXiv 2309.07535*

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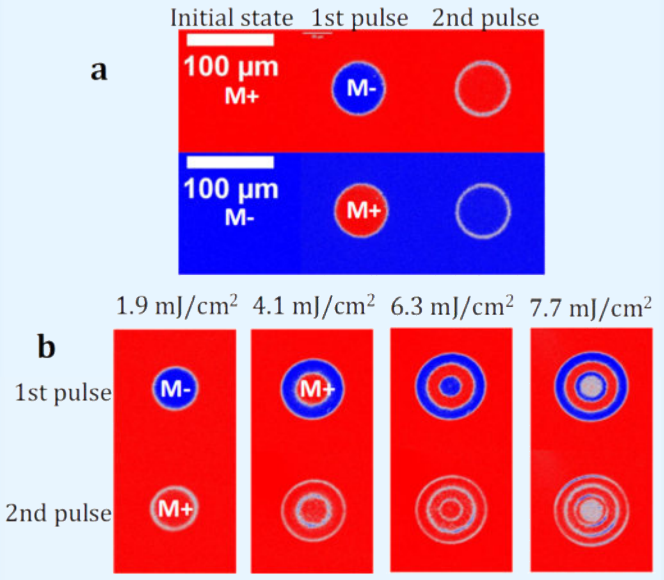
In plane reorientation induced single laser pulse magnetization reversal

We demonstrates that single pulse all optical helicity independent switching can be generalized for a large range of rare earth–transition metal multilayers. The threshold fluence for switching is observed to be independent of the pulse duration and, at high laser intensities, concentric ring domain structures are induced, unveiling multiple fluence thresholds. These striking switching features point towards an intrinsic precessional reversal mechanism.

Single pulse all optical switching represents the ability to reverse the magnetization of a nanostructure using a femtosecond single laser pulse without any applied magnetic field. Since the first switching experiments carried out on GdFeCo ferrimagnets, this phenomenon has been only recently extended to a few other materials, MnRuGa alloys and Tb/Co multilayers with a very specific range of thickness and composition.

Here, by combining experimental results and theoretical models, we demonstrate that single pulse switching can be obtained for a large range of rare earth–transition metal multilayers, making this phenomenon much more general. Surprisingly, the threshold fluence for switching is experimentally observed to be independent of the laser pulse duration. Moreover, at high laser intensities, concentric ring domain structures are induced. These striking features contrast to those observed in Gd based materials pointing towards a different reversal mechanism. Concomitant with the demonstration of an in-plane magnetization reorientation, a precessional reversal mechanism explains all the observed features.



Single-pulse switching under zero applied field. A. Background subtracted images after each single pulse with 1.9 mJ/cm² laser pulse at 50 fs. B. Background subtracted images after first single with 50 fs laser pulse of different fluences.

This is a first detailed materials paper study, allowing to develop and understand ultrafast single shot magnetization switching in Gd free materials. This work is an important milestone for the research in the field of all-optical switching toward applications, including future developments on theory, experiments and applications. Our results will further expand the pivotal role that spintronics can play for the future of ultrafast and ultralow power microelectronics, so important for the digital world.

Teams: MRAM, Theory / Simulation

Collaboration: Institut Jean Lamour, Nancy (France)

Funding: ANR (ANR-17-CE24-0007 UFO project), EU & Marie Skłodowska-Curie COMRAD (861300)

Further reading: *Field-Free All-Optical Switching and Electrical Readout of Tb/Co-Based Magnetic Tunnel Junctions,* D. Salomoni, Y. Peng, L. Farcis, S. Auffret, M. Hehn, G. Malinowski, S. Mangin, B. Dieny, L. D. Buda-Prejbeanu, R. C. Sousa, and I. L. Prejbeanu, Physical Review Applied 20, 034070 (2023). *Open access: hal-04227118*

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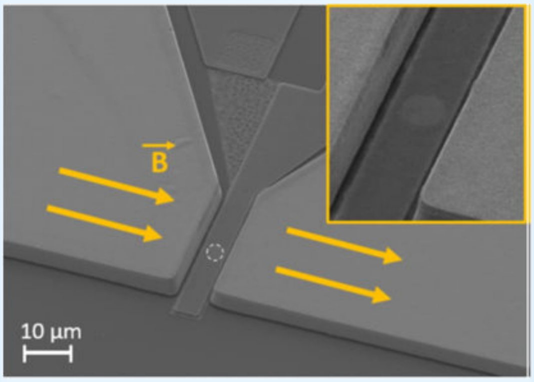
A high gain flux concentrator greatly amplifies the sensitivity of a magnetic field sensor

The large magnetometers currently used onboard satellites for space exploration cannot be installed in the tiny nanosatellites (cubesat) that are envisioned for multipoint measurements. As a first step towards the realization of a miniature space magnetometer, we have demonstrated a strong amplification of the sensitivity of a magnetic field sensor on chip.

