Trends in MAGnetism 2023
Rome, Italy – 4-8 September, 2023

Book of Abstracts

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Trends in Magnetism is a multidisciplinary forum where to share the latest advancements in magnetism, with a particular focus on trending topics. TMAG 2023 is the third event in a series of international conferences initiated by the PetaSpin association, which started with TMAG 2020 held in Cefalù in 2021 (https://www.petaspin.com/tmag2020/) and TMAG 2022 in Venice (https://www.petaspin.com/tmag2022/).

The trending topics of TMAG 2023 will be related to "Spintronic devices including *multiphysics* based design" and "biomedical applications of magnetism" where we want to create a chance for the experts in those fields to meet and move the scientific community forward.

The conference program will include six perspective talks and two keynote speakers.

Scientific Program committee

Giovanni Finocchio, University of Messina, Italy
Paola Tiberto, INRiM – Torino, Italy
Giovanni Carlotti, University of Perugia, Italy
Mario Carpentieri, Politecnico di Bari, Italy
Massimo Chiappini, INGV – Roma, Italy
Marco Lanuzza, Università della Calabria, Italy
Alessandra Manzin, INRiM – Torino, Italy
Giulio Siracusano, University of Catania, Italy
Zheng Zhongming, Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences, China

Publication committee

Giulio Siracusano (co-chair), University of Catania, Italy
Davi Rodrigues (co-chair), Politecnico di Bari, Italy
Andrea Meo, Politecnico di Bari, Italy
Anna Giordano, University of Messina, Italy

Conference Chairs

Giovanni Finocchio
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Program at a glance

	Mon4	Tue5	Wed6	Thu7	Fri8	
8:00 - 9:00	**Registration**					8:00 - 9:00
9:00 - 9:30	**Opening**	*Hyunsoo Yang,* ***Invited***	*Han Xiufeng(P),* ***Invited***	*Johan Åkerman,* ***Invited***	*Bernard Dieny,* ***Invited***	9:00 - 9:30
9:30 - 10:00	*Salvador Pané i Vidal,* ***Invited***	*Bin Fang,* ***Invited***	*Mathias Kläui,* ***Invited***	*Kang Wang,* ***Invited***	*Bethanie Stadler,* ***Invited***	9:30 - 10:00
10:00 - 10:15	*Marek Przybylski, Oral*	*Andrea Meo, Oral*	*Williams Savero Torres, Oral*	*Victor Lopez Dominguez, Oral*	*Gaspare Varvaro,* ***Invited***	10:00 - 10:15
10:15 - 10:30	*Igor Rozhansky, Oral*	*Jae-Chun Jeon, Oral*	*Hiroki Hayashi, Oral*	*Kosuke Fujiwara, Oral*		10:15 - 10:30
10:30 - 11:00	*Andrea Migliorini, Oral* *Yves Acremann, Oral*	*Sanghoon Kim, Oral* *Alessandra Manzin, Oral*	*Ross Knapman, Oral* *Davi Röhe Rodrigues, Oral*	*Nikolai Khokhlov, Oral* *Zheng Zhenyi, Oral*	*Minori Goto, Oral* *Kausik Das, Oral*	10:30 - 11:00
11:00-11:30			***C O F F E E B R E A K***			11:00 - 11:30
11:30 - 13:00	*Peter Fischer (P),* ***Invited*** *Kai Liu,* ***Invited*** *Peter Rickhaus ,* ***Invited***	*Andrei Kirilyulk (P),* ***Invited*** *Katrin Schultheiß,* ***Invited*** *Lisa Herrera Diez,* ***Invited***	*Andrew Kent (P) ,* ***Invited*** *Gregory Fuchs,* ***Invited*** *Vito Puliafito ,* ***Invited***	*Jairo Sinova (P) ,****Invited*** *Olena Gomonay,* ***Invited*** *Yaroslav Tserkovnyak,* ***Invited***	*Gianluca Gubbiotti (P),* ***Invited*** *Stefano Bonetti,* ***Invited*** *Victorino Franco,* ***Invited***	11:30 - 13:00
13:00 - 13:30	***LUNCH BREAK (FREE)***		***LUNCH (SPONSORED)***	*Franca Albertini,* ***Invited***	***Closing and award cerimony***	13:00 - 13:30
13:30 - 14:30				***LUNCH BREAK (FREE)***		13:30 - 14:30
14:30 - 15:00			*Riccardo Tomasello,* ***Invited***			14:30 - 15:00
15:00 - 16:00	*Poster Session-A*	*Poster Session-B*	*Guoqiang Yu,* ***Invited*** *Mi-Young IM,* ***Invited***	*Andrei Slavin,* ***Invited*** *Pedram Khalili Amiri ,* ***Invited***		15:00 - 16:00
16:00 - 17:00			***Coliseum Tour*** ***Group A* 16:10*** ***Group B* 16:10*** ***Group C* 16:50*** ***Group D* 16:50*** ****Departure Time***	*Stuart Parkin (keynote),* ***Invited***		16:00 - 17:00
17:00 - 17:30	*Yoshichika Otani,* ***Invited***	*Caroline Ross,* ***Invited***		**Free Time**		17:00 - 18:00
17:30 - 18:00	*Jordi Sort,* ***Invited***	*Jingsheng Chen,* ***Invited***				
18:00 - 19:00	*Award contributions*	*Henri Jaffres (keynote),* ***Invited***		**Social Dinner**	**Walking tour (to reserve)**	18:00 - 19:00
19:00 - 20:30	**WELCOME RECEPTION**				**Dinner in Trastevere (to reserve)**	19:00 - 20:30
20:30 - 22:00						20:30 - 22:00

Notes:

The conference location will be in the heart of Rome, in Grand Hotel Palatino, Via Cavour 213 – ROME Grand Hotel Palatino

The conference Room is in SALA CESARINI in second floor - second level

The Coffee break is in the hotel bar (ground floor)

The Award Contributions, the Poster Session-A and B is inside SALA CESARINI

Social Dinner is in the Castelli Romani outside Rome, departure at 17:30 Transfer to Social Dinner Place by BUS Meeting point Htl Palatino

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Rome, Italy - 4-8 September, 2023

Program in detail

	Monday 4
8:00 - 9:00	Registration
9:00 - 9:30	Opening ***Giovanni Finocchio*** , co-Chiar, University of Messina, Italy ***Paola Tiberto*** , co-chair, INRiM (Istituto Nazionale di Ricerca Metrologica) Torino, Italy
	Session Chair: ***Vito Puliafito***
9:30 - 10:00	***Salvador Pané i Vidal*** , ETH Zurich, Switzerland - *"Magnetic Small-Scale Robots for Biomedical Applications"*
10:00 - 10:15	***Marek Przybylski,*** AGH University of Krakow, Poland - *"MgZn and CuZn Micro- and Nanoparticles for MRI Thermometry"*
10:15 - 10:30	***Igor Rozhansky*** , University of Manchester, United Kingdom - *"Spin-Light Coupling in Proximitized Dirac Materials"*
10:30 - 10:45	***Andrea Migliorini*** , Max Planck Institute for Microstructure Physics, Halle, Germany - *"Energetically efficient current-induced domain wall motion in interface-engineered racetracks"*
10:45 - 11:00	***Yves Acremann*** , ETH Zurich, Switzerland - *"Observing femtosecond spintronics by time and spin resolved photoelectron spectroscopy"*
11:00 - 11:30	***C O F F E E B R E A K***
	Session Chair: ***Riccardo Tomasello***
11:30 - 12:00	***Peter Fischer (P)*** , Lawrence Berkeley National Laboratory, Berkeley, USA - *"Exploring and harnessing new levels of complexity, frustration and chirality with 3d nanomagnetism"*
12:00 - 12:30	***Kai Liu,*** Georgetown University, USA - *"Magneto-ionics with alternative ionic species"*
12:30 - 13:00	***Peter Rickhaus,*** Qnami AG, Basel, Switzerland - *“Revealing magnetic textures in ferro- and antiferromagnetic memory devices using Scanning NV magnetometry”*
13:00 - 15:00	***LUNCH BREAK (FREE)***
15:00 - 17:00	**Poster Session-A (chairs: Anna Giordano - Andrei Kirilyulk - Liza Herrera Diez)**
	Session Chair: ***Hyunsoo Yang***
17:00 - 17:30	***Yoshichika Otani,*** University of Tokyo, ISSP, Japan - "*Octupole domain wall dynamics in novel chiral antiferromagnets Mn3X (X = Sn, Ge)*"
17:30 - 18:00	***Jordi Sort ,*** Autonomous University of Barcelona, Spain **-** *"Voltage-control of magnetism: fundamental mechanisms and prospective applications in low-power memory and artificial synapses* **"**
18:00 - 18:15	*Award contribution 1 -* ***Christian Rinaldi*** *,* Politecnico di Milano, Italy- *"The exploitation of ferroelectrically-controlled spin-to-charge current conversion towards ultralow power devices"*
18:15 - 18:30	*Award contribution 2 -* ***Jonathan Leliaert*** *,* Ghent University, Belgium - *"Advancing theranostic applications of magnetic nanoparticles through multicolor imaging"*
18:30 - 18:45	*Award contribution 3 -* ***Shun Okumura*** *,* The University of Tokyo, Tokyo, Japan- *"Instability of skyrmion strings induced by longitudinal spinpolarized currents"*
18:45 - 19:00	*Award contribution 4 -* ***Philippe Talatchian*** *,* SPINTEC, Grenoble, France- *"Coupling superparamagnetic tunnel junctions for stochastic unconventional computing"*
19:00 - 20:30	***WELCOME RECEPTION***

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Trends in MAGnetism 2023
Rome, Italy - 4-8 September, 2023

	Tuesday 5
	Session Chair: ***Pedram Khalili Amiri***
9:00 - 9:30	***Hyunsoo Yang,*** National University of Singapore, Singapore - *"Unconventional computing and energy harvesting using spin-devices"*
9:30 - 10:00	***Bin Fang,*** Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences, China - *"Highly sensitive spin-torque diode and its application in neuromorphic computing"*
10:00 - 10:15	***Andrea Meo*** , Politecnico di Bari, Italy - *"A micrometric accelerometer based on arrays of magnetic tunnel junctions"*
10:15 - 10:30	***Jae-Chun Jeon*** , Max Planck Institute for Microstructure Physics, Halle, Germany - *"Multicore memristor realized by high resolution electrical detection of mobile domain walls "*
10:30 - 10:45	***Sanghoon Kim,*** University of Ulsan, Korea- *" Bulk-Rashba Effect in Pt/Co/W Artificial Superlattices"*
10:45 - 11:00	***Alessandra Manzin,*** INRiM, Torino, Italy *"A novel 3D micromagnetic solver for simulating arrays of nanomagnets and nanodevices interacting in the space"*
11:00 - 11:30	***C O F F E E B R E A K***
	Session Chair: ***Kai Liu***
11:30 - 12:00	***Andrei Kirilyulk (P)*** , Radboud University, Nijmegen, The Netherlands - *"Ultrafast opto-magneto-electronics for non-dissipative information technology"*
12:00 - 12:30	***Katrin Schultheiß*** , Helmholtz-Zentrum Dresden-Rossendorf, Germany - *"Pattern recognition with nonlinear magnonic hardware"*
12:30 - 13:00	***Liza Herrera Diez,*** CNRS-Université Paris-Saclay, France - *"Magneto-ionics in CoFeB alloys"*
13:00 - 15:00	***LUNCH BREAK (FREE)***
15:00 - 17:00	**Poster Session-B (chairs: Guoqiang Yu - Alessandra Manzin - Gregory Fuchs)**
	Session Chair: ***Paola Tiberto***
17:00 - 17:30	***Caroline Ross ,*** Massachusetts Institute of Technology, USA - *"Designing magnetic garnets for spintronics and photonics "*
17:30 - 18:00	***Jingsheng Chen,*** National University of Singapore - Singapore - *"New strategy for spin logic device and efficient switching of antiferromagnet"*
18:00 - 18:45	***Henri Jaffres (keynote),*** Université Paris-Saclay, UMR CNRS-Thale, France - *"Orbitronics: orbit currents induced by charge/spin currents, FMR or light for torques or TeraHz emission"*

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Rome, Italy - 4-8 September, 2023

	Wednesday 6
	Session Chair: *Peter Fischer*
9:00 - 09:30	***Xiufeng Han(P),*** Chinese Academy of Sciences, China - *"From Spintronics to Magnonics"*
9:30 - 10:00	***Mathias Kläui****,* Johannes Gutenberg University Mainz, Germany - *"Skyrmions in Spin-Orbitronics and Orbitronics – novel science and applications in memory and non-conventional computing "*
10:00 - 10:15	***Williams Savero Torres*** , Université Grenoble Alpes / CEA / IRIG / SPINTEC, Grenoble, France - "*Room temperature spin-to-charge interconversion in ferroelectric Germanium Telluride nanodevices* "
10:15 - 10:30	***Hiroki Hayashi*** **,** Keio University, Japan - *"Observation of long-range orbital transport in ferromagnet"*
10:30 - 10:45	***Ross Knapman*** , University of Duisburg-Essen, Germany - *"Spacetime magnetic hopfions"*
10:45 - 11:00	***Davi Röhe Rodrigues*** , Politecnico di Bari, Italy - *"Single magnetic tunnel junction implementation of a bio-realistic firing neuron"*
11:00 - 11:30	***C O F F E E B R E A K***
	Session Chair: *Olena Gomonay*
11:30 - 12:00	***Andrew Kent (P)*** , New York University, USA - *"Spintronics with Ferrimagnetic and Antiferromagnetic Insulators"*
12:00 - 12:30	***Gregory Fuchs*** , Cornell University, USA - *"Imaging the switching of antiferromagnetic and multiferroic devices using a single spin microscope"*
12:30 - 13:00	***Vito Puliafito*** **,** Politecnico di Bari, Italy -"*Theory of simulated oscillator-based Ising Machine"*
13:00 - 14:30	***LUNCH (SPONSORED)***
	Session Chair: *Davi Röhe Rodrigues*
14:30 - 15:00	***Riccardo Tomasello,*** Politecnico di Bari, Italy - *"Generation of two distinct skyrmion types in magnetic heterostructures and voltage-induced switching from one type to another "*
15:00 - 15:30	***Guoqiang Yu,*** University of Chinese Academy of Sciences, Beijing, China - *"Research progress of magnetic skyrmions in thin film heterojunctions"*
15:30 - 16:00	***Mi-Young IM*** , Lawrence Berkeley National Laboratory, Berkeley, USA - *"Controlli"ng topological spin textures from generation to movement for advanced microelectronic application"*
16:00 - 18:45	***Coliseum Tour*** ***note: Group A* and B* 16:10 / Group C* and D* 16:50 (* Departure Time)***

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Trends in MAGnetism 2023
Rome, Italy - 4-8 September, 2023

	Thursday 7
	Session Chair: *Andrei Slavin*
9:00 - 9:30	***Johan Åkerman,*** University of Gothenburg, Sweden - "*Spin wave and spin Hall nano-oscillator based Ising Machines*"
9:30 - 10:00	***Kang Wang,*** University of California, Los Angeles, USA - *"Voltage control magnetism and their applications"*
10:00 - 10:15	***Victor Lopez Dominguez*** - Universitat Jaume I-*" Non-based charge computing by voltage-controlled skyrmionic magnon Switch "*
10:15 - 10:30	***Kosuke Fujiwara*** , The University of Tokyo, Japan - *"Nonlinear magnon spin currents induced by the electric field in noncentrosymmetric spin systems"*
10:30 - 10:45	***Nikolai Khokhlov*** , Radboud University, Nijmegen, Netherlands - *"Double pulse all-optical coherent control on magnetization reorientation in the presence of anomalous damping in antiferromagnets "*
10:45 - 11:00	***Zheng Zhenyi*** , National University of Singapore - *"Coexistence of magnon-induced and rashba-induced unidirectional magnetoresistance in antiferromagnet "*
11:00 - 11:30	***C O F F E E B R E A K***
	Session Chair: *Mario Carpentieri*
11:30 - 12:00	***Jairo Sinova (P) ,*** Johannes Gutenberg University Mainz, Germany - *"The emergent research landscape of altermagnetism: d-wave unconventional magnetism and its new connections"*
12:00 - 12:30	***Olena Gomonay,*** University of Mainz, Germany - *"Weak vs hidden magnetization: magnon dynamics in anti- and altermagnets"*
12:30 - 13:00	***Yaroslav Tserkovnyak ,*** University of California, Los Angeles, USA - *"From energy storage to neuromorphics based on topological spin textures"*
13:00 - 13:30	***Franca Albertini,*** IMEM-CNR, Parma, Italy - *"Magnetic shape memory Heuslers for energy and biomedical applications"*
	LUNCH BREAK (FREE)
	Session Chair: *Giovanni Finocchio*
15:00 - 15:30	***Andrei Slavin,*** Oakland University, Rochester, USA - *"Thermodynamic coherent amplifier of spin wave modes"*
15:30 - 16:00	***Pedram Khalili Amiri*** , Northwestern University, USA - "*Progress and perspectives on antiferromagnetic memory and computing devices* "
16:00 - 17:00	***Stuart Parkin (keynote),*** Max Planck Institute for Microstructure Physics, Halle, Germany - *"Chiral Spintronics"*
17:00 - 17:30	**Free Time**
17:30- 22:00	**Social Dinner**
	Social Dinner is in the Castelli Romani outside Rome, departure at 17:30 Transfer to Social Dinner Place by BUS Meeting Point Htl Palatino

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	Friday 8
	Session Chair: *Gianluca Gubbiotti*
9:00 - 09:30	***Bernard Dieny ,*** SPINTEC, Univ.Grenoble Alpes/CEA-INAC/CNRS, France **-** *"Towards innovative treatments of cancers and diabetes based on magneto-mechanical stimulation of cells"*
9:30 - 10:00	***Bethanie Stadler,*** University of Minnesota, USA **-** *"Predictable, engineered nanowarming using magnetic nanobars for restoring cryopreserved bio-specimens"*
10:00 - 10:30	***Gaspare Varvaro ,*** CNR-ISM, nM2-Lab, Roma, Italy - *"Synthetic antiferromagnets for biomedical and flexible spintronic applications"*
10:30 - 10:45	***Minori Goto*** , University of Fukui, Japan - *"Poly-Crystalline Silicon-inserted Vertical Spin Valve"*
10:45 - 11:00	***Kausik Das*** , Polish Academy of Sciences, Warszawa, Poland - *"Magnetic dynamical properties and ferromagnetic resonance in $Ga_{1-x}Mn_xN$ layers"*
11:00 - 11:30	***C O F F E E B R E A K***
	Session Chair: *Victor Lopez Dominguez*
11:30 - 12:00	***Gianluca Gubbiotti (P),*** CNR-IOM, Perugia, Italy **-** *"Exploring the third dimension in magnonics"*
12:00 - 12:30	***Stefano Bonetti,*** Ca' Foscari University of Venice, Italy - *"Terahertz electric field driven dynamical multiferroicity in SrTiO3"*
12:30 - 13:00	***Victorino Franco,*** University of Seville, Spain - *"Magnetocaloric effect: from materials to devices"*
13:00 - 13:30	***Closing and award cerimony***
18:00 - 19:00	**Walking tour (to reserve)**
19:00 - 22:00	**Dinner in Trastevere (to reserve)**

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Poster sessions

Poster Session-A , Monday 4, 15:00 - 17:00 SALA CESARINI	
Monday Sala **A** **POSITION POSTER**	**Presenting Author - Poster title**
MA1	***Anitha Kumari Rajeev Aarathy*** - University of Kerala, India - *"Physicochemical properties and AC magnetic field induced heating properties of solvothermally prepared thiospinel: Fe3S4 (greigite) nanoparticles "*
MA2	***Daniele Centanni -*** Università Parthenope di Napoli, Italy - *" Sustainable design of large aperture magnets for high energy physics and medical diagnostics "*
MA3	***Giulio Siracusano*** - University of Catania, Italy - *"Effective processing pipeline PACE 2.0 for enhancing chest x-ray contrast and diagnostic interpretability"*
MA4	***Jozef Kimák -*** Charles University, Prague, Czech Republic - *"Ultrafast inverse Cotton-Mouton effect in thin film of noncollinear antiferromagnet Mn3NiN "*
MA5	***Ryota Yambe*** - University of Tokyo, Japan - *"Symmetry analysis of light-induced magnetic interactions via Floquet engineering"*
MA6	***Aleksandr Buzdakov -*** I-FEVS, Turin, Italy - *"Phase diagrams for magnetic field and temperature induced ferromagnetism in antiferromagnetic FeRh "*
MA7	***Torstein Hegstad-*** Radboud University, The Netherlands - *"Identifying signatures of ultrafast skyrmion nucleation in reciprocal space"*
Monday Sala **B** **POSITION POSTER**	**Presenting Author - Poster title**
MB1	***Simone Laterza*** - University of Trieste, Italy - *"All-optical spin injection in silicon revealed by element-specific time-resolved Kerr effect"*
MB2	***Rein Liefferink,*** Radboud University, Nijmegen, The Netherlands - "*space-time dynamics of topological magnetic fluctuation states"*
MB3	***Mrudul Muraleedharan*** - Uppsala University, *Sweden* - *"Role of laser intensity and electron coherence in ultrafast demagnetization in FePt"*
MB4	***Bruno P. Alho*** -Universidade do Estado do Rio de Janeiro, Brazil - *"Study of magnetic and magnetocaloric effect on the high entropy alloy Gd0.2Tb0.2Dy0.2Ho0.2Er0.2Al2"*
MB5	***Stefano Lumetti*** -Silicon Austria Labs GmbH, Austria - *"Design of planar AMR sensor arrays for 3D magnet motion tracking"*
MB6	**Raffaele Silvani -** Università degli Studi di Perugia, Italy - *"Micromagnetic simulation of confined spin eigenmodes innanostructured magnetic films with different software packages"*
MB7	***Sergey Erokhin*** - General Numerics Research Lab, Jena, Germany- *"Atomistic and mesoscopic modeling of ferromagnetic/antiferromagnetic nanocomposite materials"*
MB8	***Marko Jesenik*** - University of Maribor, Slovenia - *"Hysteresis model based on a measured main hysteresis loop and first order reversal curves"*
MB9	***Perla Malagò*** - Silicon Austria Labs GmbH, Austria - *"Design and optimization of linear AMR sensor response"*
MB10	***Julien Mordret*** - Univ Rennes, CNRS, France - *"Constrained domain wall in atomic-sized constrictions between ferromagnetic nanostructures"*
Monday Sala **C** **POSITION POSTER**	**Presenting Author - Poster title**
MC1	***Paula Ribeiro*** - Universidade do Estado do Rio de Janeiro, Brazil - *"Spin reorientation transition in Dy1-xTbxAl2 compounds"*
MC2	***Matthias Riepp*** - Université de Strasbourg, CNRS, France - *"Structural and Magnetic Inhomogeneity in GdCo Studied by X-ray Resonant Magnetic Reflectivity"*
MC3	***Yan Li*** - King Abdullah University of Science and Technology, Saudi Arabia - *"Unconventional Spin Pumping and Magnetic Damping in an Insulating Compensated Ferrimagnet"*
MC4	***Mathieu Moalic*** - Adam Mickiewicz University,Poznan, Poland - *"Antidot lattice with perpendicular magnetic anisotropy: dynamics between edge modes and bulk modes"*
MC5	***Sanghoon Kim*** - University of Ulsan, Korea- *"Giant in-plane anisotropy of magnetic damping in epitaxial Cr/Fe bilayer"*
MC6	***Aitian Chen*** - King Abdullah University of Science and Technology, Thuwal, Saudi Arabia - *"Switching magnetic strip orientation using electric fields"*
MC7	***Markus Weißenhofer*** -Uppsala University Sweden - **"** *Exceptional temperature-dependence of Brownian dynamics of topological magnetic textures"*
MC8	***Dennis Wuhrer -*** University of Konstanz, Germany - *" Magnon squeezing in conical spin spirals "*
MC9	***Mahsa Seyed Heydari-*** University of Konstanz, Germany - *" Influence of disorder at Insulator-Metal interface on spin transport "*

Poster sessions

Poster Session-B, Tuesday 5, 15:00 - 17:00 SALA CESARINI

Tuesday Sala **A** **POSITION POSTER**	**Presenting Author - Poster title**
TA1	***Salima Labidi*** - Badji Mokhtar University, Annaba, Algeria - *"Structural, Electronic, magnetic and Thermal Properties of ZnO/Fe Wurtzite Phase - First-Principle Investigation"*
TA2	***Debarghya Dutta*** - University of Basel, Switzerland - *"Engineering spin textures and dynamics in magnetic van der Waals heterostructures"*
TA3	***Kotaro Shimizu -*** The University of Tokyo, Japan - "*Emergent electric field and magnetic resonance in a one-dimensional chiral magnet"*
TA4	***Esteban Garzón -*** University of Calabria, Rende, Italy -*"MRAM Based Associative Memory For In-Memory Computing"*
TA5	***Aijaz Lone*** - King Abdullah University of Science and Technology, Thuwal, Saudi Arabia -*" Multilayer Spintronic device as a synapse and neuron for neuromorphic computing"*
TA6	***Luciano Mazza*** - Politecnico di Bari, Italy - *"Binary neural networks realized with cascade MTJ vortices"*
TA7	***Eleonora Raimondo*** - University of Messina, Italy - *"Probabilistic Computing with magnetic tunnel junctions"*
TA8	***Dominique J. Kösters*** - Radboud University, The Netherlands - *"Benchmarking neuromorphic hardware for simulating quantum magnetism with machine learning "*

Tuesday Sala **B** **POSITION POSTER**	**Presenting Author - Poster title**
TB1	***Andrea Grimaldi*** - University of Messina, Italy - *"Coherent and probabilistic Ising machines with magnetic tunnel junctions"*
TB2	***Oliver Fridorf*** - Aarhus University, Denmark - *"Resistive-based temperature sensor based on spintronics devices"*
TB3	***Dimitris Kechrakos*** - School of Pedagogical and Technological Education, Athens, Greece - *"Mechanism of spin-orbit torque switching of magnetization inCo1-xTbx multilayers with vertical composition gradient"*
TB4	***Elena Semenova*** - General Numerics Research Lab, Jena, Germany - *"Phase diagrams of precession regimes in spin-torque diodes for energy harvesting"*
TB5	***Satoshi Haku*** - Keio University, Yokohama, Japan - *"Drastic reduction of spin-orbit torque by inserting NiO thin film"*
TB6	***Hiroyuki Moriya*** - Keio University, Yokohama, Japan - *"Spin Hall effect in the insulating regime"*
TB7	***Nozomi Soya*** - Keio University, Yokohama, Japan - *"Temperature dependence of spin-orbit torque in Ni81Fe19/AlOx/SrTiO3 heterostructure "*
TB8	***Mari Taniguchi*** - Keio University, Yokohama, Japan - *"Nonlocal orbital torques in magnetic multilayers"*
TB9	***Dongxing Zheng*** - King Abdullah University of Science and Technology, Thuwal,Saudi Arabia - *" Magnon-mediated magnetization switching in all oxide heterostructures"*
TB10	***Federica Celegato -*** Istituto Nazionale di Ricerca Metrologica (INRIM), Torino, Italy - *"Electric field control of magnetization reversal in FeGa/PMN-PT"*

Tuesday Sala **C** **POSITION POSTER**	**Presenting Author - Poster title**
TC1	***Emily Darwin -*** Empa, Switzerland - *"Antiferromagnetic interlayer exchange coupled Co68B32/Ir/Pt multilayers"*
TC3	***Mateusz Gołębiewski -*** Adam Mickiewicz University, Poznań, Poland - *"Magnonic properties of 3D Nickel Gyroid Networks"*
TC4	***Eunji Lim*** - University of Ulsan, Korea - *"Growth mechanism of the spin current source forming the interface with the L10 FePt layer"*
TC5	***Oksana Koplak -*** Politecnico di Milano, Italy - *"Design and functional properties of SmCo films for MEMS devices"*
TC6	***Andriani Vervelaki*** - University of Basel, Switzerland- *"Revealing the spin texture of the 2D vdW Cr2Ge2Te6"*
TC7	***Kousik Bagani*** - University of Basel Switzerland - *"Layer dependent magnetization in 2D vdW Cr2Ge2Te6"*
TC8	***Piotr Józef Bardziński -*** University of Wrocław, Wrocław, Poland -*"BMagnetic anisotropy alteration by shock-compression of single grain flux-grown icosahedral AlCuFe quasicrystal"*
TC9	***Mahieddine Lahoubi -*** University of Badji Mokhtar Annaba, Algeria - *"Magnetic field-induced phase transition and weak ferromagnetism in nonsuperconducting optimally doped PrBCO cuprate"*
TC10	***Daria V. Kuntu*** - Ioffe Institute, St. Petersburg, Russia - *"Ultrafast laser-induced spin dynamics in van der Waals 2D antiferromagnets NiPS3 and FePS3"*

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Magnetic Small-Scale Robots for Biomedical Applications

Salvador Panè Vidal

Swiss Federal Institute of Technology _ETH Zurich Switzerland

The use of robots is becoming increasingly prevalent in our world, with examples ranging from robotic surgical systems to flying drones and autonomous planetary rovers. A new type of robotic system that are gaining popularity are untethered magnetic micro- and nanorobots. These miniaturized devices can move through fluids using external magnetic fields, and have the potential to deliver drugs and perform other medical tasks within the confined spaces of the human body. Other applications include water remediation and “on-the-fly” chemistry.

The recent advancements in magnetic small-scale robotics can be largely attributed to progress in material science and manufacturing. While numerous applications have been demonstrated, there are still several areas that require further research, including complex locomotion, multifunctionality, biocompatibility, and biodegradability. As a result, new material-based concepts and innovative fabrication techniques are urgently needed to address these challenges and improve the field of small-scale robotics. This discussion will explore various material-based concepts and innovative fabrication techniques aimed at overcoming translational hurdles and further enhancing the capabilities of small-scale robotics.

MgZn and CuZn Micro- and Nanoparticles for MRI Thermometry

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We carried out comprehensive structural, magnetic and toxicity studies of MgZn and CuZn ferrites that can be used as contrast agents for Magnetic Resonance Imaging (MI) thermometry. Large, micrometer size, particles were prepared by ceramic technique. Ultra-small, polymer-coated nanoparticles were synthesized using a one-step thermal decomposition method [1]. SQUID magnetometry measurements were cross-correlated with XRD results and compared with magnetic properties determined by Mössbauer spectroscopy, allowing us to understand the magnetic structure of studied ferrites. The temperature dependent magnetic measurements were used as guidance to select the most suitable MgZn and CuZn ferrites compositions for MRI thermometry near human body temperature. The inflammation studies indicate that MgZn ferrites are more suitable from the toxicology point of view for MRI thermometry [2].

We evaluated the advantages and disadvantages of using ferrite particles embedded in agar gel phantoms as MRI temperature indicators for low-magnetic field scanners. The advantages of high-field MRI, like higher sensitivity and, consequently, higher spatial resolution are well known. However, the more open designs for the low-field scanners are better suited for MRI-guided interventional procedures and reduces claustrophobic issues for patients. Thus, low-field scanners possess qualities that are beneficial for medical imaging. We compare the temperature-dependent intensity of MR images at low-field (0.2 T) to those at high-field (3.0 T). Due to a shorter T1 relaxation time at low-fields, MRI scanners operating at 0.2 T can use shorter repetition times and achieve a significant T2* weighting, resulting in strong temperature-dependent changes of MR image brightness in short acquisition times. In addition to the advantages listed above, we discovered a surprising benefit when using low-field scanners. The percentage changes of the temperature-dependent image intensities are larger for low-field scanners compared to high-field scanners. As a consequence, there are two potential advantages of conducting MRI thermometry at 0.2 T compared to 3.0 T. First, the temperature measurement itself can be more accurate, and second, the acquisition time can be shorter [3].