The current magnetometers used on space missions have extremely high performances but are much too large (15 cm, 500 g) to fit within a cubesat (typical size = 1 dm^3). We have reached an important step toward the realization of a miniature magnetic field sensor that could compete with these large magnetometers by developing a high gain flux concentrator that amplifies by more than two orders of magnitude the sensitivity of a magnetic sensor on chip.



Scanning electron microscope image of the flux concentrator with a circular junction within the air-gap (positioned dashed circle). Inset: zoom on the junction in the air-gap.

Our aim was to improve the performances of magnetic tunnel junctions, which are already used as miniature magnetic sensors, for example as read-head in hard disk drive. Besides the enhancement of the sensitivity of the magnetic tunnel junction itself by optimizing the material properties and studying the influence of its shape, the most dramatic improvement has been obtained by designing a high gain flux concentrator. This flux guide amplifies the external field by concentrating the flux lines at the location of the junction. The design of the flux concentrator has been proposed by our partners at LPC2E, a space laboratory in Orléans. The technical realization was rather challenging since the mm-size flux concentrator is 5-7 µm thick with a 10 µm air-gap. Depositing such a thick layer could not be performed with the available deposition tools. Moreover the spacing between the two structures (10 µm) is comparable to their thickness. To overcome this difficulties, we developped an electrochemical deposition technique on a dedicated bench in the PTA clean-room. The soft ferromagnetic material is deposited in a thick resist mold on a metallic seed layer. The flux concentrator is placed around the junction (see figure) and allows for a field amplification by a factor of 440. This very large gain compares advantageously with single-stage flux concentrators developped by other groups that show amplification by a factor 10 to 100.

The demonstration of this large amplification is an important step toward the realization of a miniature magnetic field sensor with high performances that could also have bio-medical applications. It has attracted the interest of the French magnetic community and given rise to new collaborations with academic and industrial partners.

Team: Magnetic sensors

Collaboration: Laboratoire de Physique et de Chimie de l'Environnement et de l'Espace (LPC2E), Orléans (France)

Funding: CNES ATTRACT-MAROT, ANR Marot (ANR-22-CE42-0020)

Further reading: *Large amplification of the sensitivity of symmetric-response magnetic tunnel junctions with a high gain flux concentrator*, S. Manceau, T. Brun, J. Fischer, C. Ducruet, P. Sabon, C. Cavoit, G. Jannet, J.-L. Pinçon, I. L. Prejbeanu, M. Kretzschmar, C. Baraduc, Applied Physics Letters 123, 082405 (2023). *Open access: hal-04194941v1*

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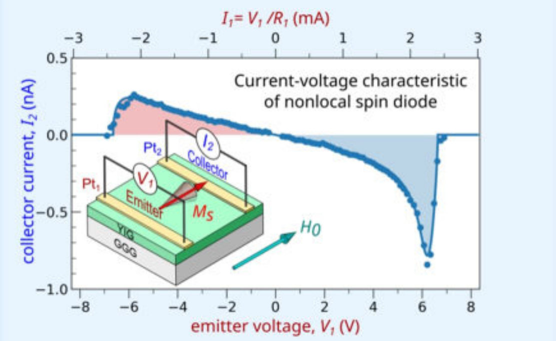
The spin diode

Spin electronics applies to a wide range of materials: metals, where spin is transported by electrons, but also magnetic insulators, where spin is transported by magnons. The latter are of interest because in certain insulators, such as yttrium iron garnet (YIG), it is predicted that one could reach a state of superfluidity, i.e. spin transport without energy dissipation. We have shown why this magnetic material does not live up to the expectations of ideal magnon transport.

Reaching an electrical control of spin currents carried by magnons is of great interest to obtain an ideal diode device by achieving quantum condensation, known as Bose-Einstein condensation. A spin diode in this state has perfect nonlinear properties, as it carries spin currents without any loss of energy, in analogy to a superconductor, that transports electric current without resistance.



Current-voltage characteristic curve of a spin diode made of YIG material conducting spin current via magnon propagating between two Pt electrodes.

In two consecutive articles, we have studied nonlocal magnon transport in extended thin films of yttrium iron garnet (YIG), a material with highly favorable nonlinear threshold. Two platinum wires are deposited on a magnetic film, and act as magnon emitters and collectors, respectively (see figure). These adjacent wires allow the electrical control of the magnon chemical potential by the spin transfer effect. A strong enhancement of the spin current is expected when the magnon chemical potential is shifted towards the gap of the magnon band.

We report, when the electrodes are sufficiently spaced, a diode-like current-voltage characteristic due to the nonlinear increase in the population of low-energy magnons. However, the gain obtained remains small, several orders of magnitude lower than expected. In a first paper, we discuss this setback by a rapid saturation of the low-energy magnon population, which limits the spin diode effect and thus fails to reach a state of large magnon concentration and hence large spin current. The whole material therefore behaves like a magnon liquid, but without the quantum effect. In the second article, we explain why the diode effect can only be achieved at large distances between the electrodes. At short distances, the spin transport is dominated by the competing high-energy thermal magnons, which respond only linearly to the voltage applied between the electrodes. Fortunately, their contribution decays rapidly with distance, revealing the spin diode effect of low-energy magnons, which have a much larger characteristic decay length once the separation between the electrodes exceeds a few µm. We propose an analytical model that integrates the effects of both low-energy magnons and thermal magnons, which confirms the experimental observations. These results show that it is not possible to achieve the formation of a Bose-Einstein condensate in YIG, but instead suggest that a magnetohydrodynamic fluid regime is formed at high power due to this increase in the spin-spin relaxation rate, as would occur in an ultrapure electronic conductor such as graphene, a phenomenon known as the Gurzhi effect.

Team: Spin Insulatronics

Collaborations: CEA-SPEC, Saclay (France), Univ. Bretagne Occidentale, Brest (France), Lab. Albert Fert, Palaiseau (France), Univ. Lorraine, Nancy (France)

Funding: ANR Maestro (ANR-18-CE24-0021), Harmony (ANR-21-CE24-0031), EU PALANTIRI-101046630

Further reading: *Nonlocal magnon transconductance in extended magnetic insulating films part I and II,* R. Kohno, K. An, E. Clot, V. V. Naletov, N. Thiery, L. Vila, R. Schlitz, N. Beaulieu, J. Ben Youssef, A. Anane, V. Cros, H. Merbouche, T. Hauet, V. E. Demidov, S. O. Demokritov, G. de Loubens, and O. Klein, Physical Review B 108, 144410 and 144411 (2023). *Open access: hal-04207174 and hal-04207180*

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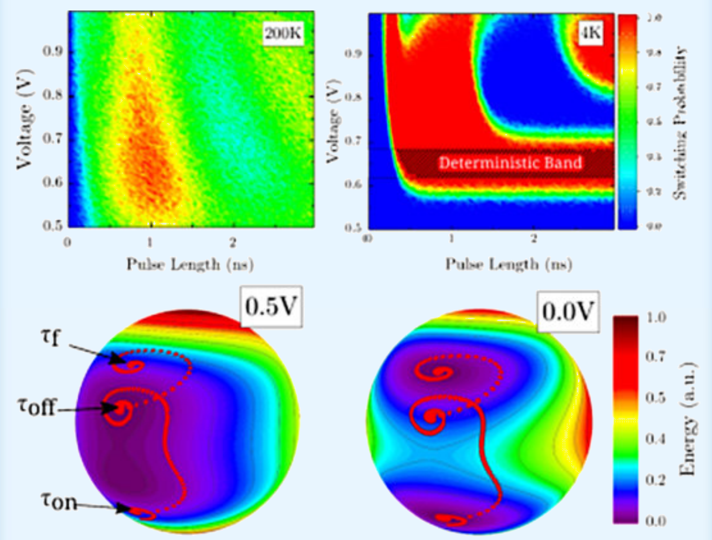
Deterministic switching in voltage controlled magnetic anisotropy at low temperature

Cryoelectronics has the potential to become important in high-performance computing applications and in the context of quantum computing. For low-temperature operation, it becomes imperative to reduce power dissipation, and improved device efficiency could even offset the power consumption required for cooling. For magnetic memories, we demonstrated how voltage-controlled magnetic anisotropy (VCMA) is a promising approach to minimize the write energy per bit, since as a purely voltage-driven effect it minimizes Joule heating losses while requiring very short switching pulses of 0.1-1 ns.

Magnetic random-access-memories show promising characteristics at low temperature, notably longer retention times, higher tunneling magneto-resistance (TMR) and improved endurance, making them good candidates for efficient cryoelectronics.

At 300 K, conventional VCMA reversal shows regions of switching alternating with non-switching regions corresponding to a return to the initial state, as shown in the figure. According to our simulation results at 4 K however, a deterministic switching voltage window appears between 0.6 V and 0.7 V, defining a critical switching voltage V_C that is independent of the pulse width. This is a major finding, since the VCMA reversal mechanism could not be implemented without relaxing the stringent constraints on pulse width variability.



Switching probability phase diagrams and energy landscape of VCMA reversal at low temperature with deterministic reversal.

The existence of this switching band can be understood from the possibility of the magnetization to follow an optimal reversal trajectory, where the applied voltage pulse reduces the perpendicular anisotropy, bringing the magnetization closer to the in-plane direction. As seen from the energy representation projected on the unit sphere, the precessional motion induced by the sudden change of anisotropy can be such that the precession motion is enough for the magnetization to cross the equatorial plane without having enough energy to cross back to the hemisphere where it departed from.

The reason why the reversal only exists at low temperature is related to the existence of an energy saddle point, where any thermal fluctuation creates a random final state. The switching band loses its deterministic nature for temperatures above 50 K with high-reliability deterministic switching only expected for sub-10 K operation.