For biomedical applications, ferrites in a form of nanoparticles coated with a polymer layer are more suitable for clinical settings. CuZn ferrite nanoparticles coated with a poly(ethylene glycol) (PEG) layer were synthesized. The resulting nanoparticles are stable in water and biocompatible. Embedding these particles into an agarose gel results in significant modification of water proton relaxation times T1, T2, and T2* determined by nuclear magnetic resonance measurements. The results of the spin-echo T2-weighted MR images of an aqueous phantom with embedded CuZn ferrite nanoparticles in the presence of a strong temperature gradient show a strong correlation between the temperature and the image intensity [1].

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Spin-Light Coupling in Proximitized Dirac Materials

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The atomically thin nature of two-dimensional (2D) van der Waals materials makes them highly susceptible to the influence of their neighbors, thereby enabling the design of their electronic band structure by proximity phenomena. We reveal a remarkable terahertz (THz) spin-light interaction in 2D Dirac materials that arises from proximity effects of magnetic and spin-orbital character. We demonstrate theoretically that the electric dipole spin resonance (EDSR) of Dirac electrons displays distinctive features in the THz range, upon emerging spin-pseudospin proximity terms in the Hamiltonian. To capture the effect of fast pseudospin dynamics on the electron spin, we develop a mean-field theory and complement it with a quantum-mechanical treatment

As a specific example, we investigate the THz response of a single graphene layer proximitized by a magnetic substrate, using realistic parameters. Our analysis demonstrates a strong enhancement of the THz-light absorption with the increase of the spin-pseudospin coupling, pointing towards promising prospects for THz detection and efficient generation and control of spins in spin-based quantum devices.

The derived features of THz spin-light coupling suggest that EDSR could be a powerful experimental probe in the studies of proximitized layers and to elucidate spin-dependent phenomena. The EDSR framework allows one to quantify proximity induced spin splitting and gives a direct access to spin-relaxation mechanisms. The derived description of coupled spin-pseudospin dynamics could be implemented in graphene quantum dots and nanoflakes, the basic elements realizing qubits for quantum computing in THz range. While spin-orbit interaction has been used to realize fast qubit rotations and control using electric field, EDSR has not been exploited in graphene or bilayer graphene due to the low intrinsic SOC. The spin-to-charge conversion at the graphene-ferromagnet interfaces promotes the concept of optospintronics in THz range, with potential developments in graphene THz detection.

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Energetically efficient current-induced domain wall motion in interface-engineered racetracks

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Current-induced domain wall motion in nanoscopic magnetic racetrack devices [1] could facilitate the development of ultra-fast and energy-efficient memory and logic technology. In racetracks, the efficiency of domain-wall-shift is determined by the threshold current density, the domain wall mobility and the maximum domain wall speed. These properties result from the complex interfacial interactions which arise in ferromagnetic (FM) and synthetic antiferromagnetic (SAF) multilayers [2,3]. Therefore, investigating the role of the interfaces in multi-layered films, and engineering their properties, is of paramount importance to reduce the energy consumption in domain-wall-based devices.

Here we show that sophisticated interface engineering can be used to dramatically improve the efficiency of the films for state-of-the-art domain-wall-based applications (see figure 1). Firstly, we introduce engineered spin Hall layers to boost the spin-orbit torque in ferromagnetic multilayers and consequently reduce the threshold current density to operate the racetracks. Our devices perform up to three times more efficiently than racetracks with conventional spin Hall layer (e.g. Pt). Secondly, we engineer synthetic antiferromagnetic multilayers to improve the exchange coupling strength, which consequently allows to reach higher domain wall speed and mobility. We evaluate the potential performance of a nanoscopic (100-nm-size), single-domain-wall memory device from engineered FM and SAF films. We found relevant improvements in both the writing energy and latency, potentially leading to sub-10-fJ and sub-1-ns writing operations, which would outperform conventional memory technologies [4].

Our work clearly demonstrates that careful interface engineering can drastically boost the efficiency of current-induced domain wall motion, which is of significant importance for lowering the energy consumption and allowing fast operation in domain-wall-based memory and logic technology.

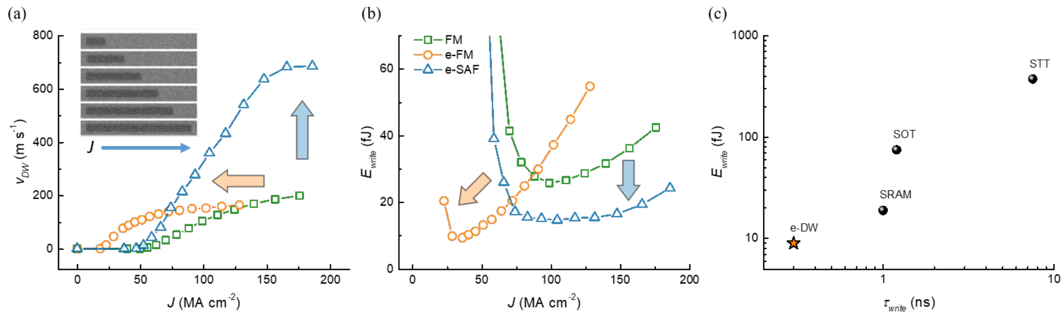

Figure 1: The impact of interface engineering on (a) current-induced domain wall motion and (b) estimated writing energy for nanoscopic domain-wall devices. Inset in (a) shows differential Kerr images of domain wall motion in microscopic racetracks. (c) Comparison with conventional memory technologies in terms of expected writing energy and latency [4].

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Observing femtosecond spintronics by time and spin resolved photoelectron spectroscopy

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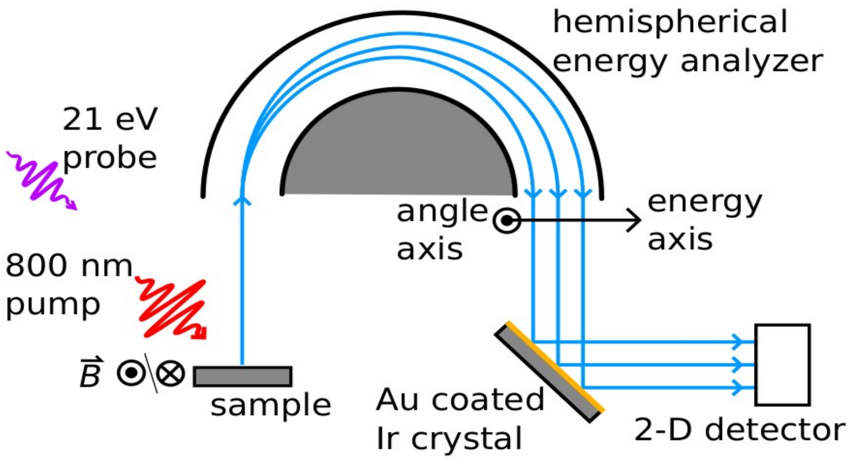
The generation of spin current pulses by laser-driven demagnetization links the field of ultrafast magnetism to spintronics. This spin transport and its cause is difficult to directly observe. We demonstrate that femtosecond spin injection can be detected on the femtosecond time scale by spin and time resolved photoemission experiments.

We study thin, epitaxial iron films which are excited by a 800 nm pump laser beam. Photoemission by a higher harmonic generation source (photon energy: 21 eV) in combination with an electron spin polarimeter is used to measure the chemical potentials of the minority- and majority electrons. This way, we observe the spin voltage [1], which acts as the driving force for the spin current.

If we deposit a thin gold film onto the iron sample and excite the iron film through the transparent substrate, we can study spin injection and accumulation. The dynamics of the spin polarization in the gold film [2] can be described by a “spin capacitance”, which is similar to the capacitance in charge-based electronics.

An outlook into future opportunities provided by momentum microscopes at free electron lasers will be given. These instruments allow for time, spin and angel-resolved photoelectron spectroscopy. The high transmission thereby mitigates the limitations imposed by space charge.



Experimental setup for femtosecond spin-resolved photoelectron spectroscopy [3]: The sample is probed by radiation from a high harmonic generation source. The photoelectrons are detected by an imaging SPLEED spin detector at the output of a hemispherical energy analyzer.

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Exploring and harnessing new levels of complexity, frustration and chirality with 3d nanomagnetism

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The scientific and technological exploration of three-dimensional magnetic nanostructures is an emerging research field that opens the path to exciting novel physical phenomena, originating from the increased complexity in spin textures, topology, and frustration in three dimensions[1-3]. The concept of chirality which requires three dimensions, is essential to understand e.g., fundamental interactions in cosmology and particle physics, the evolution of life in biology, or molecular chemistry, but has recently also attracted enormous interest in the magnetism community. Tailored three-dimensional nanomagnetic structures are expected to open a tremendous potential for novel applications in magnetic sensor and information processing technologies in terms of improved energy efficiency, processing speed, functionalities, and miniaturization of future spintronic devices. These three-dimensional structures are distinct from traditional bulk systems, as they harness the scientific achievements of nanomagnetism, which aimed at lowering the dimensions down to the atomic scale, but expand those now in a bespoke way into the third dimension.

Another approach to explore and harness the full three-dimensional space is to usecurvature as a design parameter [4-5]. The interactions between two neighboring spins on a curved surface can be vastly different to those on a flat surface, as e.g., the symmetric exchange interaction favoring parallel/antiparallel alignment is no longer parallel at a curved surface. The local curvature impacts physical properties across multiple length scales, ranging from the macroscopic scale, where the shape and size vary drastically with the curvature, to the nanoscale at interfaces and inhomogeneities in materials with structural, chemical, electronic, and magnetic short-range order. In quantum materials, where correlations, entanglement, and topology dominate, the local curvature opens the path to novel characteristics and phenomena that have recently emerged and could have a dramatic impact on future fundamental and applied studies of materials. Particularly, magnetic systems hosting non-collinear and topological states and 3D magnetic nanostructures strongly benefit from treating curvature as a new design parameter to explore prospective applications in the magnetic field and stress sensing, micro-robotics, and information processing and storage.

The exploration of 3d nanomagnetism requires significant advances in modelling and theory, synthesis and fabrication, and state-of-the-art nanoscale characterization techniques to understand, realize and control the properties, behavior, and functionalities of these three-dimensional magnetic nanostructures. I will present an overview of current research in this area, and will present a perspective into future opportunities where curiosity-driven and use-inspired research will enable novel applications in spintronics.

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Magneto-ionics with alternative ionic species

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Magneto-ionic (MI) effects have shown promise for energy-efficient nanoelectronics, where ionic migration can be used to achieve atomic scale control of interfaces in magnetic nanostructures, and in turn modulate a wide variety of functionalities. To date, magneto-ionics have been mostly explored in oxygen-based systems, while there is a surge of interest in alternative ionic systems [1]. We have recently demonstrated effective MI control using a variety of ions. In hydrogen based systems, we have found a sensitive and reversible chirality switching of magnetic domain walls [2] and writing/deleting of skyrmions [3] via hydrogen chemisorption/desorption. In hydroxide based α-$Co(OH)_2$ films, a reversible paramagnetic to ferromagnetic transition is observed after electrolyte gating with a low turn-on voltage [4]. In nitride based Ta/CoFe/MnN/Ta films, chemically induced MI effect is combined with the electric field driving of nitrogen to effectively manipulate exchange bias (Figs. 1a-1b) [5]. These effects offer an ideal platform to gain quantitative understanding of magneto-ionics at buried interfaces, leading to electric modulation of magnetic functionalities. They are also relevant for 3-dimensional information storage as a potentially contactless way to address spin textures, such as in interconnected magnetic nanowire networks (Fig. 1c) [6].

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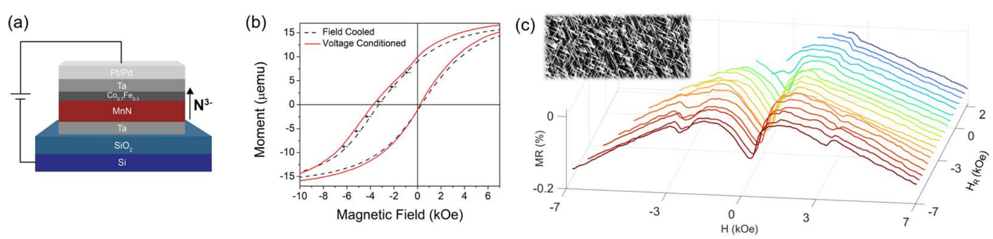

Figure 1: (a) Schematic illustration and (b) the corresponding exchange bias effect that is electrically enhanced in a Ta (10 nm)/MnN (30 nm)/CoFe (1 nm)/Ta (10 nm)/Pd (10 nm) thin film sample at 10 K. (c) First-order reversal curve measurements of magnetoresistance of interconnected Co nanowire networks (inset).

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Revealing magnetic textures in ferro- and antiferromagnetic memory devices using Scanning NV magnetometry

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For the vast majority of spintronic memory devices, information is stored in binary states. The “0” and “1” states are distinguished by a different magnetization direction of the free layer in STT-MRAM (Spin Transfer Torque Magnetic Random Access Memory) devices. For antiferromagnetic devices, bits can be defined by their antiferromagnetic domain structure or by single domains. Despite the large gap in maturity of the two technologies, reliable device operation requires knowledge of the microscopic magnetic texture in both cases.

Here, we will show an analysis of ferro- and antiferromagnetic bit states using Scanning NV magnetometry (SNVM). The technique is able to detect unsaturated spins in antiferromagnets and small magnetic inhomogeneities in STT-MRAM devices. We analyze industrial-scale STT-MRAM arrays using SNVM and reveal previously hidden obstacles. We will apply this knowledge to a specific type of antiferromagnetic memory devices. By analyzing the two types of memories with the same technique, we can contrast their benefits and challenges.

Octupole domain wall dynamics in novel chiral antiferromagnets Mn_3X (X = Sn, Ge)

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AFMs possess inherent advantages such as terahertz spin dynamics and low stray fields, making them attractive for domain-wall applications. However, their magneto-electric responses have made it challenging to work with them. Recent studies on noncollinear chiral AFMs Mn_3X (X = Sn, Ge) have allowed us to detect and manipulate their magnetic octupole domain states. In this study, we have demonstrated that Mn3X can have a fast magnetic octupole domain wall (MODW) motion when driven by an electric current. We have observed that Mn_3Ge's Néel-like MODW can be accelerated up to 750 m s^{-1} with a current density of only 7.56×1010 A m^{-2}, even without an external magnetic field (Fig. 1). The MODWs show high mobility with a low critical current density. Our theory proposes that the MODW motion in noncollinear AFMs is a result of spin-transfer torque generated by the current-induced nonequilibrium spin accumulation. These findings open up new possibilities for developing antiferromagnetic domain-wall-based applications.

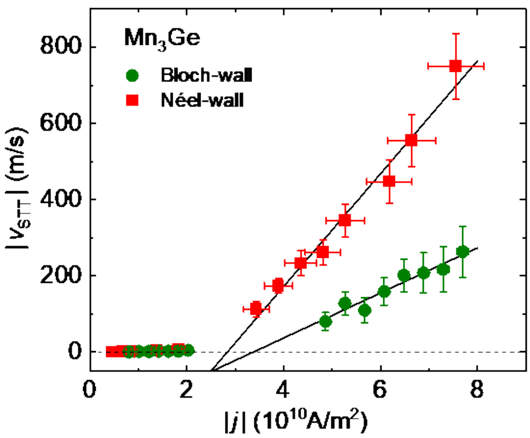

Figure 1: Bloch- and Néel- like MODW speeds |v_{STT}| as a function of the injected current in |j| in Mn_3Ge.

Voltage-control of magnetism: fundamental mechanisms and prospective applications in low-power memory and artificial synapses

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Manipulating magnetism with voltage has an enormous potential to boost energy efficiency in nanoscale devices since the use of electric field (instead of magnetic fields or electric currents) minimizes Joule heating effects and the associated power dissipation. In my talk, I will first overview the main existing mechanisms to control magnetism with voltage and I will then present some recent results obtained in our group.

During the last few years, we have demonstrated the possibility to induce reversible, non-volatile changes in the magnetic properties (e.g., coercivity) of nanoporous films consisting of metal alloys (*e.g.*, CuNi, FeCu) or oxides (e.g., FeO_x, $CoFe_2O_4$), by applying an electric field through a liquid electrolyte gate at room temperature [1]. In addition, we have made significant progress in the field of magneto-ionics (i.e., voltage-driven ion transport in magnetic materials), which has traditionally relied on controlled migration of oxygen or lithium ions. Here, I will show that voltage-driven transport of nitrogen ions can be also triggered at room temperature in transition metal nitride (CoN, FeN, CoFeN) films via liquid electrolyte gating [2]. Nitrogen magneto-ionics can induce reversible ON-OFF transitions of ferromagnetic states at faster rates and lower threshold voltages than oxygen magneto-ionics. This is due to the lower activation energy needed for ion diffusion and the lower electronegativity of nitrogen with cobalt, compared with oxygen. Remarkably, and in contrast to oxygen magneto-ionics, nitrogen transport occurs uniformly through a plane-wave-like migration front, without the assistance of diffusion channels, which is particularly interesting for the implementation of multi-stack memory devices. Furthermore, we will show that both oxygen and nitrogen magneto-ionics can be used to emulate some important neuromorphic/synaptic functionalities (spike amplitude-dependent plasticity, spike duration-dependent plasticity, long-term potentiation/depression). By cumulative effects of DC and pulsed voltage actuation (at frequencies in the range 1 – 100 Hz), learning, memory retention, forgetting and self-learning by maturity (post-stimulated learning) can be mimicked [3]. The latter can serve as a logical function for the device to decide between self-learning or forgetting emulation, at will, post-voltage input. This constitutes a novel approach to emulate some specific neural functionalities (*e.g.*, learning under deep sleep), that are challenging to achieve using other classes materials currently employed for neuromorphic computing applications.

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The exploitation of ferroelectrically-controlled spin-to-charge current conversion towards ultralow power devices

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Information and communication technology is reaching 20% of global electricity production in a few years. Architectures far beyond the well-established CMOS platform are required for electronics to switch greener. A remarkable pathway was suggested by Intel in the work titled "Beyond CMOS computing with spin and polarization" [1]. New-generation computing devices require non-volatility to preserve their functionality without memory refresh and this is conveniently implemented by either ferromagnetism or ferroelectricity. Furthermore, the information processing of such devices must conveniently scale with the geometrical dimension so as to allow for increased efficiency at high packing densities. A viable path in this respect is the exploitation of spin-to-charge current conversion mechanisms such as inverse spin Hall [2] or inverse Rashba-Edelstein effects [3], in which a spin current or accumulation is translated into either a charge current or a voltage.

Ferroelectric Rashba semiconductors (FERSC) such as germanium telluride (GeTe) offer an intrinsic link of ferroelectricity and Rashba-type spin-orbit coupling [4, 5]. As a major consequence, the ferroelectric polarization of epitaxial thin films of GeTe can be reliably switched back and forth by electrical gating and used to reverse the sizeable spin-to-charge conversion by the spin Hall effect [6].

Here we discuss the doping and alloying of germanium telluride as a perspective to achieve control over ferroelectricity, conductivity, electronic band structure and spin-to-charge current conversion. We will show the advancement in the development of scalable and energy-efficient non-volatile ferroelectric spin-orbit logic devices, in which information is conveniently stored in the ferroelectric state, while processing and read-out are enabled by polarization-dependent spin-to-charge current conversion.

GeTe and its alloys may represent a viable path towards spintronic-based transistors with ultralow power consumption, possibly facilitated by the monolithic integrability with silicon.

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Advancing theranostic applications of magnetic nanoparticles through multicolor imaging

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Magnetic nanoparticles (MNP) are already widely employed in diagnostic and therapeutic applications in biomedicine. For example, in magnetic hyperthermia the particles are used as heat sources to increase the temperature of the surrounding tissue in order to damage tumor cells. An imaging tool that is capable of reconstructing the spatial distribution of multiple MNP types simultaneously would allow to combine diagnosis and therapy into one theranostic platform, fully based on MNP. Moreover, the same platform could be used during therapy to monitor its progress, allowing for dynamic control.

As a specific example of how such a theranostic platform could function, we present an implementation using the promising MNP imaging technique magneto-relaxometry (MRX) imaging. All information about the MNP types, tissue viscosity, tissue temperature and particle interactions is encoded in the MRX relaxation curves. In a first step we successfully employed MRX imaging to distinguish between various particle types and to allow their simultaneous imaging [1]. Secondly[2], a magnetic characterization technique is presented in which the particles are excited by specific pulsed time-varying magnetic fields. This way, we can selectively excite different nanoparticles so that the resulting measurement contains information on their spatial distribution without the need for any a priori assumptions or complex postprocessing procedures to decompose the measurement signal, which contrasts earlier methods.

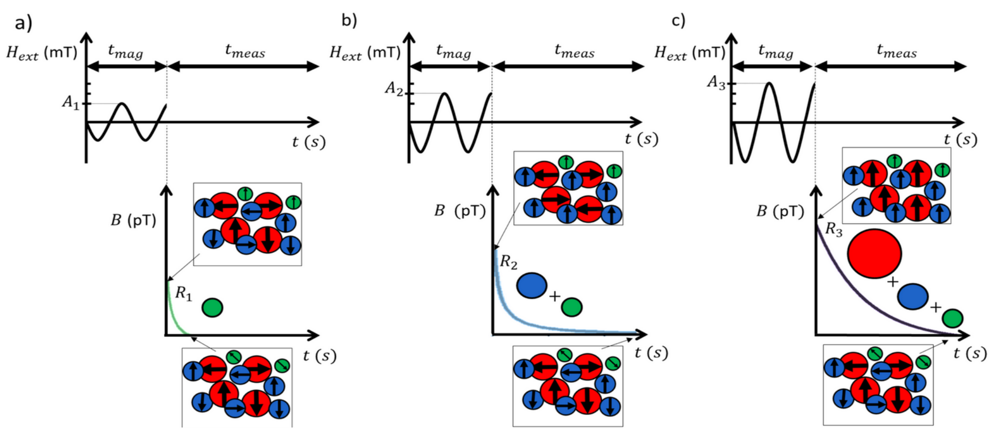

Figure 1: Overview of how the amplitude of an externally applied alternating magnetic field determines how particles with a) a small coercivity b) small and medium, and c) small, medium and large coercivity are aligned with the external field direction. In a second step, their magnetic relaxation is measured, allowing to individually reconstruct the spatial distributions of the different particle types.

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The non-Hermitian skin effect in magnetic systems

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The non-Hermitian skin effect, in which eigenstates exhibit localized behaviors drastically different from the extended Bloch waves of Hermitian systems, is among the most scrutinized dissipative phenomena. The localization of the eigenstates at a system's edge hints at non-reciprocal transport towards the latter. However, non-Hermitian Hamiltonians are obtained as an approximation that might wash out critical information on the timescales and conditions required for the non-reciprocal accumulation of bulk modes to take place. Using a symmetry-based approach, we derive a master equation that reduces, in the mean-field limit, to the non-Hermitian Hamiltonian under investigation and investigate the spin-wave dynamics. Our analysis uncovers the limitation of non-Hermitian approaches and clarifies the origin of the skin effect and the ensuing non-reciprocity in magnetic systems. Our results highlight the connection between the non-Hermitian skin effect and the classical magnetization dynamics, suggesting that our predictions can be tested in multilayered magnetic structures with interlayer Dzyaloshinskii-Moriya interactions.

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Instability of skyrmion strings induced by longitudinal spin-polarized currents

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One of the fascinating aspects of two-dimensional topological spin textures, so-called magnetic skyrmions, is their interplay with spin currents. It is well established that spin-transfer torques exerted by in-plane spin currents give rise to a motion of magnetic skyrmions resulting in a skyrmion Hall effect [1]. In films of finite thickness or in three-dimensional bulk samples the skyrmions extend in the third direction forming a string [Figure 1(a)]. This string is aligned with the applied magnetic field and nonreciprocal spin waves can propagate along skyrmion strings [2].

In this work, we investigate the influence of spin currents that flow parallel to the skyrmion string. We show that, remarkably, such a current component immediately destabilizes the string in a clean system. This instability is caused by the longitudinal current leading to the emission of translational Goldstone modes with finite wavevectors along the string, in contrast to the transversal current that couples only to the Goldstone mode with $k_z = 0$. As a result, helix-shaped deformations develop [Figure 1(b)], whose amplitudes grow with time and eventually break the string. Employing an analytical stability analysis complemented by micromagnetic simulations, we demonstrate that both a single string and skyrmion string lattice are destabilized by this mechanism [3].

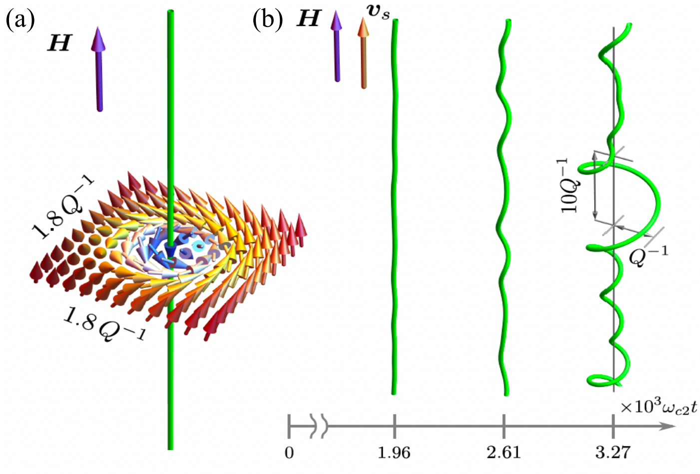

Figure 1: (a) Illustration of a skyrmion string that is aligned with the applied magnetic field H. Each cross-section perpendicular to H contains a skyrmion texture, and the green lines represent the skyrmion strings. (b) Micromagnetic simulations of a string destabilized by a longitudinal spin current v_s.

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Coupling superparamagnetic tunnel junctions for stochastic unconventional computing

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Besides non-volatile memory applications, magnetic tunnel junctions are very promising for unconventional computing [1]. These nanoscale devices consist of two ferromagnetic layers separated by a thin insulating tunneling barrier, with magnetization orientations forming two stable configurations (parallel and antiparallel) separated by an energy barrier. For energy barriers lower than approximately 15 kT, thermal fluctuations at room temperature lead to random changes in magnetization between the two stable configurations' time scales ranging from 10 ns to 100 ms. A magnetic tunnel junction whose magnetic configuration fluctuates due to a small energy barrier is called a superparamagnetic tunnel junction (SMTJ). Most interaction schemes for multiple SMTJs involve protocols that rely on extra peripheral circuitry, which poses a challenge for creating large probabilistic networks. Our approach involves coupling SMTJs using linear circuit elements, offering a simpler, more compact, and robust solution for building large SMTJ arrays. To evaluate SMTJ coupling, we compute the $t=0$ Pearson cross-correlation C(0) of the joint SMTJ states. In Fig. 1, we plot the C(0) cross-correlation versus the applied voltage for our circuit. We achieve a maximum coupling amplitude of 58% between the two SMTJs, twice as large as previously demonstrated in the literature [2, 3]. Furthermore, we can control both the amplitude and sign of the coupling by adjusting the applied voltage. For voltages below 1850 mV, the cross-correlation is negative, indicating antiferromagnetic configurations. Above 1850 mV, the cross-correlation becomes positive, corresponding to ferromagnetic configurations. This tunable bipolar coupling is an important feature for probabilistic computing schemes and paves the way for implementing energy-based models like Boltzmann machines and invertible logic networks in hardware. This work is supported by StochNet ANR-21-CE94-0002-01 and G-INP Bourse Présidence.

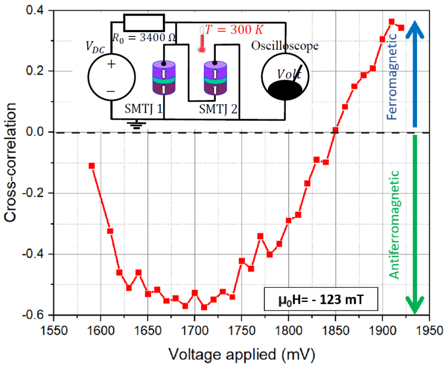

Figure 1: Setup of coupling two SMTJs and the evolution of the $t=0$ Pearson cross-correlation C(0) extracted from the coupled SMTJ system as a function of the applied DC voltage.

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Unconventional computing and energy harvesting using spin-devices

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Spintronics can offer alternative solutions for unconventional computing and one such application is neuromorphic computing. However, the experimentally demonstrated spintronic neurons have been very limited and the proposed models till now are either non-spiking or require a reset pulse after firing. Moreover, stochastic neuronal dynamics that occurs in biological neurons have not yet been well emulated despite its key role in performing probabilistic inference in the face of uncertainty. Here, we propose a spintronic artificial neuron device based on the heavy metal (HM)/ferromagnet (FM)/antiferromagnet (AFM) spin-orbit torque (SOT) heterostructure [1]. The spintronic neuron device fires when the input current exceeds a threshold and can reset itself when the current stimulus goes back to zero due to the exchange bias of the FM/AFM layer. We also show that the magnetization switching is inherently stochastic in a range of currents because of the competition between the SOT and AFM pinning effect. We further implement a restricted Boltzmann machine (RBM) and stochastic integration multilayer perceptron (SI-MLP) using our proposed neuron, which show the capability of reconstructing unknown images and a high prediction accuracy, respectively. Our results offer a spintronic device solution to emulate biologically realistic spiking neurons.

There is a great interest to generate electricity using ambient RF energy. We address this using the spin-torque diode effect of spin-torque oscillators (STOs) [2]. For the application in rectification and energy harvesting, the spin-diode effect is demonstrated by measuring the rectified dc voltage. Due to the canted anisotropy, the free layer of the individual STOs shows a large RF sensitivity as a result of non-linear dynamics. We demonstrate series connections have an advantage for rectification due to the additive effect of the diode voltages from STOs. Using eight oscillators in series, the rectified voltage is enhanced and we have achieved a rectification efficiency of 6% at -20 dBm, which outperforms the Schottky diode capability at sub μW power. By integrating the electrically connected eight STOs with conventional electronics, we demonstrate the battery-free energy-harvesting system by utilizing the wireless RF energy to power electronic devices such as LEDs. We also demonstrate the capability of this energy harvesting system in holding dc power using a time-varying signal, which is useful in harvesting energy from discrete commercial sources such as a WiFi router. Our results highlight the significance of electrical topology (series vs. parallel) while designing an on-chip STOs system.

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Highly sensitive spin-torque diode and its application in neuromorphic computing

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Spin-torque diodes (STDs) offer the possibility of using spin torque to generate rectification voltage with promising applications in microwave detecting [1] and energy harvesting [2][3]. Up to now, the detection sensitivity of STDs has already surpassed that of semiconductor Schottky diode detectors. However, how to take advantage of the microwave rectification in STDs to realize neuromorphic computing keeps some challenges. In our previous work [4], we first proposed the sparse neuromorphic computing based on STDs. The nonlinear rectification characteristics of STDs with injection locking mechanism can be used to mimic a neuron with a ReLU-like activation function. Rrecently, we demonstrate a highly sensitive STDs with ultralow current density based on magnetic tunnel junction with perpendicular magnetic anisotropy (PMA). By introducing the interfacial PMA, the demagnetization field is roughly compensated, leading to a low effective demagnetizing field and the reduction of current density required to excite the self-oscillation. Utilizing the injection-locking mechanism, a high detection sensitivity of 3,785 V/W is reached at the current density of -2.36×105 A/cm2 in the absence of magnetic field. Furthermore, we construct an artificial neural network with the STD neurons to perform the recognition of handwritten digits in the Mixed National Institute of Standards and Technology (MNIST) database, where a produced accuracy of up to 94.92% is obtained [5]. In addition, we propose that nanoscale STDs based on a magnetic tunnel junction can be used to implement population coding and demonstrate that a basis set obtained from a single STD by time multiplexing can realize the generation of cursive letters. These works provide a route to develop low-power consumption high-sensitivity STDs for Internet of Things applications and neuromorphic computing [6].