By investigating the VCMA switching for low-energy systems at temperatures below 50K, we predict the existence of a deterministic switching regime that, coupled with lower switching energies, could be advantageous as a non-volatile memory technology. Possible device heating must still be assessed to evaluate local Joule heating, which could create instabilities in the optimized reversal process.

Team: MRAM

Collaboration: Institut Néel, Grenoble (France)

Funding: ANR Crymco (ANR-20-CE24-0009), PEPR quantique (PRESQUILE)

Further reading: *Engineering of Voltage Controlled Magnetic Anisotropy Magnetic Tunnel Junctions at Cryogenic Temperatures*, P. B. Veiga, R. C. Sousa, L. D. Buda-Prejbeanu, S. Auffret, I. Joumard, L. Vila, I. L. Prejbeanu, B. Dieny. IEEE Transactions on Magnetics, 59, 3401105, (2023).
Open access: hal-04205048

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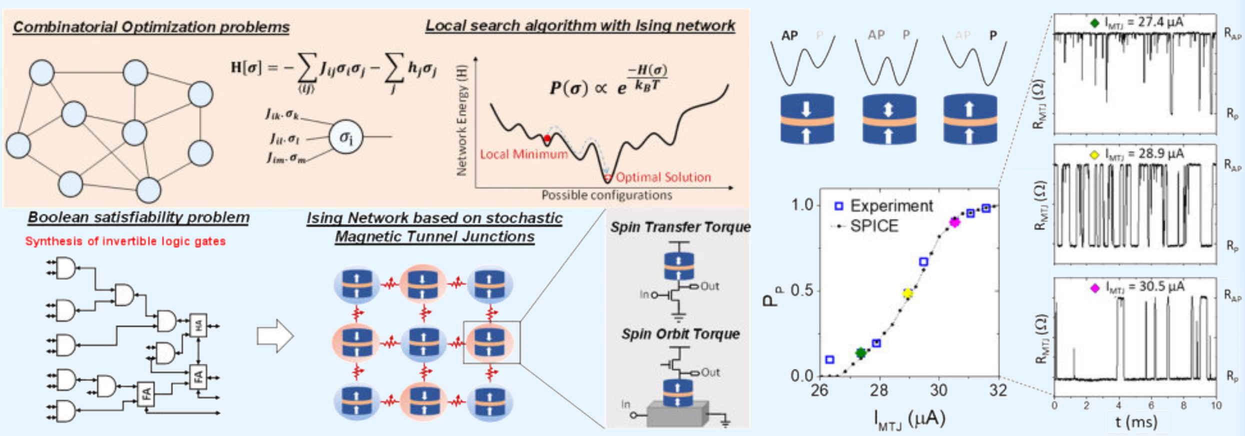
Resistively-coupled stochastic MTJ for energy-based optimum search

We studied recurrent networks of binary stochastic Magnetic Tunnel Junctions (sMTJ), aiming at efficiently solving computationally hard optimization problems. After validating a prototyping route, we investigated the impact of hybrid CMOS+MTJ building block variants on the quality of stochastic sampling, a key feature for optimum search in a complex landscape. We carried out a functional and power consumption analysis on asynchronous Ising networks for factorization task, supported by our SPICE model.

Discrete optimization problems are ubiquitous in modern society, spanning a wide range of fields such as logistics, finance, telecommunications, and manufacturing. However, as the search space increases exponentially with problem size, looking for optimal solutions can become extremely time and energy consuming, especially on conventional computing architectures. Originally describing the dynamics of ensembles of coupled spins, the Ising model has inspired some of the best performing optimization algorithms. Notably, this model relies on local updates and leveraging randomness to provide good quality solutions in a reduced time.

In this context, our approach is to emulate an Ising model with building blocks based on stochastic tunnel magnetic tunnel junctions (MTJ) spontaneously interacting through a resistive coupling network. To produce these stochastic computing units, we integrated MTJs onto CMOS wafers, and adjusted the MTJ stack to convert thermal noise into random fluctuations. In an Ising network, these fluctuations need to be biased by a decoupled input signal. Our study underscores the advantage of the Spin-Orbit Torque (SOT) writing mechanism on three-terminal MTJs for enhanced tunability. We carried out circuit-level simulations to demonstrate the successful factorization of an 8-bit semi-prime number by a network of 48 coupled stochastic units, gradually decreasing the randomness through the coupling resistances, and performing a power consumption analysis.

This study lays the groundwork for further optimization of stochastic building blocks and coupling components within scalable networks for an energy-efficient demonstration of a fully-integrated prototype.



Scope of this work is to apply the Ising model to solve efficiently the Boolean satisfiability problem. Boolean clauses are represented by interconnected logic gates, mapped to networks of resistively-coupled stochastic magnetic tunnel junctions. MTJs can be manipulated by spin-transfer torque (STT) or spin-orbit torque (SOT).

Teams: Spintronics IC Design, MRAM, Artificial Intelligence

Collaborations: CEA-LETI/LDMC, Grenoble (France)

Funding: RENATECH network, Carnot SIGMA project, France 2030 EMCOM (ANR-22-PEEL-0009), NSF-ANR grant StochNet (ANR-21-CE94-0002-01).

Further reading: *Designing networks of resistively-coupled stochastic Magnetic Tunnel Junctions for energy-based optimum search*, K. Garello K. Danouchi, L. Soumah, C. Bouchard, F. Disdier, A. Fassatoui N. T. Phan, M. Ezzadeen, B. Delaet, B. Viala, G. Prenat, L. Anghel, P. Talatchian, I. L. Prejbeanu, F. Andrieu, L. Hutin, contributed talk at IEDM conference (2023). Open access: hal-04359859

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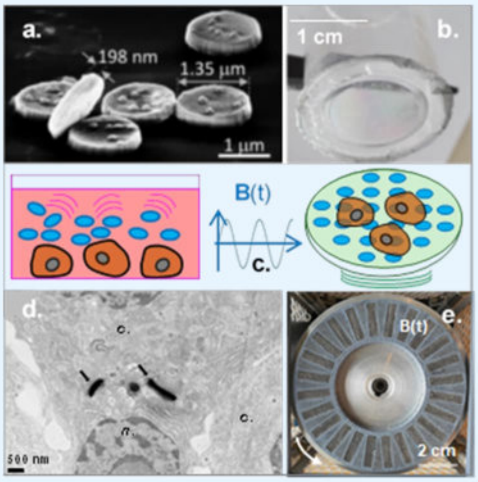
Vibrating magnetic microparticles to stimulate insulin secretion

In the context of intensive research on treatments against diabetes - major health threat to millions of people, we report here on an innovative approach based on mechanobiology. Chronic hyperglycemia is regulated by a supply of insulin, if insufficiently secreted. We show that the mechanical stimulation of pancreatic beta cells, via the vibration of magnetic microparticles - either dispersed among the cells or embedded in a polymer membrane -, can trigger the insulin secretion.

Firstly studied for the destruction of cancer cells (Kim et al, Nat. mat., 9, 2010; Leulmi et al, Nanoscale, 7, 2015), our magnetic particles (MPs) composed of gold-coated permalloy ($Ni_{80}Fe_{20}$) disks, in a vortex magnetic state, have been tested here for stimulating the insulin production function of pancreatic beta cells. Magnetically actuated by a rotating magnetic field of low frequency, their vibrations exerted mechanical forces on the beta cells (INS-1E β-islet pancreatic cells). The magnetic disks - Au/NiFe/Au - of 1.3 µm diameter, with NiFe thicknesses of 60 to 200 nm, were first used dispersed in the cell culture medium, deposited on the surface of the pancreatic cells, and submitted to the rotating magnetic field.



a. dispersed NiFe particles (SEM image) b. PDMS membrane with embedded array of MPs. c. sketches of pancreas cells stimulated by i) dispersed MPs, ii) MPs embedded in PDMS membrane. d. TEM image of INS-1E cells + MPs, internalized after an applied field B(t) of 40 Hz (SYMMES). f. Rotating magnetic field source: 24 NdFeB magnets in a circular rotating plate.

Here, the cell response to this mechanical stimulation shows an increase in the amount of produced insulin, versus the basal insulin secretion from unstimulated cells. The insulin secretion depends on the concentration of particles, frequency of the magnetic field and duration of the stimulation. A significant increase in insulin release is observed in particular for the largest particles concentration (50 $\mu g.mL^{-1}$) and field frequencies (20 to 40 Hz), with exposure times between 10 and 30 min. Interestingly, this magnetomechanical actuation potentially triggers the internalization of the particles into the cell cytoplasm, as observed by TEM (Transmission electron microscopy) imaging.

A second type of magnetic actuation was investigated, less invasive, consisting of a global mechanical stimulation of the pancreatic cells, grown on a flexible polymer magnetoelastic membrane. In this second approach, similar magnetic particles are embedded in a 5 µm thick PDMS (polydimethylsiloxane) membrane. The rotating magnetic field induces the membrane vibration, globally transmitted to the pancreatic cells. In this configuration, the insulin secretion is again significantly enhanced by the mechanical stimuli.

In both cases, the amount of secreted insulin can be comparable to an effective glucose response. We also controlled that this magnetomechanical treatment does not lead to the pancreatic cell death.

While some diabetes still require invasive treatments based on daily insulin subcutaneous injections, this mechanotransduction effect, remotely triggered, may open new doors towards diabetes treatments.