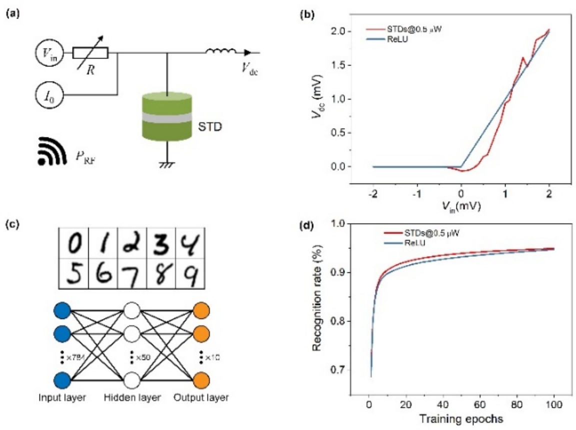

Figure 1: (a) A schematic illustration of a single STD neuron. (b) The activation function of STD neurons (red line) at the microwave frequency f_{RF} = 450 MHz and P_{RF} = 0.5 μW, compared to the ReLU (blue line) activation function. (c)The structure of the Artificial Neural Network (ANN) we constructed to recognize the handwriting digit in the MNIST database. (d) The transition in the recognition rate obtained from the neural network constructed with the STDs, compared to a conventional neural network with a ReLU activation function.

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A micrometric accelerometer based on arrays of magnetic tunnel junctions

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In this work we propose a design for a micrometric spintronic-based accelerometer based on arrays of magnetic tunnel junctions (MTJs). Some of the MTJs are placed on fixed substrates (fixed-MTJs) and work as spin torque diodes (STDs), whilst other are on movable substrates (free-MTJs) that are displaced once an external excitation is applied to the device and work as spin torque nano oscillators (STNOs). The displacement of the free-MTJs, induced by the external acceleration, causes the variation in the dipolar coupling that alters the synchronization with the fixed-MTJs and thus the rectification voltage generated via spin diode effect [1,2] varies.

Here we study and investigate the proposed design to find the optimal conditions under which the sensor yields an output signal, and this exhibits a linear output. Fig. 1(a) shows how the time-varying output differential voltage ($\Delta V_{dc,\text{diff}}$) as response to an external acceleration with a constant profile of $10\ g$ reproduces the behaviour of displacement of the free-MTJ (d) from its initial position in a simple system composed of an array of three MTJs. Moreover, Fig. 1(b) shows linear dependence of $\Delta V_{dc,\text{diff}}$ and d, extracted after 1 ms, on the acceleration in the range between -10 and 10 g. The device can be extended to multiple arrays of MTJs based on a similar approach where free-MTJs are confined between fixed-MTJs, offering multiple differential voltage measurements and a robust coupling.

The results show the robust sensing and read-out mechanism provided by the spin diode effect and confirm the potential of the proposed device of becoming an alternative to the current state of the art technology.

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Multicore memristor realized by high resolution electrical detection of mobile domain walls

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The current-induced manipulation of mobile domain walls in nanoscopic magnetic wires and their electrical detection are keys to the development of domain-wall-based memory and logic devices that go beyond today's binary technologies [1]. A racetrack device with a single domain wall is functionally equivalent to a memristor in which the output signal is proportional to the position of the boundary core. In such device, analogue-like output can be achieved upon the current-induced motion of the domain wall which can be a platform for neuromorphic computing [2-3]. A commonly known memristor or resistive switching memory cell possesses a single boundary core that separates physical states (e.g., doped vs. undoped or conducting vs. insulating or formation vs. rapture) [4-5]. Racetrack devices, however, can possess multiple mobile domain walls in a single racetrack cell, in contrast to conventional memristors. As a result, the racetrack with multiple domain walls can generate highly complex time-signal outputs upon operation (see Fig. 1). Here we discuss how multiple mobile domain walls can be effectively traced with high resolution (spatial resolution of better than 40 nm) using a set of specially engineered anomalous Hall detectors integrated into the racetracks. In order to visualize the complex signal, we use Poincaré plots and suggest static and dynamic phase space analyses (see Fig. 1d) for interpreting the dynamics of domain walls. In particular, we introduce a multi-core memristor model to describe the dynamics of domain walls. Furthermore, we show that the domain wall dynamics and stochasticity can be readily controlled in racetracks with deep sub-micron dimensions. We strongly believe this work will serve as an important platform for for neuromorphic devices with higher-order complexity [6-7].

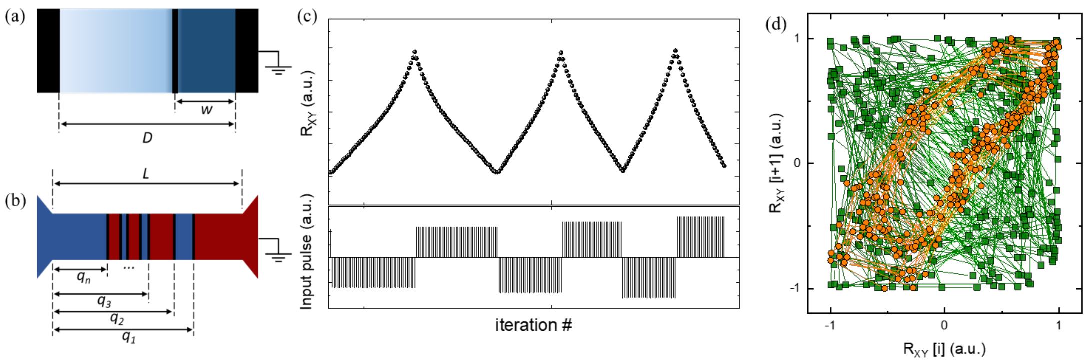

Figure 1: Schematic illustrations of (a) conventional memristor and (b) multicore memristor from multi-domain-wall racetrack. (c) Electrical detection of current induced domain wall motion with high spatial resolution (better than 40 nm). Note that 5 ns electrical pulses were applied to shift domain wall in the racetrack. (d) Poincaré plots for stochastic (green) and controlled (orange) domain wall motion.

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Bulk-Rashba Effect in Pt/Co/W Artificial Superlattices

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Spin-orbit interaction plays a crucial role for magnetization control via spin current in heterostructures composed of non-magnetic and ferromagnetic materials. Among the elements in the periodic table, such as Pt and W, which have large atomic numbers as the 5d metals, there have been reports of spin current that enables magnetization control. Additionally, efforts to achieve switching current densities below 10^{10} A/m^2 for efficient magnetization control have been made in low-dimensional materials such as topological insulators like Bi_2Se_3 and van der Waals materials like WTe_2. An important point is that the developed heterostructures must be suitable for unit structures in spin-orbit torque (SOT) magnetic random access memory (MRAM), and compatible with CMOS processes for practical applications. From this point of view, topological insulators and van der Waals materials may not be suitable for MRAM development.

In this study, we demonstrate that bulk Rashba-type band splitting is formed in an asymmetric artificial superlattice of W/Co/Pt, fabricated using atomic-level deposition techniques [1]. Due to the sizable Rashba effect, the superlattice generates spin current over 300% more efficient than Pt. Our theoretical reveal that such large bulk Rashba effect originates from orbital asymmetry induced by a W atomic layer, which is also confirmed by the x-ray magnetic circular dichroism study. Our result suggest that artificial structure without symmetry can be promising system for spin current generation.

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A novel 3D micromagnetic solver for simulating arrays of nanomagnets and nanodevices interacting in the space

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This work presents a GPU-parallelized 3D micromagnetic solver for the efficient calculation of magnetization dynamics in 3D distributions of magnetic nano-objects, strongly interacting in the space in a random or ordinated configuration. The nano-objects can be magnetic nanoparticles for biomedical applications, which can also have complex shape (e.g. spindle, flower, ring) and size leading to multi-domain state [1]. Moreover, the handled nano-objects can be magnetic nanodevices, like magnetoresistive or spintronic sensors displaced in the environment, system or body to be monitored [2].

In the developed micromagnetic solver, curved surfaces can be accurately modelled thanks to the use of a finite difference approach enabling the calculation of the exchange and magnetostatic fields on non-structured meshes [3]. To allow the accurate simulation of many objects, the magnetostatic field is locally separated into two contributions, i.e. a short-range and a long-range one. The first contribution, which includes the magnetostatic interactions internal to each object, is obtained by numerically solving the Green's integral equation. The second contribution, which takes into account the inter-object magnetostatic interactions, is determined by approximating each object as a collection of magnetic dipoles, associated with mesh elements.

The accuracy and computational efficiency of the micromagnetic solver are analysed by comparison to a standard 3D-FFT code [4], putting in evidence the reliability and flexibility of the proposed methodology in handling many objects, without any restrictions on their shape and orientation in the space. Two examples of application are given, i.e. magnetic nanoparticles for therapeutic hyperthermia and spintronic devices based on magnetic tunnel junctions for magnetic field sensing.

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Ultrafast opto-magneto-electronics for non-dissipative information technology

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The explosive growth of digital data use and storage leads to an enormous rise in energy consumption, rapidly becoming unsustainable. Ultrafast opto-magneto-electronics is an emerging field that combines the ideas and concepts of opto-magnetism and spin transport with photonics for ultrafast low-dissipative manipulation and storage of information. Both light and spin currents can control magnetic order, but mechanisms as well as corresponding time scales and energy dissipation differ. The COST Action MAGNETOFON [1] followed the best of both worlds, combining short time scales and non-dissipative propagation of light with nanoscale selectivity and strong interactions of spin currents. Here I would like to review a few major highlights, achieved with the collaboration triggered by the Action.

The interaction of femtosecond laser pulses with magnetic thin films induces a wide range of out-of-equilibrium phenomena, leading to an ultrafast demagnetization, and a subsequent magnetization dynamics. One of the results is the deterministic reversal of the magnetization or a controlled motion of domain walls by circularly-polarized pulses, reviewed in [2] On the other hand, ferrimagnetic materials follow the process of single-shot helicity-independent all-optical switching of magnetization by which a single suitably-fast excitation, under the right conditions, toggles magnetization from one stable state to another, see [3] for a review.

To increase the density of a possible magnetic memory, plasmonics and magnetism are combined, simultaneously enabling light-driven bit downscaling, reduction of the required energy for magnetic memory writing, and a subtle control over the degree of demagnetization in a magnetophotonic surface crystal. This is achieved using a regular array of truncated-nanocone-shaped Au-TbCo antennas showing both localized plasmon and surface lattice resonance modes [4].

So far, the methods of magnetization manipulation have mostly been developed independently within the fields of spintronics and ultrafast magnetism. Recently, it has been demonstrated that optically induced ultrafast magnetization reversal can take place within less than a picosecond in archetypal spin valves of [Pt/Co]/Cu/ [Co/Pt] commonly used for current-induced spin-transfer-torque switching. This finding demonstrated the unity of laser excitation with that of spin-polarized currents, and paved a road to ultrafast magnetization control by bridging concepts from spintronics and ultrafast magnetism [5].

On the other hand, bias-field-free spin-orbit-torque switching was reported in a single perpendicular CoTb layer with an engineered vertical composition gradient. The vertical structural inversion asymmetry induces strong intrinsic SOTs and a gradient-driven Dzyaloshinskii–Moriya interaction, which breaks in-plane symmetry during the switching process [6].

Ultimately, it has been also demonstrated that controlling the crystal lattice one can induce transient magnetic anisotropy and thus achieve a full reversal of magnetization, not related to heating [7]. Dynamics of this process is very peculiar and leads to non-trivial spatial patterns, including dynamic self-organization and pattern formation by magnon-polaron waves.

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Pattern recognition with nonlinear magnonic hardware

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Within the last decade, spintronics and magnonics have demonstrated impressive development in the experimental realization of Boolean logic gates. However, the exponential growth of data and the rise of the Internet of Things are pushing the deterministic Boolean computing of von-Neumann architectures to their limits or are simply consuming too much energy. Moreover, conventional Boolean computer architectures are likely to remain inefficient for certain cognitive tasks in which the human brain excels, such as pattern recognition, particularly when incomplete or noisy data are involved.

One of the most generic and abstract implementations of brain-inspired computing schemes is reservoir computing, which uses the nonlinearity and recurrence of a physical system to separate patterns of time series data into distinct manifolds of a higher dimensional output space. In this presentation, I will demonstrate the experimental realization of pattern recognition based on reservoir computing using magnons.

Recently, we reported on the nonlinear scattering of magnons in vortices in micron-sized NiFe discs [1] which we learned to control and stimulate using other magnons [2]. Now, we utilize these phenomena to employ magnons for pattern recognition without relying on magnon transport in real space [3]. I will present a comprehensive overview of experimental results demonstrating the capabilities and advantages of magnon reservoir computing in reciprocal space. Additionally, I will elaborate on the potential of modifying nonlinear magnon scattering by the distortion of the magnetic vortex using static [4] and dynamic in-plane magnetic fields.

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Magneto-ionics in CoFeB alloys

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Magneto-ionics is a rapidly growing field in spintronics that offers great promise for the development of high-performance devices for information storage and processing. The ability to manipulate magnetic properties through ionic motion in materials in a non-volatile way, rather than the volatile purely electronic means, presents exciting opportunities for the development of non-volatile and low-energy memory devices. CoFeB alloys are among the most technologically relevant materials for spintronics, therefore, the integration of magneto-ionics into CoFeB-based devices can rapidly lead to new functionalities and enhanced performance.

In this talk, I'll give an overview of this exciting field and discuss physical mechanisms and recent results [1-4] on controlling the spin-reorientation transition (SRT) in CoFeB/oxide systems. in Ta/CoFeB/HfO_2, ionic gating induces migration of oxygen-rich species within the stack, leading to different magneto-ionic regimes and spin-reorientation transitions. Our studies show that an irreversible regime I exists when going from an under-oxidised to an optimally oxidised CoFeB/HfO_2 interface, where perpendicular magnetic anisotropy (PMA) is observed, while a highly reversible and cyclable regime II is present when going from PMA to over-oxidised. This behaviour is attributed to a non-equivalent distribution and binding of the mobile oxygen species at the surface of the magnetic layer in the different magneto-ionic regimes.

We also investigated the magneto-ionic response in Ta/CoFeB/MgO/HfO_2, where dusting layers at the CoFeB/MgO interface facilitate access to regime I and stabilise PMA at the CoFeB/MgO interface. In contrast to the system with a direct interface with HfO_2, this system does not show evidence of the typical oxidation involved in magneto-ionics relying on voltage-induced migration of oxygen species. XAS measurements show a strong and reversible change in the oxygen edge upon gate voltage exposure, showing that the magneto-ionic process is mediated by the incorporation and release of oxygen species. However, XMCD measurements show that the voltage-gate induced spin-reorientation transition in the CoFeB/Pt/MgO stacks does not present any significant changes in the magnetic moment of neither Fe nor Co, which is incompatible with strong oxidation effects.

Our studies show the complexity of the magneto-ionic mechanisms and the strong influence of surface chemistry on the observed effects on the magnetic properties. Therefore, there is a need to take into account the link between magneto-ionic performance, in terms of the amplitude of the effects on the magnetic properties and their reversibility, and interface composition for the design of efficient spintronics devices with magneto-ionic functionalities.

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Designing magnetic garnets for spintronics and photonics

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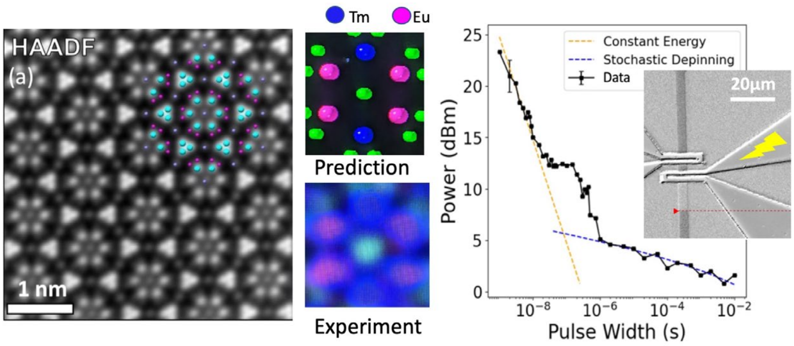
Magnetic insulator thin films provide unique functionality in spintronic, magnonic, and magnetooptical devices. Iron garnets exemplified by yttrium iron garnet are ferrimagnetic insulators with a wide range of properties manipulated by cation substitution, including a growth-induced perpendicular magnetic anisotropy in a mixed garnet resulting from ordering of the rare earth ions, and modified compensation and Curie temperatures resulting from antisite defects in off-stoichiometric garnets. Films and multilayers of rare earth and Bi-substituted garnets and garnet/metal heterostructures can therefore be grown with tunable magnetic anisotropy, damping, and magnetization. Low-damping PMA garnets exhibit high speed domain wall motion of several km/s driven by spin orbit torques from a current in a Pt layer or by spin waves excited by an r.f. antenna. Iron garnets also exhibit magnetooptical activity and high transparency in the infrared, and can be used in integrated magnetooptical isolators to control the flow of light in photonic circuits. We will discuss strategies to control the properties of iron garnets and their spintronic, magnonic and photonic behavior.



Left: High resolution plan view electron micrograph of a (111)-oriented garnet film. Blue: rare earth; purple: Fe sites. Center: in a mixed Eu,Tm garnet, the rare earths occupy specific dodecahedral sites. Right: Power of 4 GHz pulse at antenna required to translate a domain wall in a BiYIG film vs. length of pulse.

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New strategy for spin logic device and efficient switching of antiferromagnet

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Effective electrical manipulation of magnetic order is of great importance of developing next-generation high-performance spintronic memory and logic device. The current presentation includes two parts. One is new strategy for spin-orbit-torque (SOT) based logic device. The other one is efficient switching of antiferromagnets.

Scaler adder and vector majority are the common principle used in the spin logic devices mainly. Here, we demonstrate that vector adder operation can serve as a new working principle for designing complex logic. We choose current vectors as the logic input in a CuPt/CoPt crystal structure with 3-fold symmetry [1] and reveal that field-free SOT-induced magnetization switching can only be realized when the added current vector is along broken mirror symmetry axis (Fig. 1a). With this essential characteristic, we design and fabricate a logic device, by which various Boolean logic gates as well as full adder functions can be implemented within a single device (Fig. 1b), showing the superiority of vector adder in realizing complex logic functions.

SOT induced by spin Hall effect has been used to manipulate of topological magnetization in Weyl AFM Mn_3Sn. Here, we report that orbital Hall effect (OHE) is an alternative to realize electrical manipulation of Weyl AFM Mn_3Sn. The OHE source can be metallic (e.g., Mn) as well as oxide material (e.g., CuO_x). For instance, Fig. 1c and 1d shows the achieved deterministic switching results in a $Mn_3Sn/Cu/CuO_x$ heterostructure. We also demonstrate that inserting a heavy metal layer between Mn_3Sn and OHE source can enhance the orbit-to-spin conversion efficiency, which can decrease the switching current density to $\sim 1\times 10^{10}$ A/m^2.

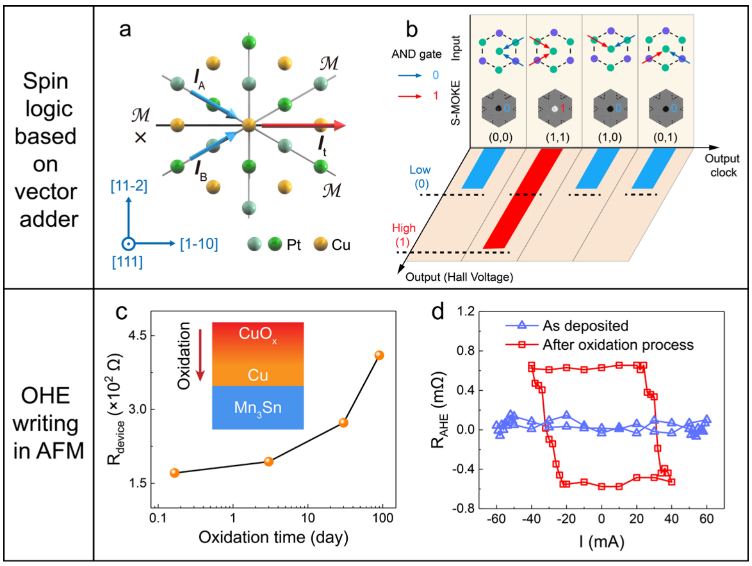

Figure 1: (a) Application of vector adder in 3-fold CuPt crystal structure. (b) Realization of AND gate based on vector adder operation. (c) and (d) OHE-driven magnetization switching in $Mn_3Sn/Cu/CuO_x$ and a Mn_3Sn/Cu heterostructures.

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Orbitronics: orbit currents induced by charge/spin currents, FMR or light for torques or TeraHz emission.

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To start in the usual situation of orbit currents generated by charge currents, I will present experiments [1] showing the strong enhancement of the current-induced torques on the Co layer of a Pt/Co bilayer by the addition of an Al layer on Co (Al protected from oxidation). The enhancement is predominant for the FL torque, up to factor of 9. The interpretation [2] comes from ab-initio calculations showing large Co orbital moments in the interfacial Co layer with a helical texture similar to the spin texture on the surface of topological insulators, see Fig.1. The calculation of the resulting torques leads to a good agreement between the calculated and enhanced experimental torques.

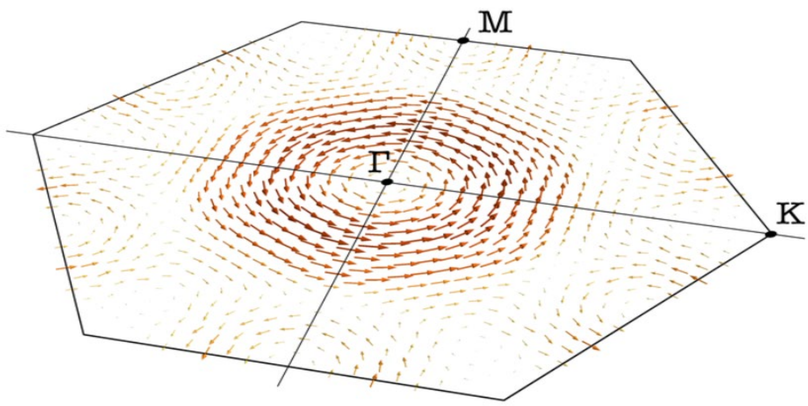

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Fig.1. Helical locking of orbit moment **L** (arrows) with momentum **k** in Brillouin zone in the plane of the Co layer at the interface with Al and in a small energy range close to Fermi energy. A similar texture between spin **S** and **k** in the plane is of much smaller amplitude.

In another set of experiments [3] on light-induced teraHz emission by NM/F bilayers (NM = nonmagnetic metal, deposited on glass substrate, F = ferromagnetic metal or alloy), we show that, in contrast with results on several ferromagnets for F, Ni leads to large teraHz signals with the same polarity for NM = Pt, Ta, W and also a large teraHz signal for NM = Cu. After measurements of the Anomalous Hall Effect contributions on Ni single layers, we can rule out AHE contributions and ascribe the teraHz signals of the NM/Ni bilayers to a significant light-induced production of orbit current by Ni and the predominance of Inverse Orbit Hall Effect (OOHE) on Inverse Spin hall Effect (ISHE) for conversion to charge current and teraHz emission. The property of Ni for the production of significant light-induced orbit current is consistent with ab-initio calculations and also with the production of orbit current by FMR of Ni.

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From Spintronics to Magnonics

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Magnonics uses magnons (spin waves) excitation, propagation, manipulation, and detection to process the information, aim to reduce the energy consumption by using low-Gilbert damping materials without Joule heating [1-3]. Many works have been focused on this exciting area, such as magnonic crystals, magnon valve, magnon junction, magnonic logic and memory, magnonic circuits, THz magnonics, cavity magnonics, and so on [4-5].

In this perspective presentation, the recent progresses in spintronics and magnonics have been summarized and compared. Especially, the interesting magnon quantum effects observed in some nanolayered vertical magnon heterojunctions micro-fabricated by our group are mainly introduced for inspiring more possibilities in this area [6-12]. Firstly, the history of the spintronics has been briefly reviewed. Moreover, the recent development of magnonics such as magnon-mediated current drag effect (MCDE), magnon valve effect (MVE), magnon junction effect (MJE), magnon blocking effect (MBE), magnon-mediated nonlocal spin Hall magnetoresistance (MNSMR), magnon-transfer torque (MTT) effect, and magnon resonant tunneling (MRT) effect, etc. existing in magnon junctions or magnon heterojunctions, have been summarized. The potential applications in magnonics memory and logic devices are prospected. From which we can see a promising future for magnonics beyond spintronics.

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Predictable, engineered nanowarming using magnetic nanobars for restoring cryopreserved bio-specimens

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A relatively new bio-application for magnetic heating of nanoparticles under alternating magnetic fields (AMF) involves the warming of cryopreserved bio-specimens [1]. The critical parameters in this application are uniformity and fast warming rates, which mitigate specimen cracking and crystallization of cryopreservation agents, respectively. Pioneering studies have shown successful nanowarming of zebrafish embryos [2], porcine fibroblasts, arteries and heart tissue [3] and rat kidneys [4] using plasmonic or magnetic warming. Superparamagnetic iron oxide nanoparticles (SPIONs) have been instrumental to the success of magnetic warming because they are commercially available and FDA approved for experimental studies. However, iron oxide has a relatively low magnetization (0.63T), and the SPIONs agglomerate due to spherical shapes and easy coherent rotation of their magentization. Here, nanowarming is explored using a subset of magnetic nanowires (MNWs), called magnetic nanobars which are defined by small sizes and shape anisotropies (eg: 10nm diameters and 100nm lengths). Nanobars have up to 4x the magnetization of SPIONS (2.1T for Fe), and their coercivities are dictated by their magnetic reversal mechanism and diameter. Importantly, nanobars have rectangular hysteresis loops that enable maximum energy transfer from AMFs because the specific loss power (SLP in W/g) is equal to the area of the hysteresis loop multiplied by frequency:

$$\text{SLP [W/g]} = 4*M_s*\mu_o H_{max}*f. \quad (1)$$

This work focuses on predicting SLP using micromagnetic simulations and on experimentally verifying the results. Surprising trends were found experimentally to show that two distinct magnetic reversal mechanisms were found, and understanding these enables optimization of heat transfer from any user specified AMF amplitude/frequency pair. Concentrations as low as 1mg/ml can provide 1000°/min warming rates thanks to SLP values up to 16kW/g. Hysteresis loops for nanobars, Fig. 1, were tailored to switch at specific applied magnetic fields for optimal heating. Specifically, material saturation magnetization (Ms = 55, 160 Am^2/kg) and NanoBar diameter (30, 50, 100 nm) were engineered to show relationship of heating to these control parameters.

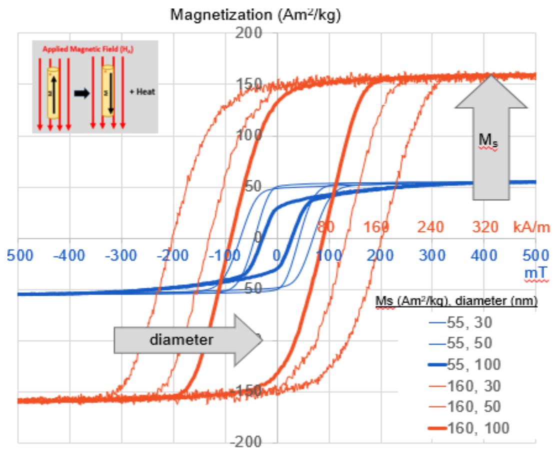

Figure 1:. Hysteresis loops show NanoBar magnetization reversal. These loops were tailored to switch at specific applied magnetic fields for optimal heating depending on the field amplitudes available for a user. Note, the area shown can be multiplied by frequency to calculate expected Watts/gram of SLP.

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Skyrmions in Spin-Orbitronics and Orbitronics – novel science and applications in memory and non-conventional computing

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Novel spintronic devices can play a role in the quest for GreenIT if they are stable and can transport and manipulate spin with low power. Devices have been proposed, where switching by energy-efficient approaches is used to manipulate topological spin structures [1,2].

Firstly, to obtain ultimate stability of states, topological spin structures that emerge due to the Dzyaloshinskii-Moriya interaction (DMI) at structurally asymmetric interfaces, such as chiral domain walls and skyrmions with enhanced topological protection can be used [3-5]. Here we will introduce these spin structures ad we have investigated in detail their dynamics and find that it is governed by the topology of the spin structure [3]. By designing the materials, we can even obtain a skyrmion lattice phase as the ground state [4]. Beyond 2D structures, we recently developed chiral interlayer exchange interactions for chiral 3D structures [6].

Secondly, for ultimately efficient spin manipulation, we use spin-orbit torques, that can transfer more than $1\hbar$ per electron by transferring not only spin but also orbital angular momentum. We combine ultimately stable skyrmions with spin orbit torques into a skyrmion racetrack memory device [4], where the real time imaging of the trajectories allows us to quantify the skyrmion Hall effect [5]. Recently, we determined the possible mechanisms that lead to a dependence of the skyrmion Hall effect on skyrmion velocity [7]. We furthermore use spin-orbit torque induced skyrmion dynamics for non-conventional stochastic computing applications, where we developed skyrmion reshuffler devices [8] based on skyrmion diffusion, which also reveals the origin of skyrmion pinning [8]. Such diffusion can furthermore be used for Token-based Brownian Computing and Reservoir Computing [9].

Beyond dynamics excited by spin-orbit torques the next step is to use orbital currents that generate orbital torques [10]. We have demonstrated that with an additional Cu/CuOx layer, the acting torques can be increased by a factor 10 [10]. This effect has been interpreted as resulting from an orbital Hall current that is converted to a spin current. Finally, an interfacial Orbital Rashba Edelstein Effect has been found, highlighting that the orbital analogues of both the spin Hall effect and the spin-based Rashba Edelstein effect exist [11].

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Spacetime magnetic hopfions

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Magnetic hopfions – 3D topologically non-trivial twisted tube rings – have seen a surge in interest in recent years. Their topology is defined by the spatial linking of their preimages, i.e. the curves in space where the magnetization points in the same direction. In contrast, the temporal dimension has so far not played a role in the definition of their topology. We present spacetime magnetic hopfions, a novel topological excitation. We show two complementary construction routes using skyrmions by braiding their center of mass position, and by controlling their internal low-energy excitations (see Fig. 1). Using collective coordinate and micromagnetic modeling we predict that spacetime hopfions can be realized, in particular, in frustrated magnets [1,2], where the spacetime Hopf index can be controlled by an applied electric field.

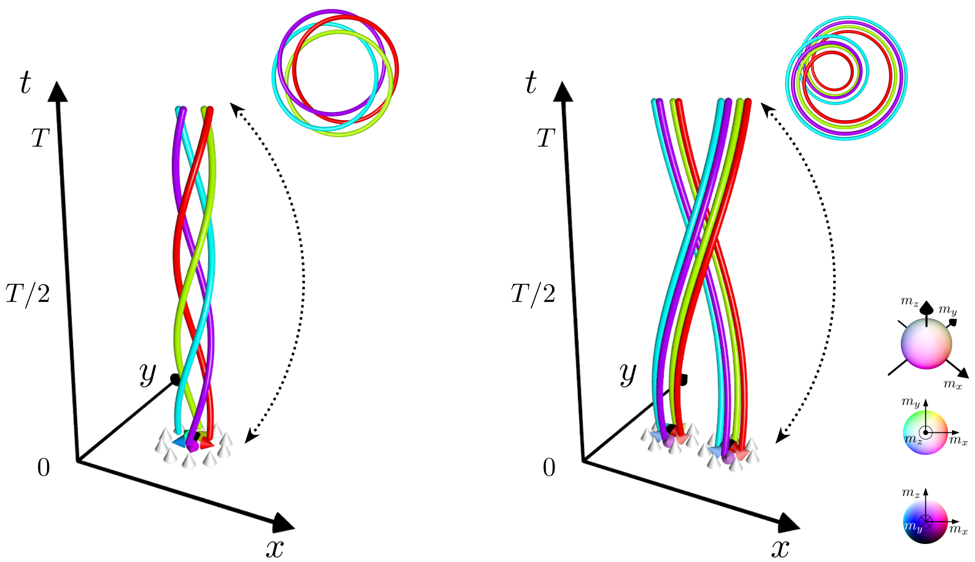

Figure 1. Two construction routes of spacetime magnetic hopfions based on skyrmion textures evolving periodically in time. In (a), the skyrmion's helicity rotates by 2π. In (b), two skyrmions swap positions. The colored curves show the preimages, and the insets show the preimages upon identification of times $t = 0$ and $t = T$.