Team: Magnetic Biotechnologies

Collaboration: IRIG/SYMMES, Grenoble (France)

Funding: EU ABIOMATER (n°665440)

Further reading: *Magnetic particles for triggering insulin release in INS-1E cells subjected to a rotating magnetic field*, S. Ponomareva, H. Joisten, T. François, C. Naud, R. Morel, Y. Hou, T. Myers, I. Joumard, B. Dieny, M. Carriere, Nanoscale, 14, 13274 (2022). *Open access: hal-03841954*

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Philippe Sabon received the CNRS 2023 collective crystal for the Repotech project

Philippe Sabon is one of the recipients of the Crystal collective award from CNRS for the REPOTECH project. The medal was awarded at the ceremony for talents CNRS 2023 organized on December 12 by the CNRS Hauts-de-France Delegation.

Philippe Sabon, research engineer and head of the nanofabrication team at SPINTEC, and manager of the Technological Service team of the PTA / LTM-SPINTEC platform, is one of the recipients of the CNRS 2023 Collective Crystal for the Repotech project.

The collective crystal distinguishes teams of women and men, support staff in research, who have led projects with outstanding technical expertise, collective dimension, applications, innovation, and impact. This distinction is awarded in two categories: "direct support to research" and "research support."

The REPOTECH project aims to develop computer tools for the Renatech network, the French nanofabrication network of the CNRS. The first tool developed is used to manage and track technological projects that structure the scientific and technological activity of the network (from simple academic collaboration between two laboratories to ANR, European projects, subcontracting, expertise, etc.). Repotech contributes to building a comprehensive management solution for Renatech users, machines, samples, and projects.

REPOTECH management portal enables users to submit feasibility requests, projects and milestones to the RENATECH network power plants. The application enables the RENATECH network to manage : 2500 projects (more than 400 in 2023) and 3.700 users

Philippe Sabon has 25 years of experience in microelectronics and nanofabrication techniques. After two years at CEA/LETI as R&D engineer on the 100 mm manufacturing line, he joined Silmag in 1995, where he worked on the technology of read heads for hard drives. In 2001, he joined IRAM CNRS and developed millimeter-wave sensors for space applications. He joined SPINTEC in 2004 to develop the PTA nanofabrication platform. He has extensive expertise in all nanofabrication processes: lithography, deposition, etching, chemical bench, and characterization. Since joining SPINTEC, he has developed new magnetic and biological sensors. Philippe Sabon holds 8 patents on magnetic sensors and nanofabrication.

At the Talents CNRS 2023 medal ceremony organized on December 12 by the CNRS Hauts-de-France Delegation, the collective crystal medal was awarded to the REPOTECH team

<u>Teams</u>: Nanofabrication, PTA, Magnetic Sensors

<u>Collaboration</u>: RENATECH Network

<u>Funding</u>: RENATECH Network

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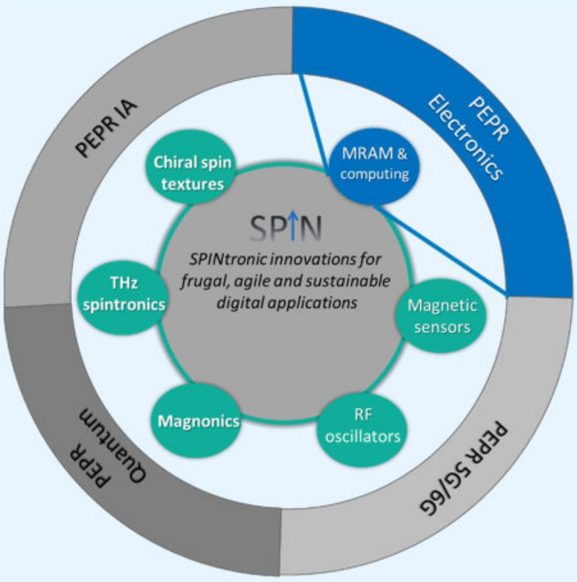
SPINTEC success in the France 2030 PEPR exploratory and acceleration programs

In the framework of France 2030 national strategy, SPINTEC is playing a key role in several PEPR: exploratory SPIN and acceleration Electronics, Quantum and AI, by proposing concepts, devices, materials and architectures for low power, agile and sustainable numerical solutions.

Within France 2030, a specific initiative is dedicated to funding the most fundamental research: the Priority Research Programs and Equipment (PEPR). These PEPRs aim to establish or strengthen French leadership in scientific areas related or likely to be related to technological, economic, societal, health, or environmental transformations, considered as priorities at the national or European level. Two types of PEPR) exist: Acceleration and Exploratory. The acceleration PEPRs are aligned with national acceleration strategies to support an ongoing transformation with well-identified products, services, uses, and stakeholders. Exploratory PEPRs aim to support a transformation that is just beginning to emerge, still in its early stages or even its infancy.