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Single magnetic tunnel junction implementation of a bio-realistic firing neuron

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Spiking Neural Networks (SNNs) are the third generation of neural networks, aiming at high parallelism and computational power by encoding information into the asynchronous spiking behavior of a topologically complex neural network [1]. Hardware implementations of SNNs overcome the typical high emulation cost by using optimized task-specific devices. In particular, magnetic tunnel junctions (MTJs) provide a highly reproducible, scalable, low-power, CMOS-compatible solution for implementing the firing behavior of neurons. We propose a single-MTJ device that allows the Huxley-Hodgkin (H-H) model of the neuron to be mapped onto the time-trace of the device's resistance, see Fig. 1.[2] Numerical simulations using experimentally based parameters reveal a bio-realistic firing profile, including a refractory period and a sharp spike, with frequencies in the MHz to GHz range at room temperature. We demonstrate that the device reproduces both the leaky-integrate and fire model, as well as the tonic spiking at constant applied current characteristic of the H-H model, without the need for a reset mechanism. The device is suitable as a drop-in replacement in current hardware implementations of SNNs and allows for a significant increase in neuron density at no significant increase in space and power requirements.

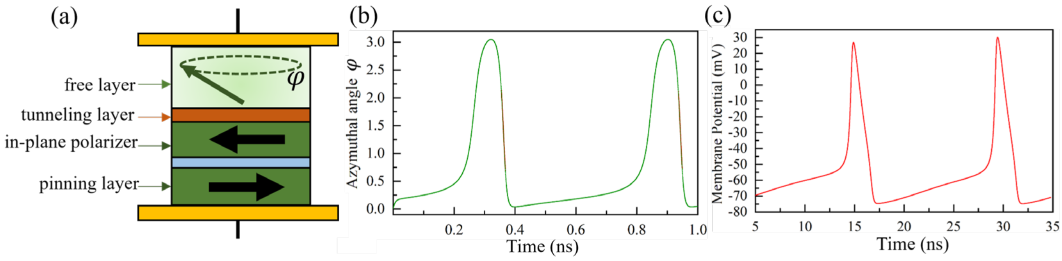

Figure 1: (a) shows a sketch of the device concept of the proposed MTJ spiking device, (b) and (c) show the profile of the magnetization dynamics of the proposed MTJ device and the potential spiking in a biological neuron according to the Huxley-Hodgkin model. Both reveal sharp spikes and a refractory period.

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Spintronics with Ferrimagnetic and Antiferromagnetic Insulators

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The discovery that electric currents can excite spin waves and reverse the magnetization of a magnetic material by transporting spin angular momentum has had a significant impact on magnetism research and technology [1,2]. While the initial focus of the field was on ferromagnetic materials and magnetic tunnel junctions, new research opportunities are with materials and nanostructures with different types of magnetic order, electronic structure and geometries. In this talk, I will provide a perspective on experiments investigating current-induced excitation and reorientation of the Néel vector in antiferromagnetic materials, including experiments in my group on hematite (α-Fe_2O_3) thin films [3-5]. I will also discuss means of quantifying spin-torques in antiferromagnetic thin films using harmonic Hall effect, which make it possible to determine the form and magnitude of the spin-torques that act on the Néel vector [4,5]. Additionally, I will discuss a new type of spin Hall nanooscillator based on hybrid magnetic nanostructures, specifically ferromagnetic metal/ferrimagnetic insulator heterostructures, permalloy/epitaxial lithium aluminium ferrite [6]. These heterostructures are particularly interesting due to the very low damping of the ferrimagnetic insulators, which enables the excitation of spin-waves at lower currents and oscillators with both higher output power and quality factors. This new type of spin Hall nanooscillator has potential applications in neuromorphic computing, by enabling electrically isolated oscillators to communicate through spin waves in an extended insulating ferrimagnetic film.

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Imaging the switching of antiferromagnetic and multiferroic devices using a single spin microscope

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Electrical switching of Néel order in an antiferromagnetic (AF) insulators is desirable as a basis for memory applications. Unlike electrically-driven switching of ferromagnetic order via spin-orbit torques, electrical switching of antiferromagnetic order remains poorly understood. In this presentation I will discuss electrical switching experiments of two canted AF insulators, α-Fe_2O_3 and multiferroic $BiFeO_3$/$TbScO_3$ heterostructures. In both cases, we study the magnetic textures of the AF insulator using a home-built scanning nitrogen-vacancy (NV) center microscope. We start by studying how the zero-field Néel vector of α-Fe_2O_3 can be initialized using a saturating external magnetic field. Our results reveal an unexpected uniaxial anisotropy. Proceeding to current-induced switching experiments on α-Fe_2O_3, we find strong current-induced switching only when the initializing magnetic field is parallel to the direction of the applied current, with no dependance on the sign of current. These results are consistent with a thermo-magnetoelastic switching mechanism, in which Joule heating and the resulting thermal expansion generates switching through induced magnetoelastic anisotropy [1]. Next I will discuss unpublished measurements on $BiFeO_3$/$TbScO_3$ heterostructures, which forms a mixed-phase multiferroic, AF material. We correlate piezoforce microscopy with NV center magnetometry to study the canted magnetism of the two $BiFeO_3$ phases. One phase is centrosymmetric, antiferroelectric and the other is non-centrosymmetric, ferroelectric, and they can be interconverted using an applied voltage. Our measurements reveal that the non-centrosymmetric phase has a weak in-plane canted moment with and some correlation between the ferroelectric polarization and the magnetic orientation.

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Theory of simulated oscillator-based Ising Machine

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This work analyzes the performances of a simulated Oscillator Ising Machine (OIM) for the solution of Max-Cut graph problems, where solving large instances is the current limitation. The analysis is done in terms of scalability of the graph size and density of connections. The OIM is based on the simulation of oscillators, described by the Kuramoto model, as nodes of the graph. The solver has been tested with problems with fixed size and variable density and with cubic problems scaling the number of nodes. We obtained the solution of a cubic problem with two million nodes, which is the problem with the largest number of nodes solved so far in literature. The parameters of the system are regulated by an annealing schedule and a systematic study of the noise is presented.

Field-driven collapsing dynamics of skyrmions in magnetic multilayers

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Magnetic skyrmions are fascinating topological particle-like textures promoted by a trade-off among interfacial properties (perpendicular anisotropy and Dzyaloshinskii-Moriya interaction) and dipolar interactions. Depending on the dominant interaction, complex spin textures, including pure Néel and hybrid skyrmions with thickness-dependent chirality have been observed in multilayer heterostructures. A quantification of these different spin textures typically requires a depth-resolved magnetic imaging or scattering techniques[1,2]. In the present work[3], we will show qualitatively different collapsing dynamics for pure Néel and hybrid skyrmions induced by a perpendicular magnetic field in two representative systems, $[Pt/Co/Ir]_{15}$ and $[Ta/CoFeB/MgO]_{15}$ multilayers. Skyrmions in the former stack undergo two morphological transitions, upon reversing the perpendicular field direction. Skyrmions in $[Ta/CoFeB/MgO]_{15}$ multilayers exhibit a continuous transition, which is mainly linked to a reversible change of the skyrmion size. A full micromagnetic phase diagram (Fig. 1) is presented to identify these two collapsing mechanisms as a function of material parameters. Since the two distinct collapsing dynamics rely on the detailed layer-dependent spin structures of skyrmions, they could be used as potential fingerprints for identifying the skyrmion type in magnetic multilayers. Our work suggests the employment of pure and hybrid skyrmions for specific applications, due to the strong correlation between the skyrmion dynamics and 3-dimentional spin profiles.

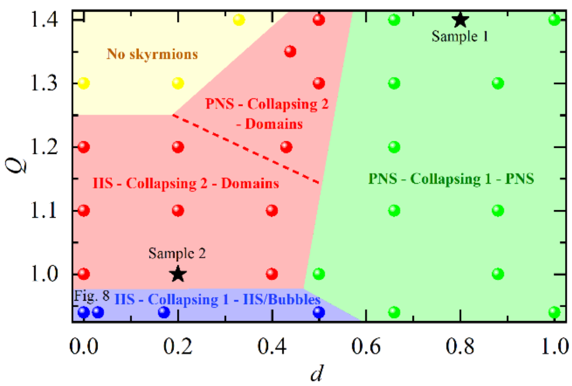

Figure 1: A phase diagram that summarizes the collapsing dynamics in the $Q - d$ space, which is obtained by micromagnetic simulations

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Research progress of magnetic skyrmions in thin film heterojunctions

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Spintronic devices based on electron spin are expected to be used in information storage and processing. In order to realize high-performance spintronic devices, one need to find smaller magnetic information carriers and effective magnetization control methods, which are essential to improve the device storage density and reduce the device power consumption. Due to their excellent properties, such as small size and low driving current density, magnetic skyrmions are expected to become the information carriers of high-density, high-speed, low-power magnetic storage and logic functional devices in the future. This report will briefly introduce our recent progress in the study of magnetic skyrmions in thin-film heterojunction materials and discuss the unresolved issues in current related research.

Controlling topological spin textures from generation to movement for advanced microelectronic application

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Topological spin textures, such as skyrmions and Bloch points, exhibit fascinating physical and spin phenomena with their non-trivial topological properties. Spin textures are not only of scientific interests, but also have high potential as fundamental components for next-generation microelectronic technologies including advanced memory, logic, and computing devices.

To realize spin texture-based microelectronics, it is crucial to reliably generate and delete spin textures, and to be able to control their movements. These matters are significant not only for the technological applications of spin textures, but also hold scientific values in terms of in-depth understanding fundamental physics and topological characteristics of topological spin textures.

We reported that creating and deleting of spin textures can be achieved by several dependable methods, and also by manipulating topological transition [1-3]. We also demonstrated the generation of spin textures with different topological charges, and the distinguishable dynamic behavior of these spin textures [4]. Furthermore, we conducted extensive investigations on the motions of spin textures, particularly skyrmions and Bloch points and proposed techniques to manipulate the movements of these spin textures along desired paths, which are essential for their technological applications [5, 6].

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Spin wave and spin Hall nano-oscillator based Ising Machines

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Mutually synchronized spin hall nano-oscillators (SHNOs) [1,2] have emerged as one of the most promising types of spintronic devices for neuromorphic computing as individual SHNOs in large arrays can be voltage [3] and memristor [4] controlled. Very recently, the first experimental steps towards SHNO-based Ising Machines were also taken [5], and their potential was evaluated theoretically [6]. In my talk, I will describe the general idea behind Ising Machines and some of the existing implementations such as D-Waves Quantum Annealer and the Optical Coherent Ising Machine from NTT Research. I will then discuss how we have tried to build similar Ising Machines using SHNO arrays. I will describe the key elements required for such an SHNO-based Ising Machine, including much larger mutually synchronized SHNO arrays and individual electrical, memristive, and optical [7] control of SHNOs. Time permitting, I will also discuss our work on spin wave based Ising Machines [8].

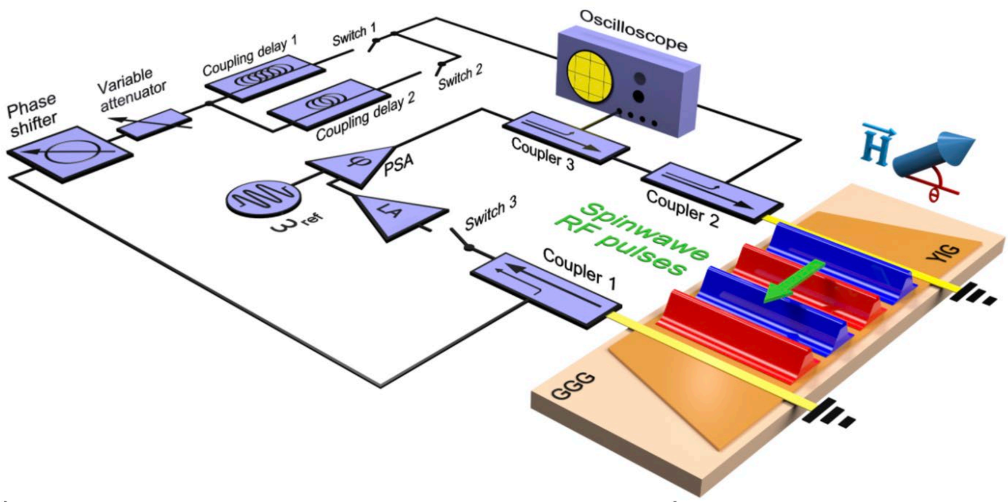

Figure 1: A schematic of a spin wave based Ising Machine with a YIG delay line where phase-binarize spin wave pulses are injected and recollected and then operated on in a peripheral microwave circuit.

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Voltage-controlled Spintronics and Information Processing Applications

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Spintronics provides an energy-efficient high-speed nonvolatile approach for next-generation memory and information processing applications to complement CMOS technology. Today, compute-in-memory is one of the approaches to improve computation performance. Magnetoresistance random-access memory (MRAM) has demonstrated potential for embedded applications in addition to traditional storage applications. Among many spintronic devices included are those based on spin-transfer torque, spin-orbit torque, and voltage-controlled magnetic anisotropy. We will discuss voltage-enabled magnetic anisotropy (VCMA) magnetic memory and the Dzyaloshinskii-Moriya Interaction (DMI), for energy-efficient operations. Combining new emerging materials, we will describe first the memory application. Then we will explore the potential of device-to-deice interaction for logic and computing applications. Additionally, stochastic properties will be examined for solving hard problems. However, challenges remained to be resolved for realizing high-density, high marketing-level applications: a high TMR (on-off ratio) >1000% ratio is needed; continuously increasing VCMA and voltage-controlled DMI coefficients will greatly improve the scaling of device density and system performance.

Non-based charge computing by voltage-controlled skyrmionic magnon Switch

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The increased power demand in computation has driven the development of novel non-charge based computing systems [1]. Global excitations in magnetic materials, spin waves/magnons, have emerged as a promising candidate to implement this new computing paradigm [2]. Magnonic circuits enable encode and carry information in both the amplitude and the phase of the spin wave [3], with low power consumption since magnon propagation does not require charge transfer. However, the main limitation of magnonic devices is their efficient integration in complex networks, e.g., to implement logic operations since there are no effective mechanisms to route them through different magnetic tracks [4, 5].

In this talk, I will present the concept and design of a hybrid skyrmionic-magnon switch, where a local magnetic texture, skyrmion, is electrically controlled as a programmable element to route magnons in magnetic wires. Low-energy short-wavelength spin waves can induce resonant rotation and breathing modes in a skyrmion, while larger spin wave energies allow for momentum transfer between the spin waves and the skyrmion[6, 7]. The proposed device works in an intermediate energy regime and wavelength, where the skyrmion acts as a scattering center for the spin wave. First, I will show the magnon spectrum and skyrmion mean size for the proposed perpendicularly magnetized material system, similar to Pt/Co and Ta/CoFeB. Secondly, I will present the results of our numerical simulations about the deflection of a spin wave by a skyrmion. Specifically, I will focus on how the magnon deflection can be controlled by modifying the magnetic anisotropy of the magnetic wire by voltage. Finally, I will show how effectively the proposed device routes spin waves in the presence of a skyrmion placed at the intersection of two ferromagnetic wires, thereby enabling the implementation of logic operations in magnonic circuits.

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Nonlinear magnon spin currents induced by the electric field in noncentrosymmetric spin systems.

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Magnons are the quantized spin wave and have attracted keen attention because they can be potentially applied for implementing alternative computing concepts and more efficient devices than conventional electronic ones. Therefore, the generation of magnon spin currents has been studied actively [1,2]. One prospective mechanism for producing magnon spin currents is laser-driven magnon spin currents [3]. The excitation energy of magnons is in the THz regime, and recent developments in high-intensity THz laser support the magnetic excitation driven by light. Furthermore, magnon excitations in multiferroic materials with broken inversion symmetry accompany electric polarization and are known as the electromagnon [4]. This feature allows a direct coupling of magnons to the electric field and enables an efficient optical control of magnetic excitations.

Here, we focus on magnon transport in multiferroic spin systems and seek a large magnon spin current which is generated by the electric field [5]. We study the second-order dc magnon spin current induced by the ac electric field in broken inversion spin systems. Applying a perturbation theory, we derived a general formula of the second order magnon spin conductivity. We found that linearly polarized light induces the magnon spin current through "the shift current mechanism" which is closely related to the nontrivial geometry of the magnon band (see Fig.1). We also study the magnon spin current induced by the circularly polarized light. The circularly polarized light induces the magnon spin current through "the injection current mechanism" which is proportional to the magnon lifetime and can be large when the magnon lifetime is long. We demonstrate spin current generation in a simple toy model and typical multiferroic material M2Mo3O8.

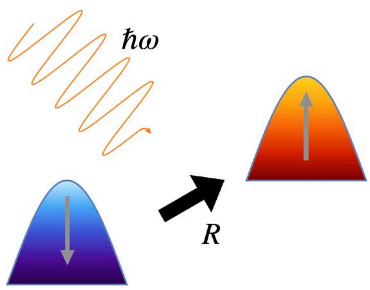

Figure 1: The schematic picture of the magnon spin shift current. The electric field creates a pair of magnons with up (red) and down spins (blue). The shift vector R measures the positional displacement of magnons with up and down spins.

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Double pulse all-optical coherent control on magnetization reorientation in the presence of anomalous damping in antiferromagnets

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Control of magnetic order with short optical pulses paves a route toward future magneto-photonic hybrid devices for data processing and storage. To date, the magnetization switching with a single laser pulse has been successfully [1]. The corresponding magnetization dynamics after single pulse fluence is rather good explored too. In this work, we aim to investigate the magnetization reorientation in the double-pump regime, when the second pulse kicks the magnetic system in a strongly non-equilibrium state.

For the experiments, we used single-crystalline rare-earth orthoferrite (Sm,Tb)FeO3 with c-cut orientation. The orthoferrite is a dielectric antiferromagnet and possesses a pronounced temperature dependence of magnetocrystalline anisotropy. This results in two second-order spin reorientation phase transitions observed as a rotation of the antiferromagnetic vector from the c-axis to the a-axis [2]. The temperatures of the transitions are 220 K and 250.

To achieve our goal, we implement the time-resolved magneto-optical pump-probe technique combined with magneto-optical imaging. We use two circularly polarized laser pulses of 50 fs with opposite helicities as the pumps and varying delay time between them. As a result, each pump does two actions: (i) triggers the magnetization dynamics due to impulsive Raman scattering with initial phase depending on its helicity [3]; (ii) heats the system on times of energy flow from the excited Fe ions to rare earth ions via the lattice, that is of 15-20 ps [4]. As a result, the interplay of the pump-pump delay, energy flow time, and anomalous growth of damping near the spin-reorientation transition produces a rather intriguing switching picture. Particularly, at the initial temperatures of the sample right below the first phase transition 200K < T < 220K, double-pulse laser excitation creates the domain with out-of-plane net magnetization. The orientation of the domain, i.e., magnetization “up” or “down”, is determined by the helicity of the first-arrived pump pulse. At temperatures of 170-190 K the picture changes and the time of pump-pump delay plays a critical role. Specifically, if the pump-pump delay is shorter than 10-20 ps, the final orientation of the formed domain is the same as the first pulse creates. It appears that the second-arrived pump manifests the final state only. At longer pump-pump delays, the magnetization changes to the opposite direction. Finally, if the initial temperature is above the first reorientation transition, there is no combination of the pumps which can form a single domain. The detailed theoretical analysis shows, the anomalous growth of damping near the spin-reorientation transition temperature plays a crucial role in such a switching picture. Reduction of the damping in theoretical model leads to an oscillatory picture of the “temperature - pump-pump delay” diagram, contradicting the experiment.

We are confident, our finding new features of spin dynamics near spin reorientation transitions in antiferromagnets and path the way to future devices for data storage.

The work is supported by the European Research Council ERC Grant Agreement No.101054664 (SPARTACUS).

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Coexistence of magnon-induced and rashba-induced unidirectional magnetoresistance in antiferromagnet

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Antiferromagnets (AFMs) are of great interest to the next-generation spintronic devices [1], due to their attractive properties like ultra-fast dynamics, negligible magnetization, and immunity to external magnetic field. However, the naturally compensated magnetization in antiferromagnet hinders the read-out function. Efficient alternatives to read AFM order are still in urgent need. In this work, we show that a kind of non-linear magnetoresistance, i.e., unidirectional magnetoresistance (UMR) [2], can read out the Néel order in an AFM insulator.

The experiments are implemented in a device made of $YFeO_3$/Pt bilayer film. When an applied current passes through Pt layer, a pure spin current j_s is generated to drive the Néel vector, to do precession away from the equilibrium position, allowing the detection of second harmonic signals. Fig. 1a plots the angle dependence of the second harmonic longitudinal voltage $V_{2\omega,xx}$ with H = 8 T at 300 K together with the spin Seebeck effect and UMR contribution. Our magnetic-field-dependent UMR measurement in Fig. 1b shows an anomalous tendency: 1) when increasing H from 0.75 T to 3 T (blue zone), the extracted UMR resistance R_{UMR} first increases and then decreases. It reaches maximum at H = 2 T as indicated by the red arrow. 2) with further increase of H above 3 T (pink zone), R_{UMR} increases monotonically.

We attributed this anomalous tendency to the coexistence of two individual AFM UMR origins in the same sample: 1) magnon-induced UMR; 2) Rashba-induced UMR. The contribution of magnon-induced UMR is verified by the micromagnetic calculation of the magnon number difference as a function of applied magnetic field (Fig. 1c). And the role of Rashba-induced UMR is also proved by the tight-binding model shown in Fig. 1d.

This work provides a convincing alternative to read out the Néel order in AFM material and may inspire more novel AFM functional devices.

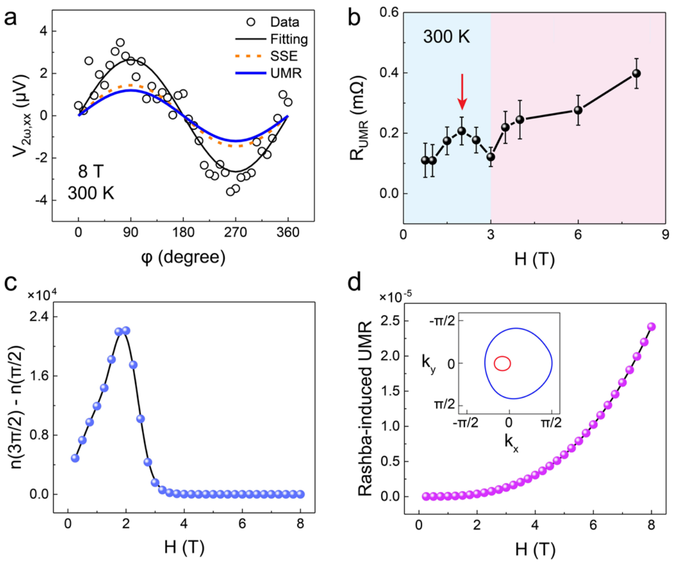

Figure 1: (a) and (b) Angle dependence and field dependence of UMR signal in AFM insulator. (c) Calculated field-dependent magnon number difference between $\varphi = 3\pi/2$ and $\varphi = \pi/2$. (d) Calculated Rashba-induced UMR as a function of magnetic field.

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The emergent research landscape of altermagnetism: d-wave unconventional magnetism and its new connections

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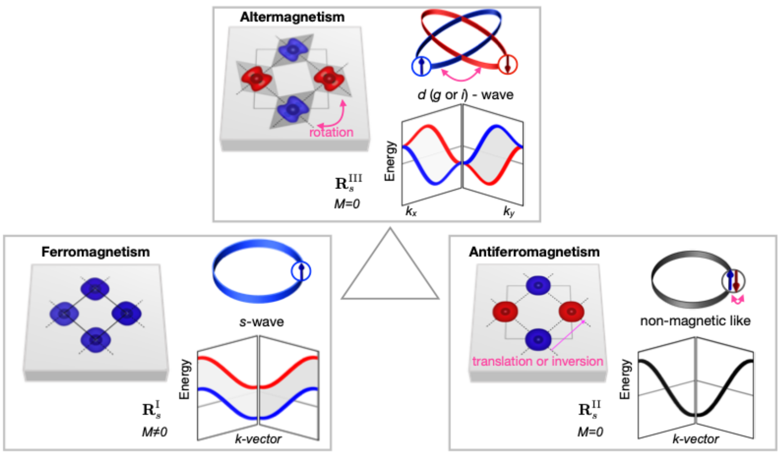
Antiferromagnetic spintronics has been a very active research area of condensed matter in recent years. As we have learned how to manipulate antiferromagnets actively and their emergent topology, further surprises awaited. Turning off spin-orbit coupling, a new fresh view at the family of antiferromagnetic ordered systems reveals also an emergent new class, with properties characteristic of ferromagnets and antiferromagnets, as well as properties unique to itself. This third phase is characterized by compensated magnetic order and a spin-splitting momentum locking, suggesting its name altermagnetism. We show that this new phase is as abundant in nature as conventional ferromagnetism and antiferromagnetism. Its discovery as a distinct phase comes by using a non-relativistic spin-symmetry formalism which, counter to magnetic symmetries, delimits the phase uniquely. Material candidates occur in both three-dimensional and two-dimensional crystals, in diverse structural or chemistry types, and in conduction types covering the whole spectrum from insulators to superconductors. Altermagnets can have impact on prominent research areas, including spintronics, ultra-fast optics, neuromorphics, thermoelectrics, field-effect electronics, multiferroics, magnonics, valleytronics, magnetic topological matter, and unconventional superconductivity.



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Weak vs hidden magnetization: magnon dynamics in anti- and altermagnets

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Antiferromagnets have emerged as crucial components in spintronic applications owing to their remarkable resilience to external fields and rapid internal dynamics. Unlike ferromagnetic materials, antiferromagnetic magnons possess the ability to carry spins of two opposing polarizations, enabling their propagation over micrometer-scale distances. This unique characteristic presents an exciting avenue for manipulating the states of magnetic materials through the utilization of low-energy spin fluxes. In this presentation, I will give an overview of the dynamics of magnons in weak ferromagnets and altermagnets, and contrast them with the dynamics observed in compensated antiferromagnetic materials.

Compensated antiferromagnets exhibit a non-zero magnetization due to oscillations of their magnetic moments, while weak ferromagnets in addition possess a small but non-zero magnetization due to the tilting of their magnetic sublattices. Near the sample surface, these two contributions can generate an effective magnetic field that effectively prevents the penetration of excitations into the sample and allows the existence of surface waves [1]. In this presentation, I will delve into the characteristics of these surface waves, focusing on their non-reciprocal nature, their stabilization through external magnetic fields, and their ability for spin transport when combined with bulk magnon modes.

Next, I will explore the dynamics of magnons in altermagnets. Building upon first-principle calculations of the exchange constants, Smekail et al. made a prediction of magnon mode splitting with opposite chirality in altermagnets [2]. This phenomenon arises from a "hidden" magnetization associated with the spin splitting of electronic bands. In this presentation, I expand the analysis of magnon spectra into the low k regime, where the influence of magnetic anisotropy becomes significant and cannot be overlooked. Furthermore, I delve into the transport properties of magnon fluxes, including their ability to transfer spin, linear momentum, and energy, as well as their scattering behavior at domain walls and the existence of the surface waves. By examining these aspects, we aim to gain deeper insights into the behavior and potential applications of magnons in altermagnets.

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From energy storage to neuromorphics based on topological spin textures

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Tools of spintronics and new magnetic heterostructure platforms developed over the past years open a wealth of opportunities to explore nonequilibrium and transport phenomena in solid-state systems. Current ideas go well beyond the conventional spin transport concepts, with much focus, in particular, on the active role of dynamic topological spin textures. Topological conservation laws thereof now allow us to envision new modalities of spintronic functionalities, which are enhanced by stable nonvolatile characteristics of certain magnetic configurations. In this talk, I will review two complementary thrusts in this research, based on topological spin textures: one [1] using their control and manipulations as a new route towards high-endurance magnetic energy storage and the other [2], employing versatile regimes of magnetic winding dynamics, to realize all basic ingredients needed for building spiking neural networks.

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Magnetic shape memory Heuslers for energy and biomedical applications

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Magnetic shape memory (MSM) Heuslers are an exciting class of ferroic materials, constantly opening new fields of research and application, arising from the strong interplay between thermal, mechanical and magnetic degrees of freedom. They have a great potential for energy related applications, such as solid state refrigeration, thermal and mechanical energy harvesting, remote actuation.

Their multifunctional properties arise from a reversible martensitic phase transformation associated with large changes in magnetization and/or magnetic order. In addition, their hierarchical twin-within-twin martensitic microstructure, and the strong spin-lattice coupling allow the cntrol of their magnetic and functional properties from the atomic to the micro-scale, by tuning growth conditions and applying external fields.

In my talk I will report on our recent results on NiMn-based MSM Heuslers, including micro/nanoscale materials obtained by different fabrication methods (e.g. epitaxial thin films, patterned and free-standing structures, ball milled powders) and I will deepen the effect of downscaling on the main properties, focusing on microstructure tuning and microstructure-related effects on the martensitic transformation. Besides discussing the obtained results in view of energy-related applications, I will highlight some new paths for the exploitation of MSM Heuslers in biomedical applications.

Thermodynamic coherent amplifier of spin wave modes

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It is shown that microwave magnonic modes having a sufficiently low frequency (near the bottom of a magnonic spectrum) could be coherently amplified in a thermally pumped, and, then, rapidly cooled gas of magnons. This effect, which has been recently observed in [1, 2], is analogous to the action of a MASER effect, but the pumping here is thermodynamic, created by the action of an incoherent heat pulse.

It has been previously shown experimentally [3, 4], that an application of heat pulse to an ultra-thin ferrite film, followed by a subsequent rapid cooling of the film, can lead to the formation of a room-temperature magnonic Bose-Einstein condensate (BEC) at the bottom of the magnonic spectrum. Now, experiments [1,2], and our current work, show that incoherent thermal pumping of a magnon gas in combination with subsequent rapid cooling, can lead to a coherent amplification of magnonic modes, such as a nonlinear *bullet mode*, having frequency below the bottom of the magnonic spectrum [1], or a *propagating spin wave mode*, having frequency above the bottom of the magnonic spectrum [4].

We developed a model (see [3] for details), based on the kinetic equations for magnon amplitudes, which describes interaction between a rapidly cooling magnon gas and an isolated low-frequency mode (ILFM), This model shows that the main reason for the ILFM amplification is the formation of non-zero chemical potential in the quasi-equilibrium magnon gas existing near the spectral bottom, and undergoing a four-magnon self-interaction. The ILFM gain is proportional to $\mu - \hbar\omega_{lf}$, where μ is the chemical potential of a magnon gas, and ω_{lf} is the ILFM frequency.

We performed numerical modeling of the ILFM amplification process, where temporal evolution of the power of an ILFM interacting with rapidly cooling magnon gas was calculated (see Fig.1). It turned out, that ILFM was substantially amplified in the process of rapid cooling of a magnon gas. The dependence of the ILFM amplification gain on the maximum chemical potential, acquired by the magnon gas in the process of a rapid cooling, demonstrated a nonlinear behavior, and a strong amplification was taking place when the chemical potential approached the threshold of formation of the magnonic BEC ($\mu_{BEC}/\hbar \approx \omega_m = 5.3$ GHz). At the end of the cooling process ($t \approx 250$ ns) the chemical potential of the magnon gas dropped to zero, and a typical decay of the ILFM power was restored.

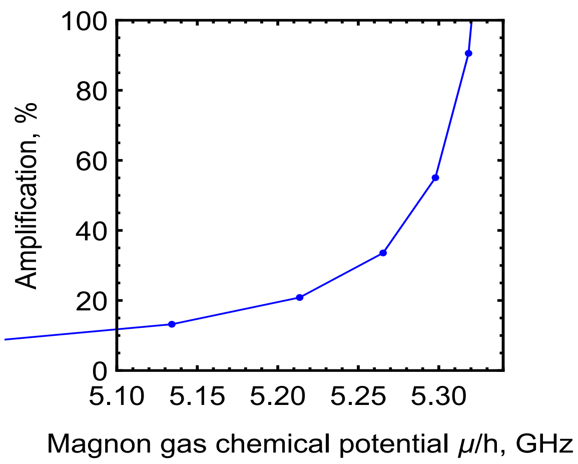

Figure 1: Relative amplification of an ILFM power as a function of the maximum chemical potential of the hot magnon gas interacting with the ILFM.

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Progress and perspectives on antiferromagnetic memory and computing devices

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This In this talk, we present recent advances in the development of magnetic memory devices based on antiferromagnetic (AFM) materials. We show strategies of electrical control of the magnetic order (i.e., writing of information) in AFM materials using spin-orbit torque (SOT) from an adjacent heavy metal layer, and discuss its experimental demonstration in AFM devices based on PtMn, $PtMn_3$, and $IrMn_3$ free layers [1, 2]. We then discuss the perspectives for electrical readout of information from AFM materials, which, due to the absence of a net macroscopic magnetization in AFM materials, has long been considered impractical. This is a grand challenge that requires new approaches to the realization of large magnetoresistive effects (MR) in heterostructures involving AFM thin films, where electrical reading and writing operations can be integrated for memory and computing applications. We will discuss recent proposals and progress in the experimental realization of large MR effects in AFM tunnel junctions. Finally, we discuss using voltage-controlled magnetic anisotropy (VCMA) as an energy-efficient and scalable mechanism to control AFM order [3, 4].

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[2] S. Arpaci et al., Nature Communications, 12, 3828 (2021)

[3] V. Lopez-Dominguez et al., Physical Review Applied 11, 024019 (2019)

[4] R. Tomasello et al., Physical Review Applied 17, 034004 (2022)

Chiral Spintronics

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Spintronics is a field of research that harnesses the electron's spin to create novel materials with exotic properties and devices especially those for storing digital data that is the lifeblood of many of the most valuable companies today. Spintronics has already had two major technological successes with the invention and application of spin-valve magnetic field sensors that allowed for more than a thousand-fold increase in the storage capacity of magnetic disk drives that store ~70% of all digital data today. Just recently, after almost a 25-year exploration and development period, a high performance nonvolatile Magnetic Random Access Memory, that uses magnetic tunnel junction memory elements, became commercially available. A novel spintronics memory-storage technology, Magnetic Racetrack Memory is on track to become the third major success of spintronics. Racetrack Memory is a high performance, non-volatile memory in which data is encoded in mobile chiral domain walls that are moved at high speeds by current induced spin-orbit torques to and thro along synthetic antiferromagnetic racetracks. Chiral domain walls are just one member of an ever-expanding family of nano-scopic chiral spin textures that are of great interest from both a fundamental as well as a technological perspective. A zoology of complex spin textures have been discovered including, in our own work anti-skyrmions, elliptical Bloch skyrmions, and fractional anti-skyrmions. Finally, I will discuss some of our recent work in superconducting spintronics that could lead to a very low energy-consuming cryogenic racetrack memory that is needed for advanced quantum computing systems.

Towards innovative treatments of cancers and diabetes based on magneto-mechanical stimulation of cells

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The mechanical vibration of magnetic particles (Fig.1) under low frequency magnetic field allows for the application of mechanical stress at the cell level. This mechanical stress induces a large variety of physiological reactions from the cells depending on the nature of the cells and on the intensity of the magneto-mechanical stimulation. A great advantage of using magnetism in this field of mechanobiology is that the induced stress can be easily tuned by playing on a number of parameters such as external magnetic field amplitude, direction, frequency. The mechanical stress has a strong influence on the cells cytoskeleton which triggers a variety of signalling pathways and consequently, of physiological reactions. Using U87 glioma brain cancer cells, we observed that a weak stimulation induces already a disorganization of the cell cytoskeleton (Fig.2) resulting in a cell contraction, a loss of motility (ability of the cell to migrate) and a stop of the mitosis (stop of proliferation). A stronger stimulation can induce the apoptosis (spontaneous death) of the cells [1,2] which can lead to a new approach towards cancer treatment, used alone or in conjunction with chemotherapy. An even stronger stimulation can result in a disruption of the cell membrane and thereby cell necrosis, which is not desirable because it goes with inflammatory reactions.

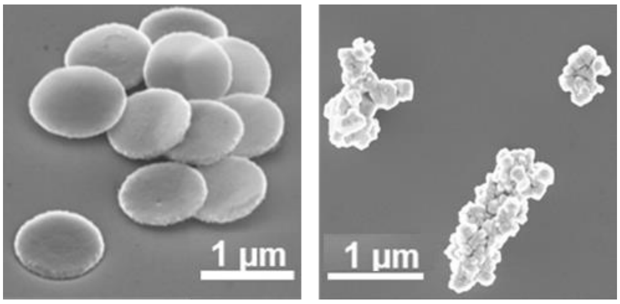

Fig. 1: Two types of superparamagnetic-like particles used for the magneto-mechanical stimulation of cells : Magnetic Au coated NiFe vortex nanoparticle (left) and magnetite nanopowder (right).

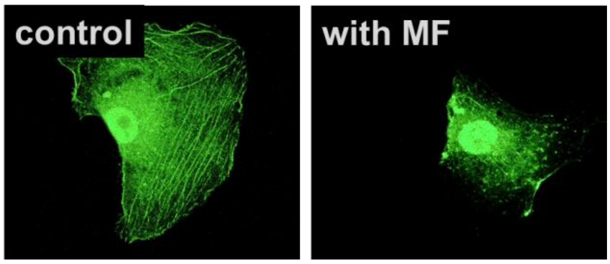

Fig. 2. U87 cancer control cell with stained actin cytoskeleton (left). Cell with damaged cytoskeleton after NP magneto-mechanical vibration (right).

Studies on cancer cells were conducted *in-vitro* as well as *in-vivo* revealing quite different results for a variety of reasons. Ongoing studies are carried out on spheroids of cells embedded in 3D gels which represent *in-vitro* models much closer to *in-vivo* situations.

Experiments were also conducted on pancreatic cells. We demonstrated that the magnetically induced mechanical stimulation of pancreatic cells allows enhancing insulin release from INS1 pancreatic cells. This observation can also open a new route towards innovative diabetes treatments [3].

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Synthetic antiferromagnets for biomedical and flexible spintronic applications

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Synthetic antiferromagnets (SAFs) composed of two ferromagnetic layers separated by a thin non-magnetic spacer has gained a renewed attention owing to their potential for many applications, including spintronics and biotechnology. The present talk focuses on Co/Pd-based SAF thin films with perpendicular magnetic anisotropy (PMA) used as building-blocks of magnetic microdisks for biomedical applications and flexible GMR spin-valves of interest for wearable devices, soft robotics, and bio-integrated electronics [1-3].

Thin film stacks consisting of multiple repeats of single PMA-SAF were prepared with the aim of fabricating free-standing SAF microdisks by lithographic processes [1]. Samples meet all essential requirements for biomedical applications while showing a saturating moment that can be adjusted without substantially impacting other magnetic features (Fig.1a left). In addition, preliminary studies indicate that the cost and time-effective nanosphere lithography can be successfully used to fabricate free-standing microdisks, thus opening the possibility of massive production (Fig.1a right). The same Co/Pd-based SAF stack was used as the reference electrode of large-area flexible GMR spin-valves obtained by direct deposition on PEN tapes [2] and by using a transfer-and-bond approach exploiting the low adhesion between Au and SiO_x [3]. As-prepared flexible systems show magnetic and transport properties comparable to those of samples deposited on rigid substrates along with a high robustness against bending (Figure 1b). To prove the high potential of such systems, they were integrated in on-skin interactive electronics to realize touchless human-machine interfaces, which are intuitive, energy efficient, and insensitive to external magnetic disturbances [2].

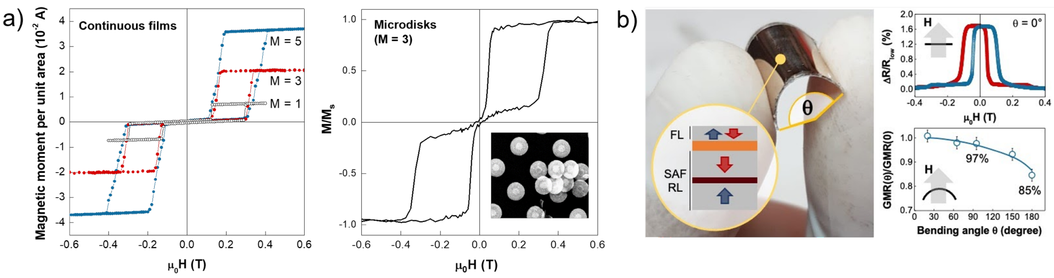

Figure 1: a) RT out-of-plane field-dependent magnetization loops of $\{[Co/Pd]_4/Ru(0.4\ nm)/[Co/Pd]_4\}_M$ thin films and SAF microdisks (inset) obtained by nanosphere lithography. b) Flexible PMA GMR spin-valve, magneto-resistive response ($\Delta R/R_{low}$) and evolution of GMR values as a function of the bending angle (θ).

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Room temperature spin-to-charge interconversion in ferroelectric Germanium Telluride nanodevices

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Spin-charge interconversion (StC) driven by spin-orbit (SO) phenomena has opened new avenues for designing spin-logic architectures with low-power consumption [1]. Recently, Intel has proposed a device called MESO (Magneto-Electric Spin-Orbit) composed by writing and reading elements. Its writing process requires magnetization reversal while the reading component relies on the StC signal resulting from SO phenomena. In the last years StC have been reported in several systems, including heavy metals [2], Rashba interfaces [3] and topological insulators [4]. However, large-scale fabrication of such devices is still a challenge.

Ferroelectric materials enabling control of StC have emerged as another promising platform for ultralow power consumption. Lately, our team has experimentally shown that in these materials the sign of the StC is driven by the ferroelectric state, which can be controlled by an electric field [5]. These findings paved the ground for designing of a new spin-logic device called FESO (FerroElectric Spin-Orbit), which exhibits the non-volatile features of MESO in a more compact structure (Fig1a). In this device, the output signal is directly controlled by the ferroelectric state, removing the need of magnetization reversal for writing that is required for MESO. Therefore, finding materials with large and room temperature StC signal, controlled by ferroelectricity, is important for the fast development of this technology.

Ferroelectric control of StC have been observed by means of spin pumping experiments in two-dimensional electron gases [5] and ferroelectric Rashba semiconductors [6]. Experiments in Germanium Telluride (GeTe) have shown large StC and ferroelectric control at room temperature. These results, demonstrate the relevance of GeTe as a promising candidate for spin-logic devices and FESO technology. Nevertheless, further development requires transport measurements in patterned GeTe nanodevices.

In this talk, we will first introduce the working principle and fabrication approach of FESO nanodevices on large-scale grown GeTe. Then we will show our all-electrical StC measurements in FESO devices nanopatterned at room temperature (Fig1b). Finally, we will discuss the advantages of our design for geometrical downscaling along with future prospects.

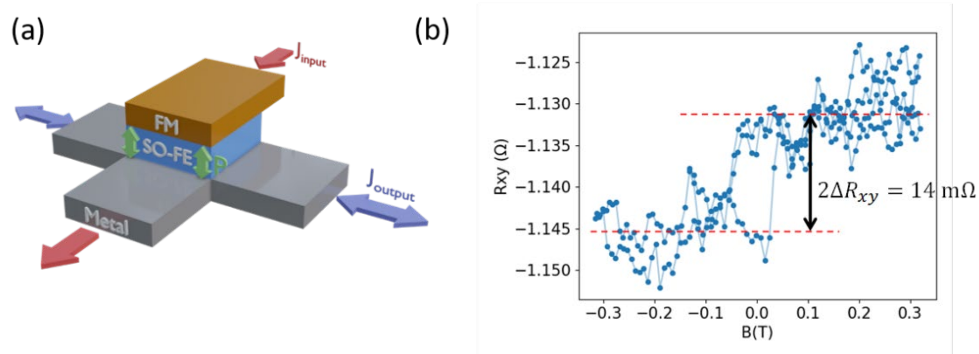

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Figure 1. (a) Schematic representation of FESO device. The output signal (J_{output}) is generated by StC when J_{input} flows through the FM/FE interface. J_{output} depends on the ferroelectric state (P) that can be controlled electrically (b) Experimental results obtained in 200 nm wide GeTe nanodevices.

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Observation of long-range orbital transport in ferromagnet

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It has been two decades since the spin Hall effect was discovered as the fundamental phenomenon generating spin currents in spintronics. Since then, a plethora of materials and their heterostructures have been vigorously studied to generate, detect, and control spin currents. As a spin current involves spin angular momentum flow, injecting it into ferromagnets induces spin torques that can electrically control magnetization. Furthermore, the spin Hall effect has been identified as a secondary effect resulting from the combined spin-orbit interaction with the orbital Hall effect [1], where the latter refers to the charge-orbital conversion phenomenon, with the orbital current being the flow of the orbital angular momentum of electrons in solids. Notably, a theoretical report around 2018 suggested that the orbital Hall effect could occur in 3*d* transition metals with more than 100 times higher efficiency than the spin Hall effect [2]. This implies that high-efficiency angular momentum flow can be generated even in light elements without spin-orbit coupling.

Our study aimed to observe generating orbital current and orbital transport by exploiting current-induced torques (orbital torques) due to the orbital Hall effect in ferromagnetic/nonmagnetic (FM/NM) metal heterostructures. We used Titanium (Ti) as the nonmagnetic metal, which has a small spin Hall effect. Additionally, the magnitude of the orbital torque varies with the strength of the spin-orbit correlation in the ferromagnet [3]. To investigate this effect, we employed nickel (Ni) and permalloy ($Ni_{81}Fe_{19}$). As shown in Fig.1, the current-induced torque efficiency strongly depends on the FM layer in the FM/Ti bilayer. In our presentation, we will discuss the results of the generation of orbital flow in light metals and the induced orbital torque and orbital transport in ferromagnets [4].

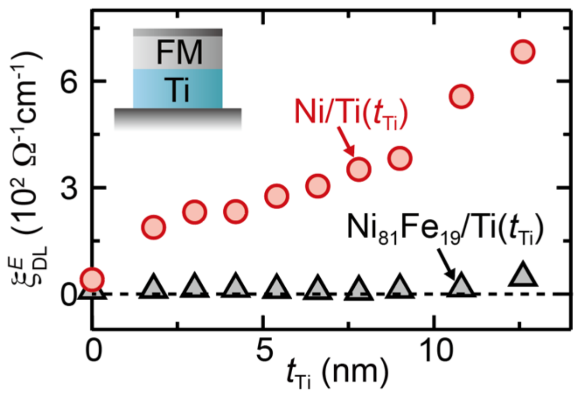

Figure 1: Titanium-thickness t_{Ti} dependence of current-induced torques efficiency $\boldsymbol{\xi^E_{DL}}$ for Ni/Ti and $Ni_{81}Fe_{19}$/Ti bilayer.

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Poly-Crystalline Silicon-inserted Vertical Spin Valve

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Spin metal-oxide-semiconductor field-effect transistors (spin-MOSFETs) are promising devices for next-generation low-power-consumption one due to their nonvolatility [1-4]. To realize these devices, high magnetoresistance ratio (MR ratio) is required. Currently, lateral spin valves utilizing silicon as the channel have been fabricated, and their MR ratios have been over 1% [5]. To increase the MR ratio, the vertical spin valve, which can shorten the channel length, is desirable. The vertical spin valve utilizing germanium has been reported [6], however, a vertical spin valve utilizing silicon has not been reported. Si-based vertical spin valve is a promising candidate since Si have high compatibility with conventional MOS technology [7] and long spin lifetime [8]. In this study, we demonstrate the Si-inserted vertical spin valve and its MR properties.

A multilayer film consisting of MgO (5) | Fe (30) | MgO barrier 1 (1.2) | Si (t_{Si}=0~5) | MgO barrier 2 (1.2) | Fe (10) | Co (5) | Au (10) (described by nm) was deposited on a single crystal MgO(001) substrate by molecular beam epitaxy. Here, MgO barrier 1 and 2 are inserted at the Fe|Si junctions for efficient spin injection. The MgO(001) substrate was annealed at 800℃ for 10 min. MgO (5) buffer layer and Fe (30) were deposited at 200℃ and room temperature, respectively. After that, the substrate was anealed at 350℃ for 30 min. MgO barrier 1 and 2, Co(5) and top electrodes were deposited at room temperature. Si and top Fe layers were grown at substrate temperatures of 550 °C and 200 °C, respectively. The vertical spin valves were fabricated by the combination of photolithography, Ar-ion milling, and lift-off methods. We measured the magnetic field dependence of device resistance (MR-curve) using lock-in amplifier. We evaluated the MR ratio as (R_{max} – R_{min}) / R_{min}, where R_{max} and R_{min} were the maximum and minimum resistance of each MR curves, respectively. We evaluated the averaged MR ratio from these results as shown in Fig 1. MR ratio decreases by increasing Si thickness. We found that the MR ratios of more than 30% and 3% were obtained at equivalent thickness of t_{Si} = 0.19 nm and 1.11 nm, respectively. This device enables highly sensitive detection of spin-dependent transport properties and magnetization behavior. Our research will contribute to the development of Si-based semiconductor spintronics. This research was supported by JST A-STEP JPMJTR20RN and JSPS Grant-in-Aid for Scientific Research (S) Grant Number JP20H05666.

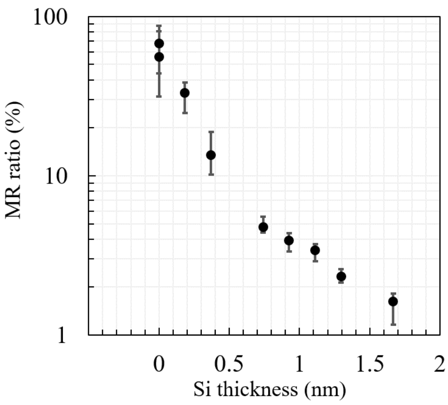

Fig. 1. Si thickness dependence of MR ratio. Error bars are evaluated by the several MR measurement for each devices.

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Magnetic dynamical properties and ferromagnetic resonance in $Ga_{1-x}Mn_xN$ layers

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$Ga_{1-x}Mn_xN$, a prominent member of dilute ferromagnetic semiconductors (DFS) family has attained a great research attention due to its ability to combine properties of semiconductors/insulators and magnetic materials in one host [1]. Moreover, GaN being a wide band gap semiconductor has dominated the photonics and high power electronics. So it remains timely and important to comprehensively understand the underlying magnetic properties of $Ga_{1-x}Mn_xN$.

Here we investigate both experimentally and theoretically the magnetic properties of GaN doped with Mn. The MBE grown ferromagnetic $Ga_{1-x}Mn_xN$ layers, with x ranging between 3% and 7%, are studied by a superconducting quantum interference device (SQUID) and ferromagnetic resonance (FMR). The magnetization measurements with magnetic field applied both in parallel and perpendicular direction to the c-axis of GaN reveal the existence of a sizeable single ion uniaxial magnetic anisotropy specific to Mn^{3+} ion in GaN wurtzite environment (a trigonally distorted tetrahedral coordination). Similarly, the angular dependence of FMR resonance fields enable us to probe both the uniaxial (trigonal) and triaxial (Jahn-Teller) anisotropies in $Ga_{1-x}Mn_xN$.

In order to analyse the experimentally observed data, an atomistic spin model computational tool, using stochastic Landau-Lifshitz-Gilbert (sLLG) dynamics [2] has been developed. The model takes into account the Zeeman interaction as well as both trigonal and Jahn-Teller anisotropies [3]. A large simulation box, with few thousand Mn ions coupled by ferromagnetic interaction $-J_{ij}\boldsymbol{S}_i\boldsymbol{S}_j$ taken up to 14th neighbours has been employed. The magnetization $\boldsymbol{M}$ and the microwave power absorbed during a ferromagnetic resonance are calculated after the system has reached a steady state [4]. Also, a Monte Carlo based simulations, using same atomistic model, have been developed to predict the Curie temperature of $Ga_{1-x}Mn_xN$. Preliminary numerical results obtained using large simulation box suggest a great relevance of this approach. This is the first simulation effort aimed at calculation of both magnetization and FMR in dilute magnetic semiconductor using atomistic approach.

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Exploring the third dimension in magnonics

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Magnonics, the research field that uses spin waves (SWs), the collective excitations of ordered magnetic materials, as a tool for signal processing, communication, and computation have rapidly grown during the last decade due to the low-energy-consumption property.[1] Magnonics systems investigated up to now are mainly planar systems that can be patterned out of an extended layer that is deposited on a flat substrate. The interest in 3D magnonic nanostructures follows the latest trend in CMOS electronics based on the expansion from 2D planar to 3D vertically integrated structures.[3]
3D magnonic systems might offer several advantages over 2D systems allowing for a large number of vertical connections between the layers thus increasing the density of elements for the fabrication of scalable and configurable magnonics.
In this talk, I will review the different strategies to build the next generation of magnonic systems. The first of them is an extension of planar patterned nanostructures, where arrays of patterned magnetic dots or antidots have a layered structure. In this case, the vertical stacking of ferromagnetic materials, placed in direct contact or separated by a non-magnetic spacer, adds new functionalities and degrees of freedom for controlling the SW band structure. An alternative approach to physical patterning is based on the use of hybrid heterostructures in the form of bilayer systems including metal-insulator, metal-heavy metal, metal-antiferromagnet, and metal-ferroelectric, where new properties of SWs such as confining and filtering, guiding and steering, non-reciprocity and reconfigurability in the magnonic band structure, emerge from the interaction between the continuous magnetic film, where spin waves propagate, and the vertical magnetic/nonmagnetic layers which induce periodic modulation of either the static or the dynamic internal magnetic field of the magnetic film itself.[4-6] 3D magnonic systems in the form of meander-shaped ferromagnetic films fabricated on top of pre-patterned substrates have been also proposed as prototypes for the transmission of SW signals in 3D magnonic networks.[7] Finally, the recent observation of SW moiré edge and cavity modes in twisted magnetic lattices will be reviewed.[8]

G.G. acknowledges petaspin association (www.petaspin.com) for the support.

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Terahertz electric field driven dynamical multiferroicity in $SrTiO_3$

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[c] Elettra-Sincrotrone Trieste S.C.p.A., Basovizza, Italy
[d] Department of Physics and ISC-CNR, "Sapienza" University of Rome, Rome, Italy
[e] Research Center for Magnetic and Spintronic Materials, National Institute for Materials Science, Tsukuba, Japan
[f] Linac Coherent Light Source, SLAC National Accelerator Laboratory, Menlo Park, USA
[g] NORDITA, 106 91 Stockholm, Sweden
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The emergence of collective order in matter is among the most fundamental and intriguing phenomena in physics. In recent years, the ultrafast dynamical control and creation of novel ordered states of matter not accessible in thermodynamic equilibrium is receiving much attention. Among those, the theoretical concept of dynamical multiferroicity has been introduced to describe the emergence of magnetization by means of a time-dependent electric polarization in non-ferromagnetic materials. In simple terms, a large amplitude coherent rotating motion of the ions in a crystal induces a magnetic moment along the axis of rotation. However, the experimental verification of this effect is still lacking. Here, we provide evidence of room temperature magnetization in the archetypal paraelectric perovskite $SrTiO_3$ due to this mechanism. To achieve it, we resonantly drive the infrared-active soft phonon mode with intense circularly polarized terahertz electric field, and detect a large magneto-optical Kerr effect. A simple model, which includes two coupled nonlinear oscillators whose forces and couplings are derived with ab-initio calculations using self-consistent phonon theory at a finite temperature, reproduces qualitatively our experimental observations on the temporal and frequency domains. A quantitatively correct magnitude of the effect is obtained when one also considers the phonon analogue of the reciprocal of the Einsten - de Haas effect, also called the Barnett effect, where the total angular momentum from the phonon order is transferred to the electronic one. Our findings show a new path for designing ultrafast magnetic switches by means of coherent control of lattice vibrations with light.

SB gratefully acknowledges the Petaspin association (www.petaspin.com) for the support in the dissemination activities related to this research.s

Magnetocaloric effect: from materials to devices

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Energy efficient and environmentally friendly thermal management have a direct impact on the sustainability of our way of life, with magnetocaloric refrigeration being a promising technology for achieving a greener cooling technology [1]. However, appliances are not yet in the consumer market due to relevant limitations of the active materials. In this talk we will overview some of the approaches that, in our opinion, can ameliorate the situation and help a smoother transition towards the adoption of the technology.

While most of magnetocaloric research in the last decades focused on room temperature magnetic refrigeration, mainly due to the widespread and continuously increasing number of refrigerators and air conditioners, the transition to new mobility paradigms, more based on electricity, and the use of hydrogen as an energy vector, has caused an incipient shift in the focus of magnetocaloric research towards hydrogen liquefaction applications. This shift of the operational temperature range affects materials selection and is heavily affected by materials criticality.

Fabrication of refrigerator beds could benefit from additive manufacturing. We will present a novel fabrication procedure for obtaining homogeneous composite filaments for additive manufacturing, demonstrating that the magnetocaloric response of the fillers is not affected by the manufacturing procedure [2].

From the point of view of addressing the mechanical stability of magnetocaloric materials, high entropy alloys (HEA) could pave the way towards more sustainable refrigerator beds. While magnetocaloric performance of HEA was considered non-competitive due to their small figures of merit, recent discoveries allowed to close the gap between traditional HEA and high-performing magnetocaloric materials [3-5].

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Physicochemical properties and AC magnetic field induced heating properties of solvothermally prepared thiospinel: Fe_3S_4 (greigite) nanoparticles

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Magnetic hyperthermia, a therapeutic modality of cancer is a great advance in the field of nanoscience. Magnetic nanoparticles (MNPs) dissipate heat by relaxation mechanisms or hysteresis losses on exposure to applied magnetic field (AMF) and can kill the cancer cells [1]. Greigite (Fe_3S_4), a thiospinel has inverse spinel structure and is analogous to magnetite (Fe_3O_4). The ferrimagnetic order and relatively higher saturation magnetization of greigite make it desirable for magnetic hyperthermia and is not investigated much in this aspect.

Surface functionalization of magnetic nanoparticles is required to reduce toxicity and improve biocompatibility. The present work involves the solvothermal synthesis of greigite nanoparticles and the surface modification with different weight percentages (5 – 40 %) of less toxic and biocompatible Poly vinyl alcohol (PVA), a synthetic hydrophilic polymer.

The structural and electron microscopy studies reveal the $Fd\bar{3}m$ space group and flaky or flower-like morphology respectively. PVA-coated greigite nanoparticles show superior colloidal stability that is apparent from dynamic light scattering technique. The in vitro cytotoxicity studies show the greigite nanoparticles are biocompatible.

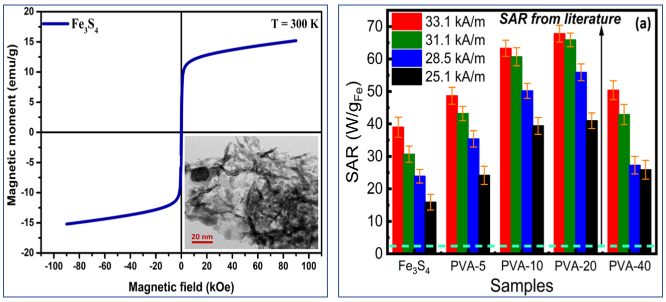

Figure 1 (a) Isothermal DC magnetization curve of greigite nanoparticles at room temperature up to magnetic field ± 90 kOe. The inset shows the TEM image of greigite depicting chain-like agglomeration of individual MNPs. (b) Bar chart showing the SAR values at various AMF amplitudes for uncoated and PVA-coated Fe_3S_4 MNPs. The dotted lines show the SAR value from literature (2 W/g_{Fe}).

The AC induction heating efficiency, quantified by specific absorption rate (SAR) for PVA-coated greigite nanoparticles (67.8 ± 2.6 W/g_{Fe}) is significantly higher than the reported values. The surface functionalization of greigite with PVA makes it a competent candidate for magnetic hyperthermia.

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Sustainable design of large aperture magnets for high energy physics and medical diagnostics

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The design of large aperture magnets is a common task in the context of High Energy Physics detectors and Medical Diagnostic devices. As for the general "green" recent trend, the design has to face with sustainability issues, as the minimization of required power and materials, at assigned detection performance. As a consequence, the classical design flow, usually based on the definition of the required magnetic field specifications in the useful volume, followed by capital+operational cost minimization at fixed geometrical constraints, needs to be reconsidered. In particular a more general optimization process, taking into account at the same time detection performance, electrical power and building materials requirements should be considered.

The potential of such novel design approach will be illustrated, without loss of generality, with reference to the proposal of a large detector magnet for the CERN's SND@LHC experiment. The underlying ideas are in principle exportable to other applications, such as the

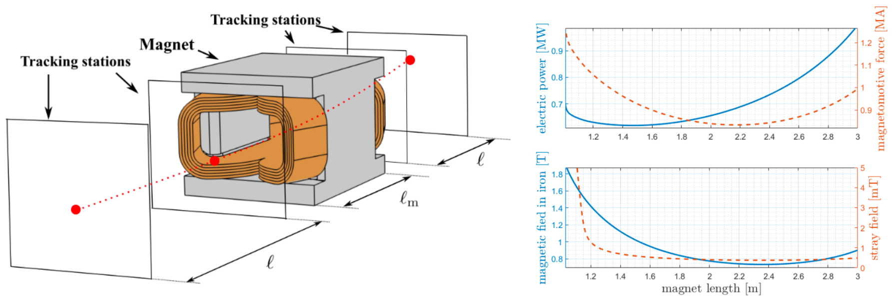

Figure 1: left) schematic structure of the magnetic detector; right) typical dependence of some design relevant quantities on the magnet's length, with reference to requirements

NMR magnets, and possibly used for superconducting magnets. In the considered application the main (conflicting) design goals are: *i*) best particle momentum resolution; *ii*) minimal electric power consumption; *iii*) minimal volume, weight and cost. The procedure is based on a semi-analytical approach, following and improving what proposed in [3] for a high energy physics experiment (SHiP). After the relevant minima are determined in the parameter's space, a full 3-D FEM validation analysis will follow.

In a realistic experimental parameters frame, with limited longitudinal and transverse size for the whole detector, we get the remarkable result that the minimum of electrical power and the minimum of the nominal magnetic field are not attained at the same point. This clearly shows the importance of the multi-optimization design approach.