Among 20 selected exploratory PEPR, SPIN aims to stimulate the pioneering French spintronics community, which is of international renown, having made major and fundamental advances in this rapidly developing field. PEPR-SPIN aims to trigger a new generation of devices through emerging and promising topics. Spintronics has the ability to generate intellectual property while also stimulating an industrial revival in a large number of sectors with major societal impact. SPINTEC will have a key role in the project, by participating namely in the overall coordination of the program (Lucian Prejbeanu is program co-director together with Vincent Cros from CNRS-Thales lab), in the main targeted projects (beyond CMOS, THz spintronics, RF oscillators for IoT and artificial intelligence applications, smart sensing), in the transverse projects on materials, advanced instrumentation and theory.



SPINTEC participation in several PEPR programs: the exploratory PEPR SPIN, closely linked to acceleration PEPRs, as Electronics, IA and Quantum

The new spintronics memories enable innovative computing architectures, highly beneficial for artificial intelligence and embedded computing. A project focused on in-memory computing is at the core of the PEPR IA and Electronics. SPINTEC will play a key role in on different research areas: two targeted projects on innovative memory solutions for in-memory and bio-inspired computing and two transverse projects on 2D materials and design of circuits and systems. In addition, the investment at PTA will complete the spintronic academic pilot line, partially equipped through other recent EQUIPEX (NANOFUTUR) and CPER (SPINFAB) funding. Finally in the framework of PEPR Quantum, SPINTEC is partnering with Néel institute to develop spin/spintronics interfaces for efficient addressing and control of qubits.

Teams: all SPINTEC teams

Collaborations: PEPR SPIN, PEPR électronique (EMCOM, CHOOSE, BEP, ADICT), PEPR quantique (PRESQUILE), PEPR IA (Emergence)

Funding: France 2030

Further reading: *https://gouvernement.fr/france-2030-600-millions-d-euros-pour-13-nouveaux-programmes-de-recherche*

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1st prize at the HEC Challenge+ Forum for the spin-off Nellow

The start-up Nellow was awarded 1st prize at the HEC Challenge+ Forum, on November 22, 2023. This award is attributed to the best business plan, among the 15 startups taking part in HEC Challenge+.

Nellow is a soon-to-be created start-up developing and exploiting a technology resulting from 15 years of fundamental and applied research by two world-leading laboratories on microelectronics solutions: the SPINTEC laboratory (CEA Grenoble, Univ. Grenoble Alpes & CNRS), and the Laboratoire Albert Fert (ex-Unité Mixte de Physique, CNRS, Thales and Univ. Paris Saclay). It is developing a new technology aiming at drastically decreasing the energy consumption of microelectronics chips. With an expertise ranging from materials and nanodevices to integrated circuit design and advanced test, around 20 people are currently working on the development of this technology. Supported by the CEA valorization program Magellan, Nellow successfully passed the "Comité à l'essaimage" of CEA in November, and aims for a creation in2024.

Nellow benefited, together with 14 selected startups, from the HEC Challenge+ program, which helps developers of innovative projects with high growth potential build their business plan, and provides assistance throughout the development process.

The prize has been awarded by a jury of 20 personalities from the business and innovation community, and presided by François Pelen, cofounder of Point Vision.

Awards ceremony at HEC. From left to right, Etienne Krieger (HEC Challenge + Director), Nellow executives Manuel Bibes (CSO), Jean-Philippe Attané (CEO) and Laurent Vila (CTO), and the Jury President François Pelen (Point Vison cofounder).

Teams: Nellow / Topological Spintronics

Collaboration: Lab. Albert Fert, Palaiseau (France)

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2023 in images

PhD and HdR defences

SPINTEC research topics

SPIN ORBITRONICS

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

TOPOLOGICAL SPINTRONICS

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

2D SPINTRONICS

The team deals with spin-dependent phenomena in several important classes of materials: Si and Ge, which are the materials of today's microelectronics, and transition metal dichalcogenides and surfaces of topological insulators, which are emerging 2D materials with exceptional optical and spin-orbit properties. We are studying model systems grown by molecular beam epitaxy and their spin properties.

ANTIFERROMAGNETIC SPINTRONICS

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, 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 footprint, their ability to be controlled electrically, and their integrability with CMOS technology to design local oscillators, microwave filters, detectors, and non-reciprocal devices.

RF SPINTRONICS

The aim of this activity is to provide a fundamental understanding and control of the excitation, manipulation and detection of the linear, non-linear and complex magnetization dynamics in single and coupled magnetic nanostructures such as magnetic tunnel junctions. Potential applications lie within smart sensor networks and unconventional computing.

MAGNETIC SENSORS

The team explores and develops new concepts for magnetic sensors and covers the entire value chain, from fundamental studies to industry support. The team i) explores the effect of gate voltage on interfacial magnetic properties for new concepts of controllable sensors; ii) develops proofs of concept for ultra-low field sensors; and iii) valorizes its expertise by supporting industrial R&D. The research is essentially experimental, based on material expertise of active stacks and magnetic flux guides, on design and microfabrication of complex devices in clean-room and on magnetic (VSM, MOKE) and electric (magnetotransport and noise) characterization. In addition, micromagnetic simulations and analytical macrospin modeling are used both to deepen our understanding of experimental observations and to further optimize our devices.