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Effective processing pipeline PACE 2.0 for enhancing chest x-ray contrast and diagnostic interpretability

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Preprocessing is an essential task for the correct analysis of biomedical images. In particular, magnetic resonance imaging and X-ray imaging might contain artifacts, low contrast, diffractions or intensity inhomogeneities. Recently, we have developed a procedure named PACE [1] able to improve chest X-ray (CXR) images comprising the enforcement of clinical evaluation of several types of pneumonia, including COVID-19. At the clinical benchmark state of this tool, there have been found some peculiar conditions causing a reduction of details over large bright regions (as in ground-glass opacities and in pleural effusions in bedridden patients) and resulting in oversaturated areas. Here, we have significantly improved the overall performance of the original approach including the results in those specific cases by developing PACE2.0. It combines 2D image decomposition, non-local means denoising, gamma correction, and recursive algorithms to improve image quality. The tool has been evaluated using three metrics: contrast improvement index (CII), information entropy (ENT), and measure of enhancement (EME), resulting in an average increase of 35% in CII, 7.5% in ENT, and 95% in EME. These improvements led to better interpretability of lesion detection in CXRs. Figure 1 shows the curves for ENT (a), CII (b) and EME (c), respectively. PACE2.0 (black line) exhibits better performance and outperforms the above methods over the vast majority of the considered cases.

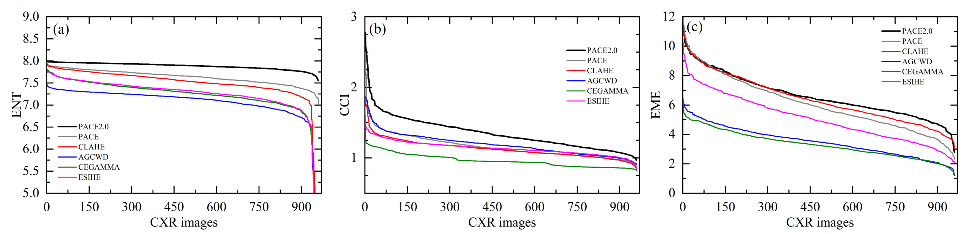

Figure 1: Results as obtained using new PACE2.0 (black line) from the public database (960 CXR images processed) and evaluated against PACE (gray line), CLAHE [2] (red line), AGCWD [3] (blue line), CEGAMMA [4] (green line), ESIHE [5] (magenta line) for Entropy (a), CCI (b) and EME (c), respectively. Our findings demonstrate that PACE outperforms these methods and provides better performance over the vast majority of the considered cases.

Additionally, the enhanced images were fed to a pre-trained Densenet-121 [6] model for transfer learning, resulting in an increase in classification accuracy from 86.9% to 94.4% and F_1 score from 93.0% to 97.1%, respectively. PACE2.0 has the potential to become a valuable tool for clinical decision support to healthcare professionals detecting pneumonia more accurately.

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Ultrafast inverse Cotton-Mouton effect in thin film of noncollinear antiferromagnet Mn_3NiN

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Metallic antiferromagnets (AFMs) have opened a new path in the research of non-volatile spintronic devices due to their remarkable characteristics. Antiferromagnetic ordering leads to a reduced sensitivity to magnetic field perturbations, multi-level stability and ultrafast spin dynamics. However, these features also make the characterization and manipulation of the AFMs, in particular of thin metallic films, which are suitable for spintronics, a challenging task[1]. Femtosecond laser pulses offer a robust, insightful and cheap experimental tool for both inducing effects on AFMs and probing the corresponding changes, e.g., via the Pump-probe method[2]. A small family of non-thermal optomagnetic laser excitations plays an important role, as they can be phenomenologically described as ultrashort (hundreds or tens of fs) magnetic fields directly affecting spins[3]. On the other hand, magneto-optical phenomena quadratic in magnetization (e.g., Cotton-Mouton effect, also known as Voigt effect) were shown to be useful for investigating pump-induced changes in metallic AFMs[4,5]. In this contribution we report on non-thermal opto-magnetic inverse Cotton-Mouton effect in 25 nm-thin film of non-collinear metallic AFM Mn_3NiN[6]. We also show that this mechanism induces ultrafast changes of the magnetic spin structure which we can experimentally study by magneto-optical Cotton-Mouton effect.

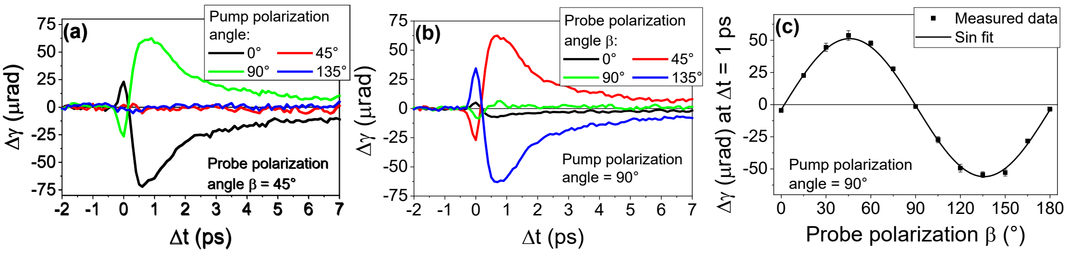

Figure 1: **(a)** Time-resolved change of ellipticity ($\Delta\gamma$) induced by pump pulses of different angles of the polarization plane. **(b)** Dynamics of $\Delta\gamma$ probed with various orientations of the probe polarization planes (β) induced by the pump pulse with 90° orientation. **(c)** Probe-polarization dependence of $\Delta\gamma$ measured at $\Delta t = 1$ ps for pump pulse with the 90° orientation (points); lines are fits by Eq. (2) in Ref. 1. Measured in 25 nm-thin Mn_3NiN on MgO substrate; sample temperature 25 K, wavelength of the pump and probe pulses 800 nm and 400 nm, respectively.

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Symmetry analysis of light-induced magnetic interactions via Floquet engineering

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Ultrafast light control of physical properties is a recent hot topic in condensed matter physics. Floquet engineering is a powerful theoretical tool for controlling physical properties by injecting light, where the time evolution of the system is described by effective time-independent interactions driven by light [1,2]. In magnetic systems, the effect of such a time-periodic field appears in the modification of the magnetic interactions, which results in a variety of phase transitions and associated material design. In particular, the modification of the anisotropic magnetic interactions, such as the Dzyaloshinskii-Moriya interaction, directly affects the spin textures. For examples, previous studies have shown that noncollinear/noncoplanar spin textures can be nucleated by light-induced magnetic interactions in a few specific systems [3,4]. Meanwhile, since induced anisotropic magnetic interactions are largely dependent on crystal symmetry, it is important to comprehensively clarify the relationship between light-induced magnetic interactions and crystal symmetry.

The present study gives a systematic understanding of the light-induced magnetic interactions that can be applied to any crystallographic point group [5]. Based on the Floquet theory and group theory, we classify three types of light-induced magnetic interactions, anisotropic two-site two-spin, two-site three-spin, and three-site three-spin interactions, in a comprehensive manner. As a result, we reveal a close relationship between the emergent magnetic interactions and the crystal symmetry, which provides a new symmetry-based guideline for material design with desired functionalities by light. We also show that a light-induced interaction triggers topological spin textures with a net spin scalar chirality.

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Phase diagrams for magnetic field and temperature induced ferromagnetism in antiferromagnetic FeRh

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FeRh is an outstanding antiferromagnet that can become ferromagnetic upon a temperature increase, applied strain or magnetic field. FeRh was first discovered in 1938 [1] and from that time it was known as a material with a counter-intuitive emergence of spontaneous magnetization upon heating. After the discovery of antiferromagnetism, it was realized that this heat-induced ferromagnetism must be interpreted as a first order phase transition from a low-temperature antiferromagnetic to a high-temperature ferromagnetic state.

It is remarkable, however, that despite the numerous works and attempts, the *H-T* phase diagram, which is practically the cornerstone in understanding any magnetic phase transition, has not yet been explored theoretically for FeRh. Moreover, although it is clear that in any antiferromagnet an external magnetic field can induce spin canting that promotes a non-collinear antiferromagnetic state, such a state has not been reported for FeRh.

Here we develop a mean-field model allowing to predict *H-T* phase diagrams for FeRh with a special attention to the canted antiferromagnetic phase. The constructed free energy F contains the following terms: the exchange interaction between the Fe sublattices; the interaction between the spins of Rh and the effective field acting on them; the interaction of the Fe spins with the external magnetic field and the magnetic anisotropy experienced by the spins of Fe. The key feature of our model is the Rh term which is constructed by considering energy levels of Rh ion.

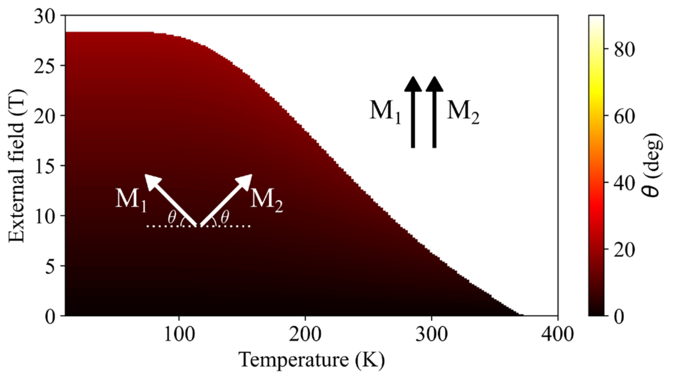

Figure 1: Example of *H-T* phase diagram for FeRh which fits experimental data in the best way (black dots are the critical magnetic fields deduced from resistance measurements).

Using experimental data, we propose possible phase diagrams which fit the experimental data in the best way (see fig.1).

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Identifying signatures of ultrafast skyrmion nucleation in reciprocal space

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Understanding ultrafast writing of nanoscale magnetic bits is a fundamental problem in magnetism and is increasingly important in technology. Magnetic skyrmions are ideal candidates to explore the limits for the smallest and fastest way to write magnetic bits, owing to their intrinsic stability and nanoscale dimensions. Recently, picosecond laser-induced nucleation of skyrmions has been discovered experimentally [1, 2], and important insights into the nucleation mechanism has been disclosed with the help of ultrafast X-ray scattering experiments supported with atomistic simulations [3, 4]. However, direct experimental detection of ultrafast skyrmion nucleation is challenging. In principle, detection of the emerging topology requires imaging the full 3D magnetization profile as a function of time. This is feasible on nanosecond time scales and beyond, but in the picosecond regime only access to X-ray scattering methods are currently available, giving only access to the out-of-plane magnetization.

In this work, we focus on a theoretical analysis of ultrafast skyrmion nucleation. We investigate if unique skyrmion signatures can be identified using only the out-of-plane component of the magnetization. We first demonstrate that for the Belavin-Polyakov skyrmion profile, there exists an one-to-one mapping between the absolute value of the out-of-plane magnetization and topological charge. In addition, we find that the skyrmion profile in reciprocal space is given by characteristic Bessel functions, which makes it distinct from other spin textures. Beyond the Belavin-Polyakov skyrmion, we lose the one-to-one mapping but still find characteristic oscillatory patterns with a period defined by the skyrmion radius in the limit of large radius to domain wall thickness. The nucleation itself is very broadly distributed in reciprocal space, in accordance with the spatially localized nature of the nucleation event. Starting from single isolated skyrmions, we explore the visibility of these signatures for various spatial nucleation patterns, including homogeneous nucleation, and nucleation in artificial skyrmion lattices. We are optimistic that our results will stimulate further theoretical and experimental investigations of ultrafast skyrmion nucleation, ultimately leading to new scenarios for the ultrafast fast writing of nanoscale magnetic bits.

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All-optical spin injection in silicon revealed by element-specific time-resolved Kerr effect

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Spintronics aims at adding the spin degree of freedom in novel electronic devices. This promising field has the potential of enhanced functionalities in terms of speed and energy consumption. Silicon is ideal due to its capability of allowing long-lived spin currents. To generate spin currents in semiconductors, the injection of spin-polarized hot electrons from a ferromagnetic film into the semiconductor substrate was proposed. This involves the superdiffusion of the charges excited by an ultrafast IR pulse and results in an efficient spin injection. These charges during the propagation in the metallic film become spin-polarized as spin-majority scattering times and velocities are bigger than the spin-minority counterparts.

Using the time-resolved resonant MOKE effect [1] we provided experimental evidence of the spin injection in silicon in the Ni/Si_3N_4/Si interface both at the Ni $M_{2;3}$ and at the Si $L_{2;3}$ edges. The results proved the existence of a magnetic state at both the edges, as well as the

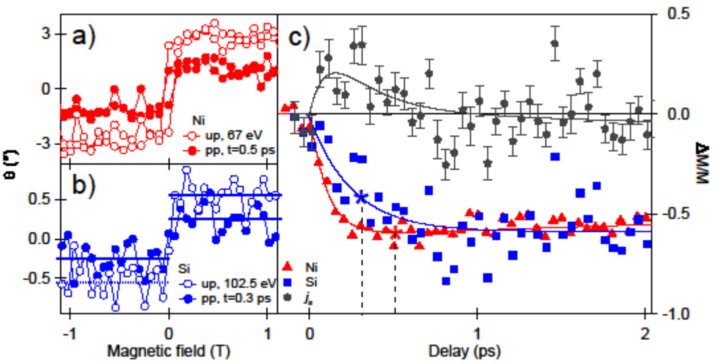

Figure 1: Unpumped and pumped RMOKE magnetic hysteresis at the Ni $M_{2;3}$ edge and at the Si $L_{2;3}$ edge (panel a and b). Panel c) dynamics of the relative change of the site resolved magnetization M (Ni - red dots and Si - blue dots) in a saturation magnetic field. From the exponential decay-recovery fit (solid lines) we extract the values for the demagnetization (τ_m) and recovery (τ_r) times. The difference of the two dynamics, defined as $(\Delta M/M)_{is}$, is also shown (gray).

onset and the propagation of a spin current in silicon [2]. The measurements were carried out at the MagneDyn beamline [3] at the externally seeded FERMI free-electron laser.

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space-time dynamics of topological magnetic fluctuation states

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Magnetic skyrmions are 2-dimensional swirling patterns of magnetization. Due to their nanometer size and high stability, they are ideal objects to investigate the physical limits for faster and smaller writing of magnetic bits. Recently, optical skyrmion nucleation with femtosecond laser pulses has been demonstrated in ferromagnetic multilayers [1,2], while X-ray studies [3] revealed that the switching was completed in less than 300ps, which is significantly faster than the characteristic timescale of skyrmions dynamics. Interestingly, atomistic spin dynamics simulations suggested that the nucleation mechanism stems from a transient topological fluctuation state in which the topological energy barrier is significantly reduced.

To gain insight into topological magnetic fluctuations, we present extensive atomistic spin dynamics simulations of a two-dimensional chiral ferromagnet. The spin dynamics in space and time reveals that these fluctuations can be understood as a competition between

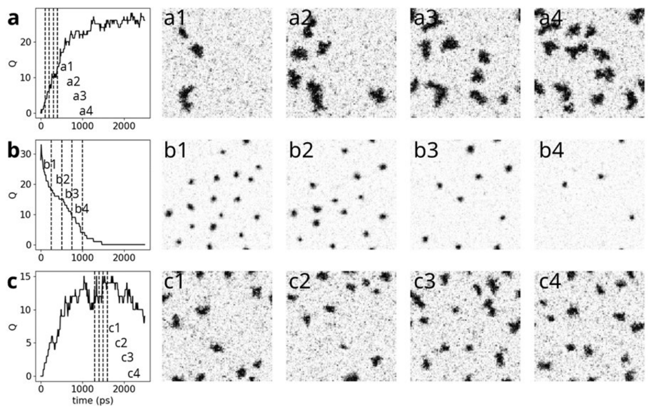

Figure: Time evolution of the topological charge Q (number of skyrmions) and selected snapshots of the out-of-plane magnetization at different constant temperatures and fields in the atomistic simulations. The timestamps of the snapshots are shown as dashed vertical lines and encoded 1-4. Rows (**a**), (**b**) and (**c**) respectively show regimes of spontaneous skyrmions nucleation, spontaneous decay and simultaneous nucleation and decay. The starting configuration in (**a**) and (**c**) is the ferromagnetic state and completely randomly aligned spins in (**b**).

skyrmion nucleation and decay, with characteristic time scales given by τ_N and τ_D respectively, both of which are dependent on temperature and magnetic field. A simple rate-equation model using fits of simulated relaxation at fixed temperature and field yields an intuitive picture of nonequilibrium topological fluctuation states featuring excellent qualitative agreement with the much more advanced atomistic spin dynamics simulations. Specifically, we explain the nucleation of skyrmions by an ultrashort heat pulse and the magnetic field-dependence of this process [4]. Our findings constitute and important step to discovering the speed-limits for fluctuation-assisted writing of nanoscale magnetic bits.

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Role of laser intensity and electron coherence in ultrafast demagnetization in FePt

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We theoretically investigate the optically-induced demagnetization [1] of ferromagnetic $L1_0$ FePt using the time-dependent density functional theory (TD-DFT). Our calculations show that the femtosecond demagnetization in TD-DFT is a longitudinal reduction and results from a nonlinear optomagnetic effect akin to the inverse Faraday effect.

We compare the demagnetization mechanism in the perturbative and non-perturbative limits of laser-matter interaction. The demagnetization scales quadratically with the electric field in the perturbative limit. The magnetization dynamics happen dominantly at even multiples ($n\omega_0$, $n = 0, 2, ...$) of the pump-laser frequency ω_0. These results are consistent with the theory of the inverse Faraday effect [2]. With a stronger laser, we demonstrate the influence of non-perturbative interaction on the demagnetization.

We further investigate the demagnetization in conjunction with the optically-induced change of electron occupations and electron correlations. The roles of electron coherence and correlation are notably distinct in the perturbative and non-perturbative regimes. Correlations within the Kohn-Sham local-density framework are shown to have an appreciable effect on the amount of demagnetization, see Fig. 1. Comparing the ab initio computed demagnetizations with those calculated from spin-dependent electron occupations, we show how the demagnetization picture from time-dependent spin-occupation numbers (i.e., neglecting coherence) poorly describes the ultrafast demagnetization process.

In addition, we show that the qualitative nature of the element-resolved demagnetization on Fe and Pt strongly depend on the laser intensity. This effect is attributed to the interplay of nonlinear spin-flip excitations and the laser-induced change of spin-occupations on the Fe and Pt atoms, i.e., optical inter-site spin transfer (OISTR) [3].

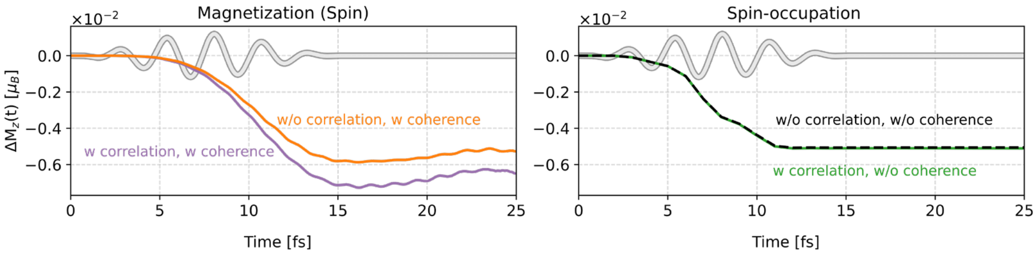

Figure 1: (Left panel) Ultrafast demagnetization with active (violet) and frozen (orange) electron correlations. (Right panel) Demagnetization due to a laser-induced change in spin-occupations, not containing the contributions from electron coherence.

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Study of magnetic and magnetocaloric effect on the high entropy alloy $Gd_{0.2}Tb_{0.2}Dy_{0.2}Ho_{0.2}Er_{0.2}Al_2$

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High entropy alloys (HEAs) have attracted increasing attention in recent years due to their unique physical and chemical properties, including their potential for magnetocaloric applications. The magnetocaloric effect is a phenomenon in which the temperature of a magnetic material changes when subjected to a magnetic field. HEAs have been found to exhibit a strong magnetocaloric effect due to their complex microstructures and high magnetic entropy change. This makes them promising candidates for use in magnetic refrigeration, which is a more environmentally friendly and energy-efficient alternative to traditional vapor compression refrigeration [1].

In this work, we report theoretical calculations of thermal and magnetic quantities such as magnetization and heat capacity, as well as magnetocaloric potentials (isothermal magnetic entropy, ΔS_T, and adiabatic temperature, ΔT_{ad}, changes) in the ferromagnetic high entropy alloy $Gd_{0.2}Tb_{0.2}Dy_{0.2}Ho_{0.2}Er_{0.2}Al_2$ using a microscopic model. The model Hamiltonian includes contributions from the Zeeman effect, crystalline electrical field anisotropy, and exchange interactions among the five different rare earth sublattices (Gd-Gd, Gd-Tb, Gd-Dy, etc.). Most of these were found by considering previous studies on pseudobinary compounds such as $Gd_{1-x}Dy_xAl_2$ [2], $Gd_{1-x}Tb_xAl_2$ [3], $Er_xTb_{1-x}Al_2$ [4], $Ho_{1-x}Dy_xAl_2$ [5], etc.

Experimental data [6] show that the Curie temperature is approximately the average of the individual components RAl_2 (R = Gd, Tb, Dy, Ho, and Er). The theoretical results are in good agreement with the available experimental data [6].

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[3] P. O. Ribeiro et al., J. Alloys and Compd. **563** (2013) 242–248.

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Design of planar AMR sensor arrays for 3D magnet motion tracking

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State-of-the-art tactile sensors based on magnetic transduction principles detect the change in flux density resulting from the applied force and often rely on conventional Hall-effect sensors [1]. Compared to the latter, magnetoresistive (MR) sensors exhibit enhanced signal-to-noise ratio, larger sensitivity and increased thermal stability. In this context, anisotropic MR (AMR) sensors are appealing due to their relatively simple and cheap fabrication process, which makes them easily prone to miniaturization thus allowing to attain high sensitivity at low cost in a compact footprint. Here, we combine numerical methods and analytical calculations to design planar AMR sensor arrays capable of tracking the 3D motion of a permanent magnet, thereby laying the foundation for realizing miniaturized 3D tactile sensors suitable to detect both normal and shear force components.

The proposed tactile sensor concept (Figure 1a) includes a permanent magnet embedded in a deformable membrane moving relative to a fixed planar array of AMR sensors. The latter are made of thin Permalloy ($Ni_{80}Fe_{20}$) stripes whose MR response is linearized via barber-pole biasing [2]. For modelling purposes, the permanent magnet's magnetic field is calculated by means of analytical expressions via the Magpylib Python package [4] and used as input in the finite-difference micromagnetic simulations (MuMax3) [3] computing the AMR sensor response: the system ground state is determined by dividing the Permalloy stripes into a finite number of regions, each with a different external magnetic field, which accounts for the field inhomogeneities at the AMR sensor position. The barber pole geometry is finally optimized via finite-element simulations (Ansys Maxwell).

Two AMR sensor array design concepts (Figures 1b and 1c) have been found which are suitable for tracking the 3D motion of sub-mm NdFeB magnets by solving a magnetic inverse problem. In both cases, the Permalloy stripes are arranged in Wheatstone bridges. The first design enables the reconstruction of the magnet position with ca. 10-μm accuracy (Figure 1d) within a motion range of 600 μm along x and y and of 300 μm along z, while the second one covers a wider motion range in all directions but with a 5-10 times lower accuracy.

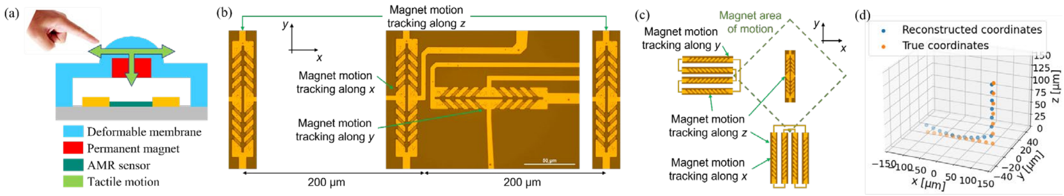

Figure 1: (a) 3D tactile sensor structure. (b) First and (c) second AMR sensor array design. (d) Example of 3D magnet motion reconstruction via the first AMR sensor array design.

These results demonstrate the possibility to track the 3D movement of a permanent magnet via suitably designed and monolithically fabricated planar arrays of AMR sensors. The versatility of the concept discussed here holds promise for the manufacture of not only tactile sensors, but also of a large spectrum of other easy-to-fabricate, miniaturized and low-cost sensors detecting a wide variety of observables (e.g., pressure, fluid flow, acceleration).

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Micromagnetic simulation of confined spin eigenmodes in nanostructured magnetic films with different software packages

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Micromagnetic simulations are essential in understanding the magnetic behavior of materials at the nanoscale, with important applications in data storage, spintronics, and magnonic devices. However, the accuracy and reliability of these simulations depend on the software used, making it crucial to compare the results obtained from different packages. Most of the software packages that are popular in the research community exploit a finite-difference method, i.e. they consider discretization of the simulated volume into cubic or rectangular cells of uniform size, while finite-element methods consider cells of different shapes and variable size.

This study focuses on micromagnetic simulations of the dynamic behavior of selected nanomagnetic nanostructures, comparing the results obtained from two different software packages: Mumax^3 [1] and Micromagnetic Module with COMSOL Multiphysics [2,3], that rely on a finite-difference and a finite-element approach, respectively. In particular, the characteristics of spin waves eigenmodes of one-dimensional and two-dimensional nanostructured thin film are analyzed, focusing of the analyses is on the spin wave modes localized in specific regions of the nanostructures.

Finally, we discuss the similarities and differences in the simulation results to put in evidence the strengths and weaknesses of the two different micromagnetic approaches.

This work has been funded by the European Union - NextGenerationEU under the Italian Ministry of University and Research (MUR) National Innovation Ecosystem grant ECS00000041 - VITALITY. Moreover, support by MUR by project IT-SPIN (PRIN-2020LWPKH7) is kindly acknowledged.

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[2] http://www.physics.fudan.edu.cn/tps/people/jxiao/comsol-module-for-micromagn.html

[3] https://www.comsol.com/

Atomistic and mesoscopic modeling of ferromagnetic/antiferromagnetic nanocomposite materials

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Ni-Mn-based Heusler materials [1] belong to a class of functional materials with unique physical properties allowing to be used in various applications such as magnetic shape memory, GMR-based devices and magnetic refrigeration. One particularly intriguing example is the ferromagnetism of Ni_2MnIn precipitates embedded in an antiferromagnetic (AFM) NiMn matrix [2], which is especially interesting due to its extremely high coercive field at room temperature.

The development of a physical model for a system of ferromagnetic (FM) precipitates embedded in an antiferromagnetic (AFM) matrix is the subject of this talk. For this system, 3D *mesoscopic* simulations are required due to two factors: (i) typical grain sizes of this nanocomposite lie in the range of tens of nanometers, and (ii) the *collective* nature of magnetization reversal of FM precipitates in the polycrystalline AFM matrix (Fig. 1a depicts a simulated structure of size on the order of a few hundred nanometers). In our case, a multiscale approach is essential since for mesoscopic micromagnetic simulations we need material constants obtained from the atomistic approach.

This study involves a quantitative comparison of simulated hysteresis loops with experimental data (Fig. 1b). The presented results demonstrate that our micromagnetic model is able to explain all the details of the remagnetization process in this FM/AFM material and proves that only taking into account the *polycrystalline* nature of the AFM matrix we can obtain a hysteretic behaviour. We have also calculated the evolution of the magnetization distribution in the FM phase (see example in Fig. 1c) for various precipitate sizes and exchange couplings with the AFM matrix. Our simulation provides the basis for the comparative analysis of these effects with experimental techniques qualified to study the magnetization distribution with the resolution of several nanometers such as magnetic small-angle neutron scattering.

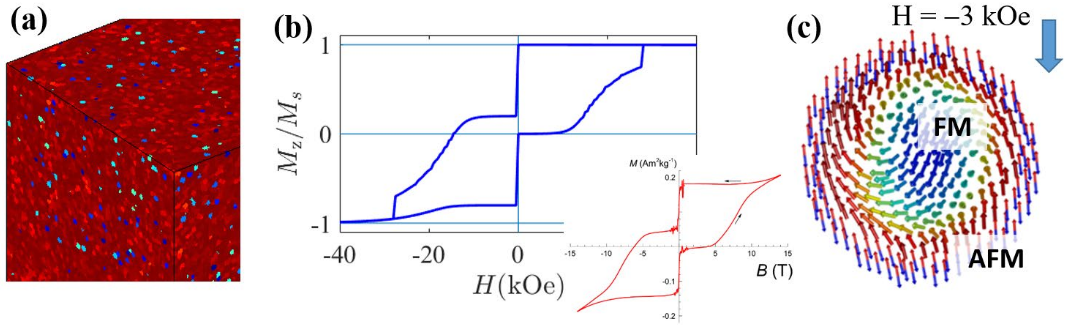

Figure 1: (a) Example of a FM/AFM polycrystalline material structure used in our simulations (warm colors – AFM crystallites, cold colors – FM crystallites). (b) Hysteresis loops of a system of FM precipitates in an AFM matrix obtained in mesoscopic modelling (blue) and experiment (red, adapted from [2]). (c) Magnetization distribution in a 50-nm spherical FM precipitate embedded in an AFM matrix with a strong AFM-FM coupling in an external magnetic field.

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Hysteresis model based on a measured main hysteresis loop and first order reversal curves

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The finite element method is often used for dimensioning of electromagnetic devices. The description of the magnetic materials should be as good as possible, so it is important that the nonlinear magnetic material is described with hysteresis.

Different hysteresis models have been developed in the past. The presented model is based on the measurement of the main hysteresis loop and first order reversal curves for increasing and decreasing magnetization. Each of them is presented with an extended Elliot expression written in (1) [1]. Based on our experience in working with magnetic materials, we added some parts to the original Elliot expression.

$$B(H) = \frac{P_1\left(H+P_3\right)}{P_4+P_2\left|H+P_3\right|} + P_5\mu_0\left(H+P_3\right) + P_6\,. \qquad (1)$$

Each of the measured curves (the left and right parts of the major hysteresis curve and each of first order reversal curves) has different parameters P1 to P6, obtained using Differential Evolution [2], and, with that, the best match was achieved between the measured and calculated curves.

The measured curves of the hard magnetic material Alnico, together with calculated curves using the Elliot expression, are presented in Figure 1 a).

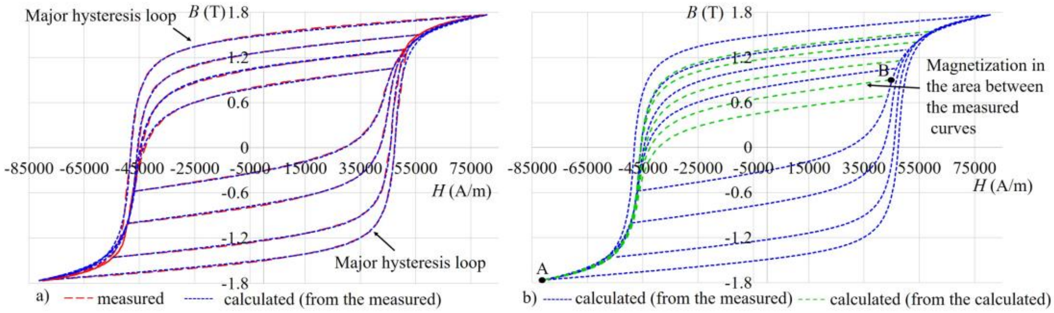

Figure 1: a) Measured and calculated hysteresis loop and first order reversal curves, b) Magnetization in the area between the measured curves.

A good feature of the presented model is the easy calculation of magnetization in the area where no measured curves are available. The curve between measures can be determined based on only two points (for example, points A and B in Figure 1 b)), and on the bases of the nearest calculated curve, which is described with (1), obtained from the measured curve using Differential Evolution for the parameter's determination. Only parameters P1 and P6 need to be corrected appropriately, as parameters P2, P3, P4 and P5 remain unchanged. A detailed description of the procedure will be presented in the final paper.

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Design and optimization of linear AMR sensor response

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Anisotropic magnetoresistive (AMR) sensors are attractive owing to their relatively simple and cheap CMOS-compatible fabrication process, which makes them easily prone to miniaturization thereby offering the possibility to achieve high sensitivity at low cost in a relatively compact footprint. In this work, a theoretical study aiming at design the optimal configuration of the biasing technique named barber-pole [1] for AMR sensors is carried out by means of finite-difference (FD) and finite-element (FE) simulations. MR sensor response strongly depends on the sensor geometry and it can be tailored to a specific magnetic field of interest by varying the dimensions of the sensor and the material parameters. Micromagnetic FD simulations performed with Mumax^3 [2] have been used to compute the MR response of Permalloy (Py) ($Ni_{80}Fe_{20}$) stripes having thickness in the range of 5 to 50 nm, width (w) from 500 nm to 10 um and length of 50 um. In order to obtain a linear sensor response, the barber-pole structure consisting of 5 nm of Chromium and 50 nm of Gold has been investigated. A systematic study was performed to determine the optimal barber-pole configuration in order to obtain a 45° angle (α) between the direction of the electrical current and the magnetization vector resulting in a linear sensor response. The optimal barber-pole length (L_{bp}) and their separation (s) were computed for different sensor geometry by calculating the electrical current distribution via FE Ansys Maxwell [3] software. Finally, a simple analytical model that involves the geometrical parameters of the sensor and of the barber-pole structure was developed to determine the value of α.

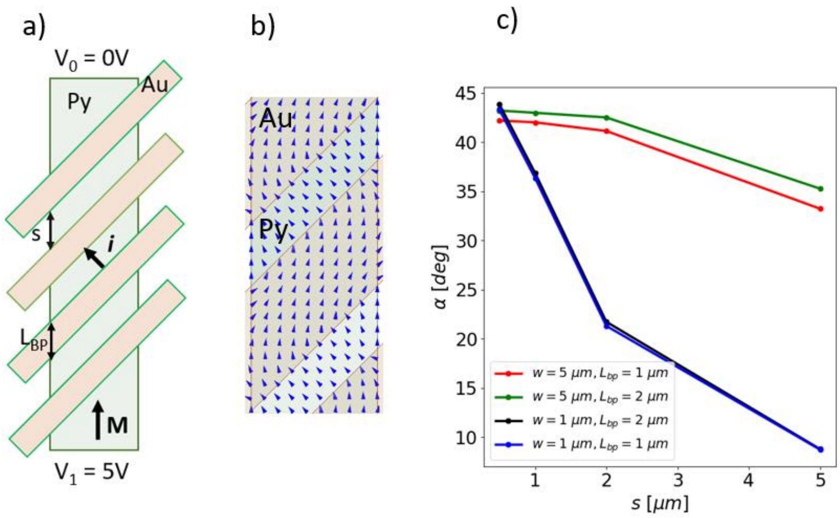

Figure 1. (a) Schematic of the AMR sensor in the so-called barber-pole configuration. (b) Distribution of the electrical current. (c) Average angle of the electrical current inside the AMR sensor.

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Constrained domain wall in atomic-sized constrictions between ferromagnetic nanostructures

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Nanometer-sized constrictions in ferromagnetic nanostructures are of great interest due to their unique properties and potential applications in nanomagnetism and spintronics [1]. By confining magnetic domains to very small regions, these structures allow to explore the fundamental properties of magnetism and even to control magnetic configurations at the atomic scale which can be used for developing new technologies. Our study focuses on the magnetization reversal within an atomic constriction that separates magnetic nanostructures of the same material in the shape of mounds, discs and Wulff polyhedrons at the nanoscale (see e.g fig. 1). We used atomistic magnetic simulations for modeling our systems. Our calculations show that the domain wall is almost entirely confined within the atomic-sized constriction in agreement with conclusions drawn from an analytical model [2]. We also found that the domain wall extension is primarily determined by the geometric properties of the islands-constriction system rather than intrinsic material properties like magnetocrystalline anisotropy, exchange coupling, or material saturation magnetization.

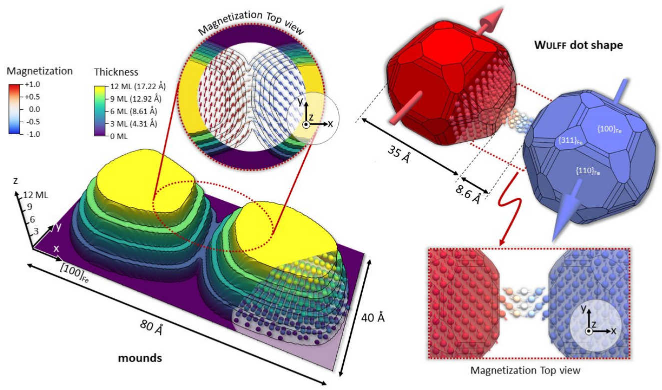

Figure 1: Atomic magnetic moment orientations for two nanoscale dots connected by an atomic constriction. The magnetization rotation takes place inside the constriction.

We demonstrate that magnetic interactions between nanometric islands connected by an atomic bridge can be approximated by two macrospins coupled by an effective Heisenberg exchange interaction for which we assessed the strength as a function of the geometric parameters of the atomic constriction. This result allowed us to successfully model the magnetic properties of large ferromagnetic island assemblies whose individual magnetic properties such as magnetization and shape anisotropy can be specified. For instance, our study revealed that the low-scale roughness of ultra-thin epitaxial films not only significantly alters the magnetic anisotropy properties but can also strongly modify the magnetization dynamic in a sub-micrometer systems. These findings are of significant importance for the future design and development of high-performance devices based on magnetic systems at the nanoscale.

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Spin reorientation transition in $Dy_{1-x}Tb_xAl_2$ compounds

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The magnetocaloric effect (MCE) was observed at the first time in 1917 by Weiss and Piccard [1] when realized a sizable and reversible temperature change in nickel near its Curie temperature. This effect is usually investigated by two processes: isothermal and adiabatic ones leading to two important characteristic thermodynamic quantities: the isothermal entropy change (ΔS_T) and the adiabatic temperature change (ΔT_{ad}).

In this work, we compare the magnetic and magnetocaloric properties of pseudobinary intermetallic compounds with $Dy_{1-x}Tb_xAl_2$ where x = 0, 0.15, 0.35, and 0.4 modelled results using a Hamiltonian that includes exchange interactions among Dy-Dy, Dy-Tb, and Tb-Tb ions, as well as the crystalline electric field and the Zeeman effects, with experimental results [2]. To reproduce the experimentally observed ferromagnetic ordering and spin reorientation transition temperatures as the Tb concentration (x) varies [2], the exchange interactions within the rare earth sub-lattice were treated as free parameters and adjusted to match the experimental results.

Our findings indicate that the heat capacity of polycrystalline materials in non-zero magnetic fields can be satisfactorily reproduced by averaging the main three field directions with respect to the crystallographic coordinate system. Moreover, we demonstrate a reasonably good agreement between the experimentally [2] determined and theoretically predicted magnetocaloric effects.

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Structural and Magnetic Inhomogeneity in GdCo Studied by X-ray Resonant Magnetic Reflectivity

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Ultrafast all-optical switching (AOS) of the magnetization in ferrimagnetic rare-earth—transition-metal (RE—TM) alloys using a single femtosecond laser pulse [1] has attracted a lot of interest, as it has the potential for novel data recording applications. Among others, one possible explanation for AOS are structural inhomogeneities on (sub)nanometer length scales [2] and the associated inhomogeneous magnetization distribution. In such a scenario, parts of the film would demagnetize more and faster than others which, in combination with the antiferromagnetic exchange coupling between RE and TM sublattices, could result in the reversal of the magnetization on macroscopic length scales. The advent of highly brilliant X-ray sources allows for studying such nanoscale magnetic inhomogeneities (and their ultrafast dynamics) in lateral and transverse directions employing X-ray resonant magnetic scattering (XRMS) in transmission and reflection geometry, respectively. The data obtained by XRMS, however, are very complex, their analysis needs careful post processing and their interpretation often requires information from complementing experiments or sophisticated simulations.

In this work we studied the in-depth structure and magnetization of ferrimagnetic GdCo alloys employing X-ray resonant magnetic reflectivity (XRMR) at the synchrotron SOLEIL, beamline SEXTANTS. For that we recorded the specular reflection over a wide angular range (0° - 60°) as well as for several energies around the Gd M_5 and Co L_3 edge. We utilize DYNA, a formalism for the reflectivity of electromagnetic waves by magnetic materials based on the transfer matrix method which includes the roughness between layers [3], in order to simulate our XRMR results. The best fit to the data is obtained for a non-homogeneous structure and magnetization, i. e., an agglomeration of Gd at the surface followed by a Gd-depleted region which is associated with a variation of the magnetic moment along the direction of the sample's surface normal. Our findings are the starting point for investigating the ultrafast laser-induced magnetization dynamics in-depth of RE—TM alloys combining *time-resolved* XRMR [4] at modern synchrotron and X-ray free-electron laser sources with simulations using the DYNA code, in order to shed light onto the possibility of AOS due to spatial magnetization variations.

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Unconventional Spin Pumping and Magnetic Damping in an Insulating Compensated Ferrimagnet

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Recently, the interest in spin pumping has escalated from ferromagnets into antiferromagnetic systems, potentially enabling fundamental physics and magnonic applications. Compensated ferrimagnets are considered alternative platforms for bridging ferro- and antiferromagnets, but their spin pumping and the associated magnetic damping have been largely overlooked so far despite their seminal importance for magnonics. Herein, we report an unconventional spin pumping together with magnetic damping in an insulating compensated ferrimagnet $Gd_3Fe_5O_{12}$. Remarkably, we unambiguously identified the divergence of the nonlocal effective magnetic damping induced by spin pumping close to the compensation temperature in $Gd_3Fe_5O_{12}$/Cu/Pt heterostructures. Furthermore, the coherent and incoherent spin currents, generated by spin pumping and spin Seebeck effect respectively, undergo a distinct direction change with the variation of temperature. The physical mechanisms underlying these observations are self-consistently clarified by the ferrimagnetic counterpart of spin pumping and the handedness-related spin-wave spectra. Our findings broaden the conventional paradigm of the ferromagnetic spin pumping model and open new opportunities for exploring the ferrimagnetic magnonic devices.

Antidot lattice with perpendicular magnetic anisotropy: dynamics between edge modes and bulk modes

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Magnonic crystals (MCs) have demonstrated a lot of potential as a way to control the propagation of spin waves (SWs). Having the ability to create and control SWs could lead to the creation of magnonic devices that are more space efficient than optical devices and more energy efficient than current electronics. In this research, we will study a type of MC created in a thin film made up of 8 repetitions of Co (0.75nm) and Pd (0.9nm) bilayers for a total of 13.2 nm [1]. This particular combination of a ferromagnetic layer and a heavy metal layer results in a strong perpendicular magnetic anisotropy (PMA) which is interesting as it makes the SW dispersion isotropic. Periodically throughout this thin-plane film, nanodots were etched out using a 10nm wide focused ion beam producing a pattern of antidots. This process not only removed some material, but also damaged the area around each antidot, creating a 'rim' around the antidots where the magnetic properties, notably the PMA have been modified. Due to this, the magnetization at the antidot's edges is almost in-plane. As shown in Fig. 1, the ground state of a circular antidot is magnetized in its edge ring in a vortex-like configuration. Through micromagnetic simulations, we analyse the dynamic coupling between edge localised and bulk modes in the film. At first, we limit our analysis to non-propagating SWs and we modify the exciting field as well as the strength of the global external static magnetic field which is oriented out-of-plane and we analyze the SW modes that exist in the rim or in the bulk. Next we will show the dynamic coupling between rims and bulk, demonstrating collective behavior on the lattice seen in Fig. 2 and promising magnonic applications.

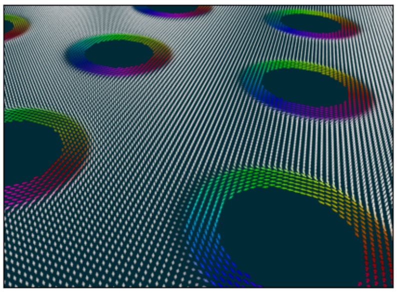

Figure 1. Magnetization in the magnonic crystal

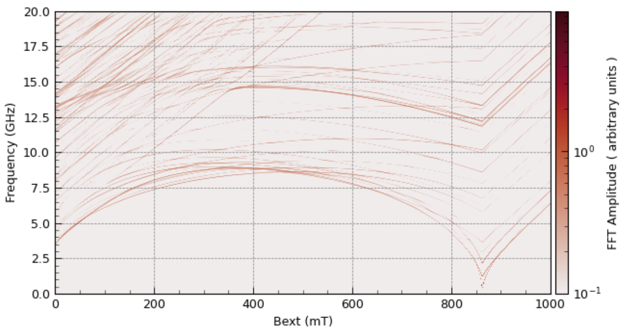

Figure 2. Resonance spectra of spin waves depending on the saturating field

The authors acknowledge funding from the Polish National Science Centre, project No. UMO2020/37/B/ST3/03936.

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Giant in-plane anisotropy of magnetic damping in epitaxial Cr/Fe bilayer

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Understanding the magnetic relaxation process in spin-torque devices for practical applications remains a challenging task. The relaxation rate, or magnetic damping α, is one of the crucial parameters that governs the critical current density for current-induced magnetization switching [1-4]. In this study, we present an investigation of the angular dependence of magnetic damping in an epitaxial Cr/Fe bilayer using ferromagnetic resonance measurement technique. Our results indicate a strong in-plane anisotropy in the total magnetic damping of the bilayer film, despite its negligible magneto-crystalline anisotropy. In this presentation, we will thoroughly discuss and propose possible mechanisms that account for such profound damping anisotropy in the bilayer, which consists of a ferromagnet and a 3*d* non-magnetic metal.

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Switching magnetic strip orientation using electric fields

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The tailoring of magnetic domains is important for both fundamental research and applications. Ordered magnetic strip domains with alternating up and down magnetization components enable stable magnetic configuration in the absence of the external magnetic field that is highly desirable for applications. The orientation of magnetic strip is closely related to domain wall resistance and spin wave propagation such that being able to modulate magnetic strip orientation is important. Although magnetic field can be employed to reorient the magnetic strip domains, electrical approaches are of interest to meet future low power consumption demands. Electric currents have recently been injected to control strip domains via spin-transfer torque; however, the manner in which the strip domains can be reoriented only by applying an electric field remains elusive.

Electric fields are considered to be an energy-efficient solution to controlling magnetism. In the past decade, considerable progress in the electric-field control of magnetism has been made in multiferroics, particularly in ferroelectric/ferromagnetic multiferroic heterostructures with significant magnetoelectric effect at room temperature. Previous studies on multiferroic heterostructures mainly focused on macroscopic magnetic properties, e.g., magnetic hysteresis loops. However, electric-field control of microscopic magnetic domains is desired to fulfill future demands for magnetic memory with high density and low power. Magnetic strip domains with alternating up and down magnetization components provide a platform to examine microscopic out-of-plane magnetization. Some work has been performed to control magnetic strip domains based on strain-mediated magnetoelectric coupling; however, the effect of electric-field-induced piezostrain eliminated the strip domains rather than manipulating their orientation. **Currently, the electric-field rotation of ordered magnetic strip domains is still not possible.**

Here, **we demonstrate the electric-field-driven continuous rotation of ordered magnetic strip domains in Ni/Pb($Mg_{1/3}Nb_{2/3}$)$_{0.7}$$Ti_{0.3}O_3$ (PMN−PT) multiferroic heterostructures** via strain-mediated magnetoelectric coupling. Using the patterning stress generated in nanotrenched polymeric layers, we obtained ordered magnetic strip domains in a Ni film on the PMN−PT ferroelectric substrate (Fig. 1a). While applying electric fields to the PMN−PT substrate, the orientation of the ordered magnetic strip domains continuously rotated from the *y*-axis to *x*-axis as observed via magnetic force microscopy (MFM) (Fig. 1b). Micromagnetic simulations demonstrated that these continuous electric-field-rotated ordered magnetic strip domains were caused by the electric-field-induced continuous modulation of the in-plane magnetic anisotropies along the *x*- and *y*-axes because of the anisotropic biaxial strain of the PMN−PT ferroelectric substrate. Our results provide an energy-efficient approach for manipulating the ordered magnetic domains using electric fields.

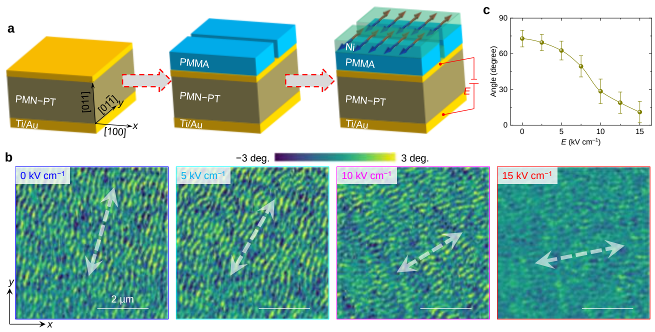

Fig. 1. Modulation of the ordered magnetic strip domains by electric fields via strain-mediated magnetoelectric coupling.

Exceptional temperature-dependence of Brownian dynamics of topological magnetic textures

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In 1827 the scottish botanist Robert Brown discovered that pollen dispersed in water perform a stochastic motion, which today bears his name. Around two centuries later it was discovered that magnetic skyrmions, topologically non-trivial quasiparticles, in ultrathin multilayer stacks also display Brownian motion [1]. However, the dynamics of skyrmions is inherently different from classical Brownian particles, due to the emergence of a Lorentz-force-like term – the gyocoupling [2].

We combine classical atomistic spin dynamics simulations and analytical calculations based on Thieles equation [2] to study the Brownian dynamics of magnetic domain walls and skyrmions. We reveal that gyrocoupling is a general aspect of ferromagnetic spin textures, as a result of the properties of the Lagrangian describing classical spin dynamics. Gyrocoupling gives rise to diffusion suppression, i.e. drastically reduced Brownian motion, for skyrmions in the absence of external potentials – where this is fundamentally linked to topology [3] – and domain walls in uniaxial nanowires [4]. We further demonstrate, studying skyrmions in random pinning potentials [5] and domain walls in biaxial nanowires [4], that the presence of external potentials can lead to a surprising and drastic enhancement of their Brownian motion, which, however, may vanish again if the external potentials can be overcome by thermal flucutations. This gives rise to a peak in the thermal diffusion at some temperature, which can be viewed as a *Walker breakdown of Brownian motion* (see Fig. 1) [4,5].

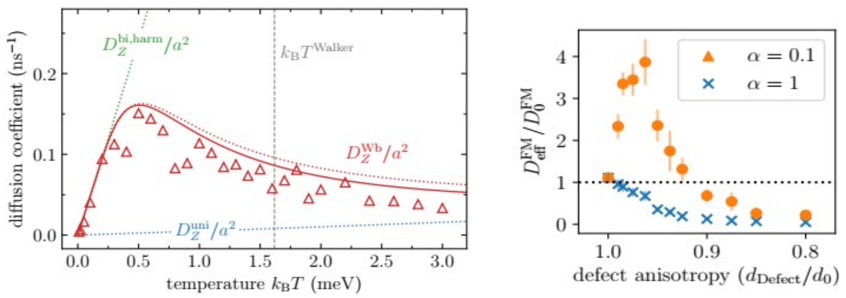

Figure 1: Walker breakdown of domain walls in uniaxial nanowires (left) and of skyrmions in random pinning potentials (right).

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[5] P. Rieger et al., in preparation.

Magnon squeezing in conical spin spirals

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We investigate squeezing of magnons [1] in a conical spin spiral configuration [2] forming due to competing Heisenberg and Dzyaloshinsky–Moriya interactions. Performing a Bogoliubov transformation, we calculate the energy of magnons propagating along the $\boldsymbol{k}$ and the $-\boldsymbol{k}$ directions which can differ due to the nonreciprocal dispersion [3].

These two modes are connected by the squeezing, hence can be described by the same squeezing parameter showing reciprocal properties under wave-vector inversion. The squeezing parameter diverges at the center of the Brillouin zone due to the translational Goldstone mode of the system, but the squeezing also vanishes for certain wave vectors.

As an example system we regard a two-dimensional square lattice-magnet on a substrate in the C_{4v} symmetry class, as shown in Fig. 1, with nearest-neighbour and next-nearest-neighbour exchange interactions J_1, J_2 and nearest-neighbour Dzyaloshinskii-Moriya interactions $\boldsymbol{D}$. Furthermore, a magnetic field $\boldsymbol{B}$ along the cone opening direction is considered. We derive possible ground state configurations and two are discussed in depth. First a spin spiral forming along the diagonal of the x-y-plane, second a spin spiral forming along the x-axis are investigated. For both configurations the squeezing parameter respects a C_{2v} symmetry and decreases towards the Brillouin zone boundary while showing curves of vanishing squeezing inside the Brillouin zone. arXiv: 2304.06338 (2023)

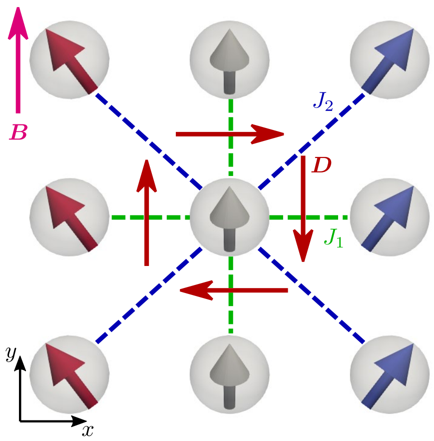

Figure 1: Directions of the Dzyaloshinsky-Moriya vectors (D) in a square-lattice magnet on a substrate in the C_{4v} symmetry class. The interaction J_1 acts between the middle site and the neighbouring sites along the x (y) direction (green line). The interaction J_2 acts between the middle site and the next-neighbouring sites along the diagonals (blue line). The magnetic field B (purple arrow) is indicated in the upper left corner.

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Influence of disorder at Insulator-Metal interface on spin transport

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Motivated by experimental work showing enhancement of spin transport between yttrium iron garnet and platinum by the thin antiferromagnetic insulator NiO[1] between them, we consider spin transport through the interface of a non-magnetic metal and a Ferro- or antiferromagnetically ordered insulator. The spin transport is carried by spin-polarized electrons in the metal and by magnons in the insulator. Spin current can be generated by a spin accumulation in the metal due to the inverse spin hall effect, microwave field existing magnons in the insulator, or by a thermal gradient (spin Seebeck effect). The spin current can be computed using Fermi's Golden Rule[2].

$$I\_(i \to f) = \frac{1}{h} \left|\langle \psi_f \middle| H_{Int} \middle| \psi_i \rangle\right|^2 \delta(E_f - E_i) \tag{1}$$

For a perfectly clean interface, the in-plane momentum is conserved for the electron-magnon scattering events which govern the spin transport through the interface. We calculate how disorder-induced broadening of scattering matrix elements with respect to the in-plane momentum influences the spin current.

As a general result, we observe that for many experimental setups, one should expect a rather small effect of interface disorder on the measured spin current. To be more specific, we entered the distribution functions for magnons and for electrons that appeared in Fermi's Golden Rule and have the result for the current as a function of temperature for various strengths of broadening.

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Structural, Electronic, magnetic and Thermal Properties of ZnO/Fe Wurtzite Phase - First-Principle Investigation

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Abstract

The ground-state properties of ZnO/Fe compound in the Wurtzite-type structure are investigated using accurate first principles total-energy calculations based on the full-potential augmented plane-wave (FP-LAPW) method within the density functional theory (DFT). The exchange-correlation potential for structural properties was calculated by the generalized gradient approximation (WC-GGA), while for electronic and magnetic properties the GGA-08 and modified Becke-Johnson (mBJ-GGA) schemes are applied. Quantities such as, equilibrium lattice constants (a, c and μ) and bulk modulus are found to be in good agreement with the available reported data. On the other hand, the estimated mBJ-GGA band gap value is in good accord with the literature. In addition, pressure and temperature effects on the lattice constants (a, c and μ), bulk modulus, energy gaps, heat capacity, and thermal expansion coefficient are investigated in the pressure range of 0-10 GPa when the temperature is changed from 0 to 1000 K.

Engineering spin textures and dynamics in magnetic van der Waals heterostructures

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The advent of two-dimensional magnetic van der Waals(vdW) heterostructures has led to novel ideas of information transfer in the field of spintronics. By probing the intrinsic spin dynamics of the electrons rather than its charge, it is possible to transfer information without ohmic losses [1]. We aim to study spin textures and dynamics using a local non-invasive scanning magnetometry technique. Our detector consists of a single nitrogen-vacancy (NV) center in diamond that is attached to an AFM cantilever to enable scanning measurements at cryogenic temperatures [2].

The electronic ground state of the NV center is a spin triplet ($S = 1$) consisting of three spin sub-levels $|0\rangle$, $|\pm1\rangle$. Additionally, the NV allows for optical detection of its spin configuration due to difference in photoluminescence (PL) emitted from the $|0\rangle$ and $|\pm1\rangle$ states. In the presence of a magnetic field, the $|\pm1\rangle$ spin states undergo Zeeman splitting, which can be precisely measured using optically detected magnetic resonance (ODMR). This makes NV center in diamond a highly sensitive magnetometer.

Our objective would be to excite, stabilize, detect, and propagate spin waves in magnetic vdW heterostructures. The material of choice is chromium chloride ($CrCl_3$), a layered in-plane XY-antiferromagnet that has the potential to host magnons, the quanta of spin[3]. Furthermore, we aim to engineer magnonic modes by tuning the magnetic exchange interaction (known as Dzyaloshinskii-Moriya interaction) by proximity coupling to atomically thin transition metal dichalcogenides (TMDs) [4].

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Emergent electric field and magnetic resonance in a one-dimensional chiral magnet

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Swirling spin textures such as skyrmions bring about an emergent magnetic field in conduction electrons through the Berry phase mechanism, leading to intriguing transport phenomena like the topological Hall effect. When such spin textures exhibit time-dependent dynamics, an emergent electric field (EEF) is generated by Faraday's law. For instance, in a one-dimensional chiral magnet, collective spin dynamics induced by an AC magnetic field on a helical spin texture brings about an EEF, which affects the transport properties of conduction electrons [1]. Although such an EEF would be useful for the realization of next-generation electronic and magnetic devices, the fundamental understanding of the spin dynamics and the resultant EEF is still lacking, especially the relation between the EEF and magnetic resonance.

In this study, we theoretically investigate the EEF associated with the spin dynamics driven by an AC magnetic field as well as the magnetic resonances in a one-dimensional chiral magnet, by numerically solving the Landau-Lifshitz-Gilbert equation (Figure 1). We show that the EEF becomes prominent at the magnetic resonant modes and that the higher frequency modes are more clearly visible than the magnetic responses. The EEF is amplified by the solitonic feature of spin textures enhanced by the magnetic field perpendicular to the chiral axis. We also find that the amplitude of the EEF is maximized when the direction of the AC magnetic field is perpendicular to the chiral axis and the static magnetic field. Furthermore, we reveal that the edge modes appear under the open boundary condition, which can generate the EEF comparable to the bulk responses at the magnetic resonances depending on the system size. To investigate the emergence of the edge modes, we also study the magnetic resonance structures by the linear spin wave theory and clarify that the edge modes appear within the magnon band gap caused by a solitonic feature of spin textures. We also demonstrate that the swirling spin textures can be driven in a specific direction by applying the AC magnetic field and the solitons can penetrate into the system from the edges by activating the edge modes. Our systematic studies on the EEF, the resonance structures, and dynamical properties would pave the way for the applications of one-dimensional chiral magnets to electronic and magnetic devices.

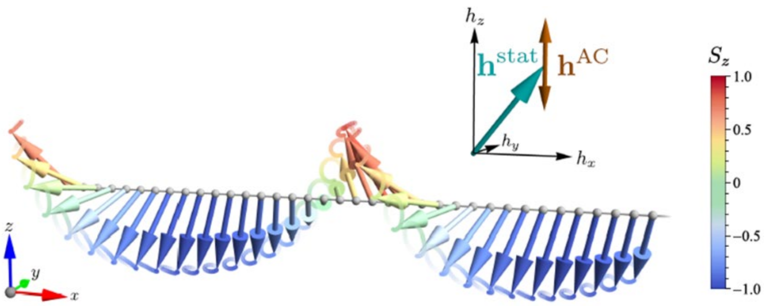

Figure 1: A schematic illustration of the dynamics of the swirling spin texture driven by an AC magnetic field $\mathbf{h}^{\mathrm{AC}}$ with a static one $\mathbf{h}^{\mathrm{stat}}$. The arrows and the colors denote the directions and the z components of spins, respectively. The pale curves attached to the arrowheads represent the trajectories of the spins in the time evolution.

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MRAM Based Associative Memory For In-Memory Computing

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This work is inspired by the 2-transistor 2-resistor (2T2R) magnetoresistive (MRAM) crossbar design, recently unveiled by Samsung [1]. We converted the original crossbar into an associative memory (AM), and transformed the associative memory into a massively parallel in-memory associative processor (AP).

Computing is increasingly dominated by the transfer of large data volumes through bandwidth-limited interfaces to the locations where computations are performed, which hampers the performance and energy-efficiency of conventional computer architectures [2]. This is leading to a change in computing paradigms. An alternative way to overcome the so-called "memory wall" is to compute in-data, i.e., directly within the memory arrays. This paradigm, which we refer to is the "in-memory computing", which employs the same memory cells for both data storage and data processing.

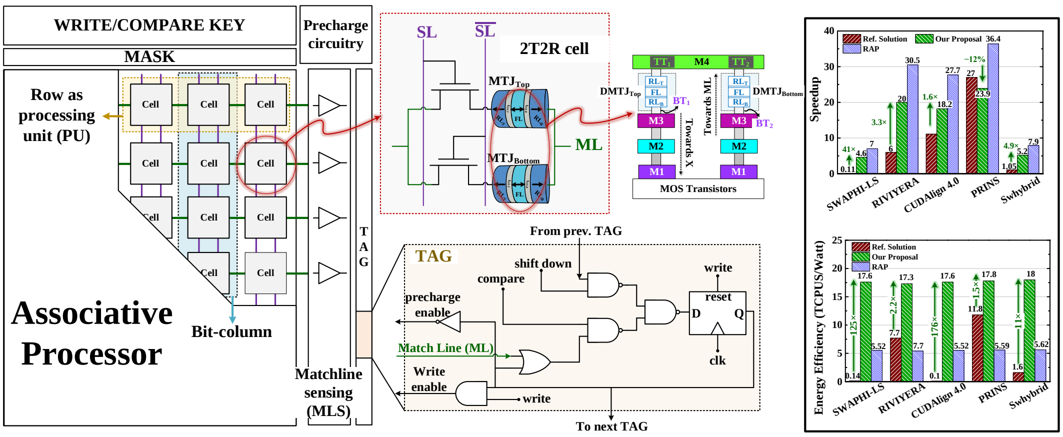

Figure 1: In-memory associative processor, highlighting the proposed associative cell, along with the illustration of the 3D hybrid CMOS/MTJ process. At the right, the speedup and energy-efficiency (TCPUS/Watt)

The associative processor (AP) is presented in Fig. 1. Its core is the 2T2R celll crossbar, whose stored states as '1' and '0' are according to the resistances of the left (now top) and right (now bottom) DMTJs. A '0' is stored by writing parallel spin (LRS) into the top DMTJ and anti-parallel spin (HRS) into the bottom DMTJ. The complementary state (HRS, LRS) is considered a '1'. The columns are supplemented with write/compare key and mask registers above the array Masking-off (i.e., rendering certain bit columns unaffected by either compare or write), is achieved by setting SLleft = SLright = '1' for compare and SLleft = SLright = '0' for write, respectively. The Matchline Sensing (MLS) column is built with row-connected sense amplifiers, which drive the TAGs. We conducted an exhaustive design space exploration, showing that the AP exhibits very low susceptibility to process variations around even and skewed corners. Then the AP was applied to Smith-Waterman DNA sequence alignment, a frequent bioinformatics workload. AP was shown to significantly outperform state-of-the-art conventional as well as other in-memory computing alternatives in terms of performance and energy-efficiency.