MRAM

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

SPINTRONICS IC DESIGN

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

MAGNETIC BIOTECHNOLOGIES

The team's research deals with mechanobiology i.e. the study of the physiological reactions of living cells to mechanical stresses. These stresses are applied by dispersing anisotropic magnetic particles among the cells and actuating the particles by external varying magnetic fields. We already demonstrated that the magneto-mechanical stimulation of cancer cells can trigger their apoptosis (spontaneous death) or can produce insulin release from pancreatic cells. Further work is in progress on magnetically assisted neuroregeneration. Our team contributions consist in fabricating the engineered magnetic mesoparticles, providing the magnetic field sources adapted to the biology experiments and leading the collaborations with our biology and medical partners.

ARTIFICIAL INTELLIGENCE

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

THEORY / 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.

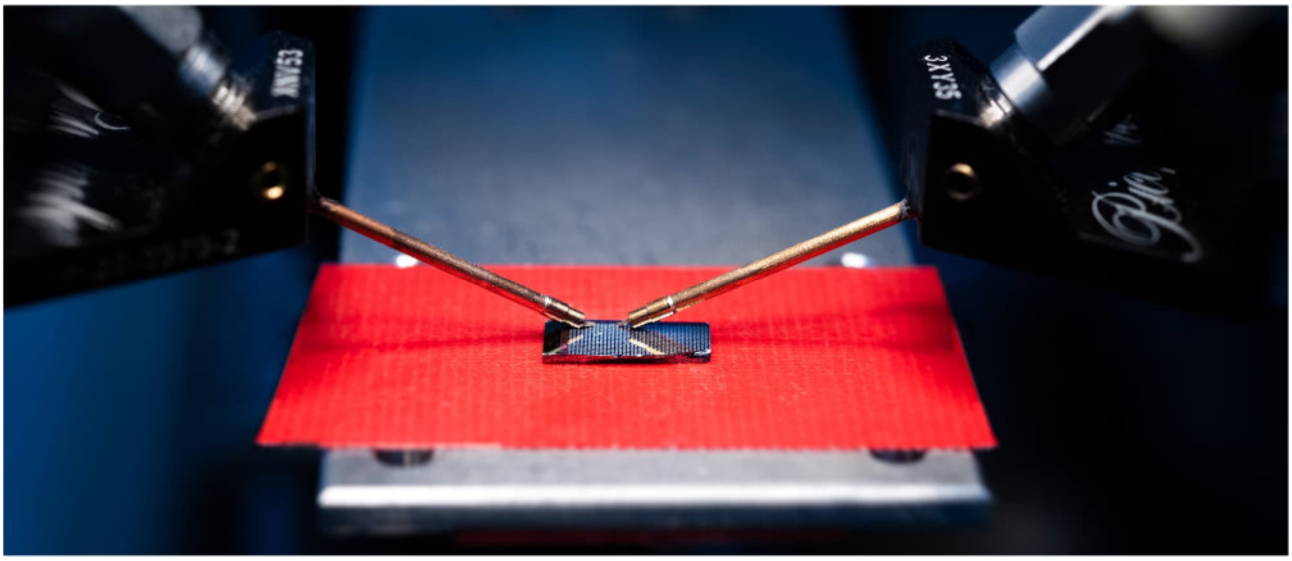
About SPINTEC

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 51 Permanent staff and more than 50 interns, 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's objective is to bridge fundamental research and innovative devices in the fast-growing field of spin electronics (spintronics). Indeed, the *international technology roadmap for semiconductors (ITRS)* now reckons that spintronics devices will play a major role in tomorrow's semiconductor chips, with high potential for fast and low-power stand-alone (e.g. DRAM) and embedded memories, magnetic field sensors, hardware components for artificial intelligence and bio-applications. In this context, SPINTEC brings together top-level scientists and applicative engineers who work in close collaboration, to ensure that discoveries at the forefront of research can be swiftly translated into technological proofs of concepts and functional devices. As such, the outcome of the laboratory is not only scientific publications and communications at international conferences, but also a coherent patents portfolio, implementation of relevant functional demonstrators, and partnerships for technology transfer. Our large scale provides the critical mass to master all required steps ranging from materials, nanofabrication, electrical and magnetic characterization, condensed-matter theory, simulation and the design of dedicated integrated circuits.

Whereas our fundamental research is mostly operated through collaborative grants with other research laboratories, applied research is often carried out in partnership with private actors. These can be large corporations (Applied Materials, Samsung, Seagate, INTEL), SME's (SNR, Singulus) or start-up companies spun-off from SPINTEC: *Crocus Technology* in 2006, *eVaderis* in 2014, *HProbe* in 2016, Antaïos in 2017, Golana Computing in 2023 and Nellow will be created in 2024.

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



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