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Multilayer Spintronic device as a synapse and neuron for neuromorphic computing

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Spintronic devices have shown promise for energy-efficient storage and neuromorphic computing [1][2]. In this abstract, we present the experimental and micromagnetic realization of a multilayer heterostructure spintronic device for the memory and neuromorphic device. We observe the discrete resistance behavior in the device and discreteness increases as we lower the temperature. We attribute this discrete resistance behavior to the magnetic domain wall pinning/depinning and gradual switching of different magnetic layers which starts dominating at low temperatures. The discrete resistance states across the range of temperatures opens a possible application of these devices in cryogenic electronics for quantum computers. The discrete resistance behavior is also observed in the micromagnetic simulations of the similar crossbars of different widths. The evolution of resistance states with current pulses providing spin transfer torque and spin orbit torque is also explored in both experiments and simulations. Considering the multi-resistance state behavior of the device, we propose its applications as a synaptic device for neuromorphic computing. We map these resistance states as the weights of a neural network architecture. Furthermore, the device also acts as a leaky integrate and fire neuron when stressed by spin orbit torque and spin transfer torque pulses. The network based on these devices is trained and tested on the MNIST data set using supervised learning algorithm and spiking neural network. The system shows the accuracy performance up to 90% which is comparable to the majority of the beyond CMOS synaptic devices.

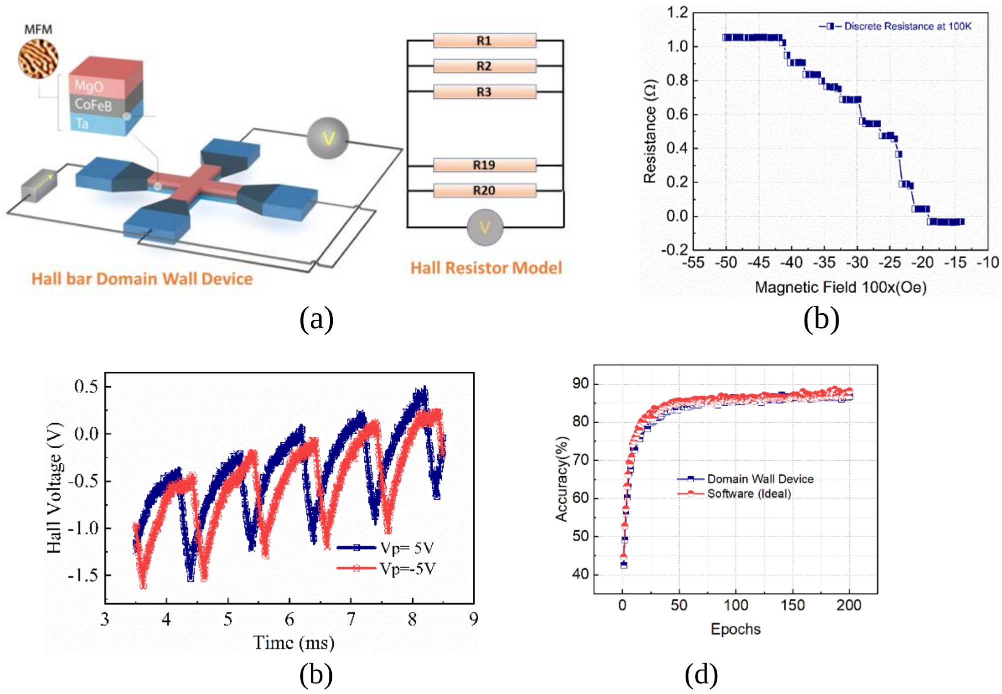

Fig. 1(a) Multilayer Hall bar device. (b) Discrete resistance states. (c) LIF neuron behavior and (d) MNIST data recognition accuracy

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Binary neural networks realized with cascade MTJ vortices

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[c] Unité Mixte de Physique, CNRS, Thales, Université Paris-Saclay, Palaiseau, France

With the soon perspective of the saturation of Moore's law, the attention of academia and industry is shifting towards novel approaches to realize computing tasks. We propose the use of magnetic vortices for the implementation of a synaptic unit of a neural network in a similar manner to [1], but with the application designed for binary weights that are encoded into the nonvolatile polarity of the vortices, represented in Fig. 1(a).

The system is based on the intrinsic properties of magnetic vortices which can switch their core polarity in the presence of an alternated stimulus with a frequency close to the resonance one [2]. It has been demonstrated that a small magnetic field leads to a shift in opposite directions of the resonance frequencies of the two polarity states of the vortex core [3], as can be seen in Fig. 1(b). We observed such phenomena in experiments with magnetic-tunnel junctions (MTJs) where the frequency shift is due to magnetic imbalances of the pillar structure in the absence of an externally applied magnetic field.

We demonstrate the usability of this technology and we propose its use of this technology for the encoding of nonvolatile binary weights of a neural network and their multiplication by a factor associated with the power of the ac input signal.

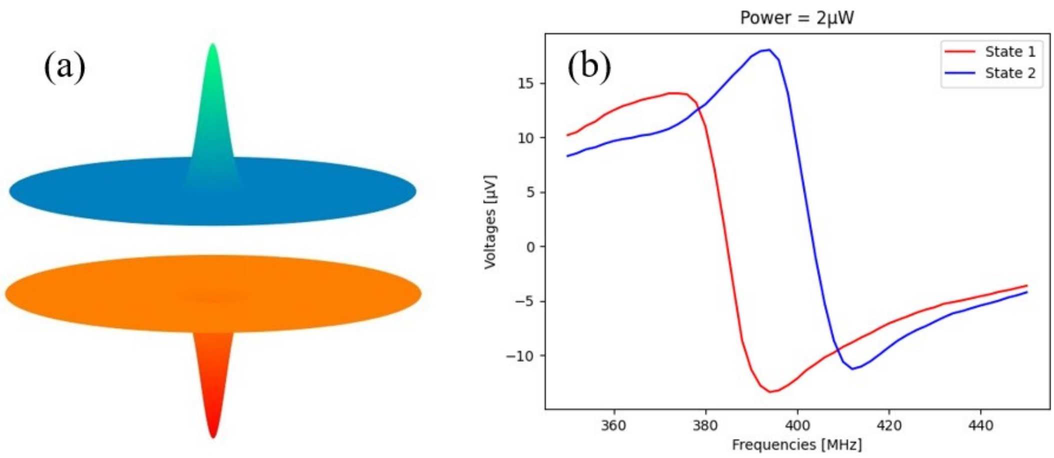

Figure 1 - (a) Schematic representation of the out of plane magnetization of the free layer of the MTJ in the two polarity states. (b) Plot of the two low-power experimental spin-diode curves observed in an exemplary device in the two polarity states.

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Probabilistic Computing with magnetic tunnel junctions

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Physics-based unconventional computing paradigms [1-2] are becoming a topic of great scientific interest due to scalable and hardware-friendly approaches for solving hard combinatorial optimization problems (COPs). A promising unconventional solver of COPs is based on the concept of Ising machines (IMs) [3], and a hardware implementation is probabilistic Ising machines (pIMs) [2,3,4], which is spintronics-compatible.

In this work we propose a probabilistic bit (p-bit) implementation with three-terminal magnetic tunnel junctions (MTJs). The perpendicular MTJ is designed so that the energy landscape of the free layer (FL) magnetization has two stable minima along the z-axis. Applying a spin-orbit torque (SOT) current the FL magnetization is brought to a metastable state aligned along the direction of the spin-current (y-axis), and when the SOT is switched off, the FL magnetization relaxes, with equal probability, towards one of the two z-axis directions. The switching probability is tuned with a spin-transfer torque (STT) current applied in the third terminal, resulting in a sigmoidal curve shown in fig. 1.

A physical implementation of a problem involves taking into account the geometrical and physical device-to-device variations, for this reason we studied the reliability of the optimal solution of an instance of a maximum-satisfiability (MAX-SAT) problem. In particular, we emulate the device-to-device variation considering a different slope value of the sigmoidal curve. The result show that within the range of variation of the experimental data the probability of obtaining the optimal solution in an instance of the MAX-SAT problem is only a few percentage points lower than the ideal case.

It is also possible to exploit the stochasticity of MTJs as a random number generator. We replace the random part of the digital p-bit with random numbers generated from several MTJs and the impact of decimal number precision is studied in reaching the solution of the MAX-SAT problem. Less than 20 MTJs are enough to obtain performance comparable to software implementation.

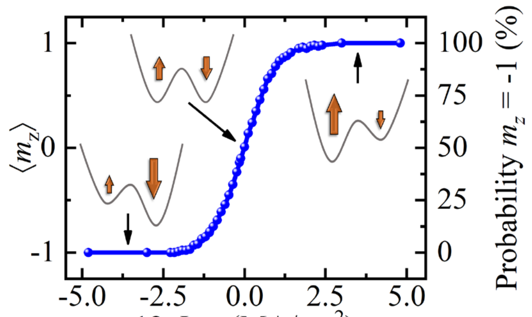

Figure 1: Sigmoidal behaviour of the FL magnetization tuned by a STT current.

Acknowledgements

This work was supported under the project number 101070287 - SWAN-on-chip - HORIZONCL4-2021-DIGITAL-EMERGING-01, the project PRIN 2020LWPKH7 "The Italian factory of micromagnetic modelling and spintronics" funded by the Italian Ministry of University and Research (MUR), and by the PETASPIN association (www.petaspin.com). The work at Northwestern University was supported by the National Science Foundation (NSF) grant numbers 1919109 and 2106562.

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Benchmarking neuromorphic hardware for simulating quantum magnetism with machine learning

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The field of ultrafast magnetism is driven by the quest to understand the dynamics of magnetic systems at ever shorter length and time scales. However, Simulating such dynamics poses big challenges, since it inevitably leads to the appearance of quantum effects. Although great successes have been achieved by modeling ultrafast spin dynamics with atomistic spin dynamics simulations, no such generally applicable simulation method was available for situations where the intrinsic quantum nature of the spins are crucial.

Recently, a new method for the simulation of quantum many body systems, inspired by machine learning, has been pioneered [1]. In this approach, the many-body wave function is approximated by an Artificial Neural Network (ANN) and the quantum states generated this way are termed neural-network quantum states (NQS). Already the simplest network, the Restricted Boltzmann Machine (RBM), was found to give competitive advantages over conventional methods, in particular in two dimensions (2D) for which quantum correlations are strongest [1, 2, 3, 4]. Although this method reduces the computational cost from exponential to polynomial, it is still much more demanding than atomistic simulations.

To resolve this problem, here we explore the feasibility of accelerating NQS simulations using dedicated neuromorphic hardware, specifically Analog In-Memory Computing (AIMC). We have done this by (i) developing and using a methodology to measure the compute time and energy on CPU and GPU for machine learning based methods, and (ii) designing an architecture and estimate the same metrics based on a state-of-the-art AIMC platform [5]. We find that AIMC can achieve up to one order of magnitude shorter computation times than conventional hardware, at an energy cost that is up to three orders of magnitude smaller [6]. This suggests great potential for NQS deployed on AIMC platforms.

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Coherent and probabilistic Ising machines with magnetic tunnel junctions

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With the rise in popularity of Ising machines (IMs) as combinatorial optimization problems (COPs) solvers [1], hardware implementation designs of the Ising spin are a research topic of fundamental importance. This is due to the overall performance of IMs being intrinsically tied to the Ising spin flipping speed. For this reason, magnetic tunnel junctions (MTJs) are a promising candidate thanks to their high working frequency, in addition to their nanoscale size, high design flexibility, low energy consumption, and CMOS compatibility [2].

In this work, we propose two three-terminal MTJ designs for the implementation of two IM-based paradigms: coherent Ising machines of coupled oscillators (cIMs) [3] and probabilistic computing with p-bits Ising machines (pIMs) [4,5]. cIM spins are obtained by exciting self-oscillations in the free layer magnetization (FL) with a spin-orbit torque current (SOT) and enforcing binarization with injection-locking using voltage-controlled magnetic anisotropy (VCMA) (see Fig. 1a). pIM spins are achieved by bringing the FL to a metastable state with an SOT pulse, which then returns to either of the two stable states with probability tuned with a spin-transfer torque current (STT).

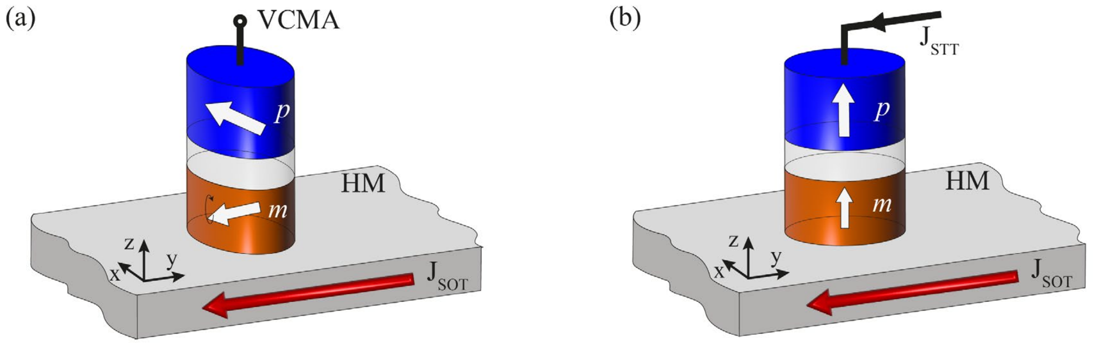

Figure 1. (a) cIM MTJ design. The FL behaves like an oscillator. (b) pIM MTJ design. An SOT pulse allows tunable RNG with the state of the FL.

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Resistive-based temperature sensor based on spintronics devices

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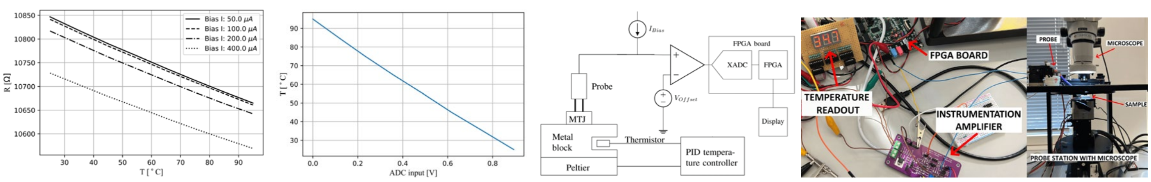
On-chip thermal sensors are one of the essential blocks in modern electronic devices, especially in microprocessors and other integrated circuits for several reasons. They are used to monitor the temperature of the device, which is critical to prevent overheating and damage to the device. High temperatures can cause thermal runaway, where the device gets hotter and hotter until it damages and can also reduce the reliability and lifespan of the device. Moreover, on-chip thermal sensors can also be used to optimize the performance of the device. Some devices, such as microprocessors, can run at higher clock speeds at lower temperatures, which improves their performance. On-chip thermal sensors can be used to adjust the clock speed of the device to maintain optimal performance while keeping the temperature within safe limits [1]. Another application of on-chip temperature sensors is for managing power consumption. By monitoring the temperature of the device, power can be dynamically adjusted to reduce heat generation and maintain safe operating temperatures, which can improve battery life in portable devices [1]. Our proposed design uses a spintronics-based sensor, in this case, a magnetic tunnel junction (MTJ) in AP-state, to convert temperature to resistance that can further be converted to a voltage by passing a small bias current. It has several advantages over its CMOS counterpart. These sensors are smaller in size, compatible with CMOS technology, and require lower power consumption. [2].

To attain the temperature sensing functionality, an I-V characteristic of the MTJs of [3] has been extracted. Device samples with high absolute resistance and a substantial relative change in resistance were chosen to achieve the highest possible resolution. The measurement results indicate that when a bias current of 400µA is applied, a voltage change of 63mV can be observed across the MTJ within a temperature range of 25-95 °C (Figure 1 (c)). To use the full dynamic range of the ADC (0-1V), an instrumentation amplifier was integrated into the system, which was also utilized for calibration purposes to match the FPGA model to the physical MTJ. This calibration is done to match the voltage across the MTJ at a specific temperature to correct the output against any change in contact resistance when probing and offset the voltage for the ADC, which needs to be performed once in each implementation. The ADC converts the input to a 10-bit number, that is applied to the FPGA. The number is compared with a lookup table based on a 2nd order polynomial model obtained from the temperature characteristics of MTJ (Figure 1(d)). Finally, the resulting temperature is displayed on an external display. Figure 1(a) shows the schematic of the proposed design, which includes all the necessary components for measuring temperature. The proposed sensor is shown to have an accuracy of $\pm 2°C$ within the designated operating range found through experiments done on the physical setup seen in Figure 1(b). This accuracy can be improved through tighter integration, as the setup added noise to measurements. Moreover, the accuracy can be further enhanced by utilizing MTJ pads that exhibit fixed resistance with respect to temperature.



(a) (b) (c) (d)

Figure 1: Proposed SST-MTJ thermal sensor. (a) MTJ resistance versus temperature (b) The analog output voltage of the CMOS interface versus temperature. (c) block diagram of the experimental setup for testing the temperature sensor. (d) Physical setup in the lab including FPGA, CMOS interface PCB, and display.

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Mechanism of spin-orbit torque switching of magnetization in $Co_{1-x}Tb_x$ multilayers with vertical composition gradient

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Growing interest in ferrimagnets for spintronics applications stems from their advantageous characteristics compared to traditional ferromagnets. Namely, the exchange-dominated fast magnetization dynamics (in the range of THz) and the low stray fields owing to the antiparallel alignment of the constituent magnetic moments. Rare-earth (RE) transition-metal (TM) ferrimagnetic alloys are candidate materials for achieving high-speed and high-density spintronics devices. Also, spin-orbit torques (SOT) provide an energy-efficient way to achieve magnetization switching in spintronic devices, while in the case of perpendicular anisotropy films, an in plane symmetry breaking mechanism is required in order to attain a deterministic switching path. While an external in-plane magnetic field could provide the required in-plane symmetry breaking and lead to deterministic switching, the presence of magnetic fields hinders the integration of SOT devices on semiconductor chips.

Recent experiments in ferrimagnetic alloys with composition-gradient along the growth direction, demonstrated the feasibility of deterministic magnetization switching of the perpendicular magnetization in the absence of external in-plane magnetic field [1]. The switching behaviour was attributed to the dynamic in-plane symmetry breaking during the switching process induced by the Dzyaloshinskii-Moriya interaction (DMI) that is present in ferrimagnetic alloys layers due to the vertical composition gradient. A theoretical understanding of the microscopic mechanism leading to these experimental observations is presently missing. In the present work, we investigate by means of extensive micromagnetic simulations the switching mechanism in Co_xTb_{1-x} films with engineered composition-gradient along the growth direction x(z) and elucidate the role of the gradient-induced DMI in the magnetization switching path. Finally, we suggest a strategy for the growth and implementation of perpendicular ferrimagnets with g-DMI that would lead to efficient, low-energy-consumption compact SOT devices.

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Phase diagrams of precession regimes in spin-torque diodes for energy harvesting

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Thin multilayered magnetic nanoelements with the in-plane shape anisotropy and strong out-of-plane crystallographic magnetic anisotropy are considered as promising candidates for spin-torque diodes to be used in energy harvesting applications (see, e.g., [1]). To be able to optimize the design of corresponding devices, it is crucially important to understand various dynamical regimes possible in such systems.

In this talk, we present a detailed analysis of the steady-state magnetization dynamics occurring in a typical magnetic nanoelement (elliptical CoFeB layer with lateral sizes 200 × 100 nm^2 and thickness 1.5 nm). We compare three simulation approaches which can be used for corresponding analysis: the macrospin approximation for $T = 0$ and full-scale micromagnetic simulations for $T = 0$ and $T = 300$ K (i.e., with thermal fluctuations included). We also take into account the 2nd-order anisotropy constant K_2, which can qualitatively change the energy landscape of the system.

We have identified at least six possible steady-state dynamical regimes as shown below on the phase diagram in coordinates anisotropy - current density. Among them, five regimes (those for relatively small currents) can be relevant for energy harvesting applications. It is important to note, that taking into account thermal fluctuations qualitatively change the corresponding phase diagram.

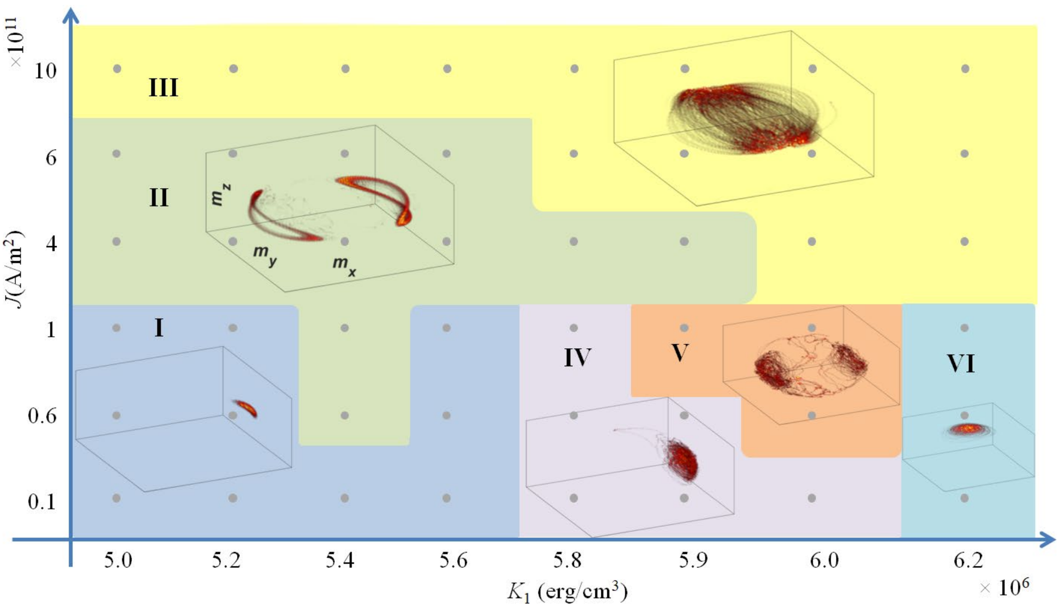

Figure 1: Phase diagram of possible magnetization dynamic regimes in a thin ellipsoidal nanoelement: I - deterministic small-angle precession; II - deterministic large-angle precession; III - DW motion; IV - quasichaotic small-angle precession; V - quasichaotic large-angle precession; VI – out-of-plane precession. Grey circles show parameter combinations for which simulations have been performed.

Financial support of the Deutsche Forschungsgemeinschaft (German Research Society), DFG-project BE2464/21-1 is greatly acknowledged.

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Drastic reduction of spin-orbit torque by inserting NiO thin film

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The utilization of spin-orbit torque (SOT) [1], which harnesses spin-orbit interactions and spin currents to manipulate magnetization, presents a promising avenue for developing efficient magnetic memory and logic devices for electronic applications. Recently, it has been discovered that orbital current, which involve the flow of orbital angular momentum, can be generated and detected [2]. Unlike spin currents, orbital currents do not rely on spin-orbit interactions in paramagnetic materials and exhibit a strong connection to crystal structure and electron orbitals in materials. Consequently, the use of orbital currents has the potential to expand the range of material choices and enable the development of spintronic devices that are both eco-friendly and highly efficient. While there has been significant interest in the generation and detection of orbital currents, we are particularly interested in exploring the uncharted territory of their transport mechanism.

Our study aimed to explore the transport mechanism of orbital currents in insulating layers. To achieve this, we fabricated Hf/Ni bilayer thin film structures employing Ni, which exhibits a robust response to the contribution of orbital currents. At the interface, we introduced NiO, an antiferromagnetic insulator, and examined the behavior of spin-orbit torque concerning the thickness of the insulating layer.

In order to estimate the magnitude of the spin-orbit torque, we conducted spin-torque ferromagnetic resonance (ST-FRM) measurements, as illustrated in Figure 1(a), and quantified the effective magnetic field resulting from the application of an electric field to the sample. As we increased the thickness of NiO, the effective magnetic field initially rose at approximately 1 nm before approaching zero. This suggests that the Neel temperature of the NiO is near room temperature at approximately 1 nm, and that spin fluctuation is present in the NiO. Such fluctuations lead to an improvement in the transparency of the spin current, resulting in a negative contribution to the spin current due to the spin Hall effect (SHE) in Hf. However, the positive contribution from orbital current due to the orbital Hall effect (OHE) appears to be unaffected by spin fluctuation, as our experimental findings demonstrate.

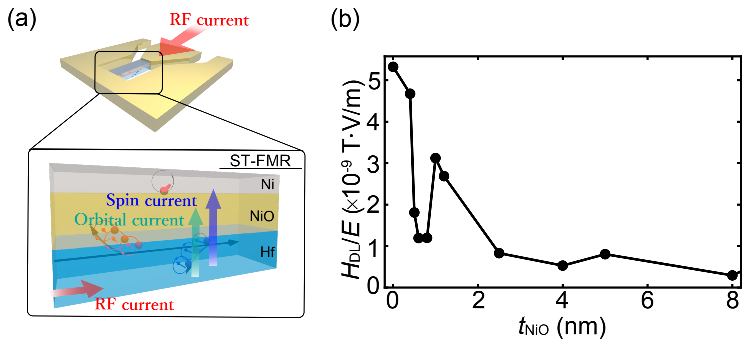

Figure 1: (a) Schematic illustration of ST-FMR measurement. Signal generator applies RF current exciting FMR in the Ni layer and generating SHE (OHE) in Hf layer. (b) The measured damping-like effective magnetic field per electric field with respect to the NiO thickness for Hf(10 nm)/NiO(t_{NiO} nm)/Ni(6 nm).

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Spin Hall effect in the insulating regime

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The physics of the spin Hall effect (SHE) is one of the most intriguing aspects of condensed matter physics. The SHE has the same origin as the anomalous Hall effect (AHE). The SHE and AHE both in metallic systems have intrinsic and extrinsic contributions [1]. The intrinsic contribution originates from the Berry curvature and the band structure of the material, whereas the extrinsic contribution originates from spin-dependent scattering on structural defects or impurities. Under these mechanisms, many experimental results have revealed that there are three distinct regimes in the metallic system of the AHE [1], characterized by the power-law relation between the anomalous Hall conductivity and the electric conductivity. Recently, these regimes have also been confirmed for the SHE [2-4], demonstrating an important correspondence between the AHE and SHE in the metallic regime. Furthermore, experimental observations have demonstrated that the scaling for the AHE also exists in the insulating regime [1], where the carrier transport is dominated by hopping. In contrast to the AHE, however, an experimental study of the SHE in this disordered insulating regime has been unclear. In this work, we report the observation of the SHE in the insulating regime [5]. To explore the SHE in the insulating regime, the electric conductivity of Pt is varied by three orders of magnitude by incorporating oxygen. We conduct the spin-torque ferromagnetic resonance for $Ni_{81}Fe_{19}$/TiN/PtO_x trilayer to estimate the strength of the SHE in the PtO_x layer. We find the scaling behavior of the spin Hall conductivity in the disordered insulating regime. The observed variation of the spin Hall conductivity over the wide range of electric conductivity is reminiscent of the scaling of the anomalous Hall conductivity, illustrating a direct correspondence between the SHE and AHE in the insulating regime.

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Temperature dependence of spin-orbit torque in $Ni_{81}Fe_{19}/AlO_x/SrTiO_3$ heterostructure

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The generation and manipulation of a spin current is fundamental for the spin-orbit torque (SOT) devices. The conversion phenomena between spin and charge currents in solids have been intensely investigated in a wide variety of systems. One of the promising platforms is the two-dimensional electron gas in a $SrTiO_3$-based structure with strong Rashba spin-orbit coupling. In a Rashba system, an in-plane charge current generates a transverse spin density, which is known as the Edelstein effect. An efficient spin-to-charge conversion through the inverse Edelstein effect has been demonstrated in metal oxide/$SrTiO_3$ heterostructures with two-dimensional electron gases at the interfaces [1]. However, evidence for the charge-to-spin conversion, a more important process for SOT technologies, has been lacking. Furthermore, the spin transport mechanism in this system has been unclear.

In this research, we demonstrate the highly efficient SOT induced by the charge-to-spin conversion via the direct Edelstein effect in a two-dimensional electron gas at an $AlO_x/SrTiO_3$ interface [2]. We conduct the spin torque ferromagnetic resonance measurements on $Ni_{81}Fe_{19}$ (4.2 nm)/AlO_x (2 nm)/$SrTiO_3$-subsurate devices, where a spin current generated by the direct Edelstein effect in the two-dimensional electron gas is injected into the $Ni_{81}Fe_{19}$ layer through the AlO_x layer and exerts a SOT on the local magnetization of the $Ni_{81}Fe_{19}$ layer. The SOT efficiency in this system exceeds 10% at room temperature, which is comparable to that of the archetypal spin-to-charge converter, Pt.

The SOT efficiency is found to be suppressed by decreasing temperature. From the analysis regarding to the carrier density and band structure of the two-dimensional electron gas, we find that the spin density generated by the Edelstein effect does not decrease with decreasing temperature. Therefore, the decrease in the SOT efficiency is ascribed to the decrease in the spin transmission rate through the AlO_x layer. We analyze the measured SOT efficiency considering the temperature dependence of the tunneling conductance of the elastic and inelastic tunnelings. The observed temperature dependence of the SOT efficiency is well reproduced by the theoretical model of the tunnelings. Our results demonstrate a crossover of the dominant spin transport mechanism from the inelastic tunneling to elastic tunneling induced by decreasing temperature.

These findings will provide a clue to unlock the full potential of oxide-based SOT devices.

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Nonlocal orbital torques in magnetic multilayers

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The development of spintronics is reliant on the manipulation of magnetization via current-induced spin-orbit torques. The spin Hall effect is a notable source of spin-orbit torques that produces a spin current from a charge current through spin-orbit coupling. Spintronics has been based on understanding and utilizing spin currents, but the orbital counterpart, orbital currents, has been overlooked. Theoretical studies suggest that orbital currents have a vital function in the dynamics of angular momentum in solids [1, 2]. The orbital Hall effect, which is the orbital counterpart of the spin Hall effect, can create an orbital current in solids. This phenomenon arises due to electric-field-induced interband superpositions of Bloch states with various orbital characteristics [2]. Recent theoretical and experimental studies have demonstrated the existence of current-induced torques produced by the orbital Hall effect called orbital torques [3, 4]. These studies have indicated that the efficiency of orbital torques is sensitive to the choice of ferromagnetic layer, which is unlike spin-orbit torques whose efficiency is not as dependent on the ferromagnetic layer. These findings point towards a new direction for spintronics that explores the physics and applications of orbital currents and torques.

In our study, our investigation focuses on the contribution of the orbital Hall effect to the generation of current-induced torques in magnetic multilayers. The results of our study demonstrate that the torque exerted on the magnetization in the Ni layer of Ni/Ti/Fe/Ti multilayers increases as the thickness of the bottom Ti layer increases. This indicates that the bulk of the bottom Ti layer is responsible for the observed torque, despite Ti's low spin Hall conductivity and the presence of the ferromagnetic Fe interlayer between the Ni and Ti layers. The observed nonlocal torque is consistent with the notion that the torque arises from the orbital Hall effect in the bottom Ti layer and the orbital transport through the Fe layer, suggesting that orbital currents can be used to exert layer-selective nonlocal orbital torques even when the source of the orbital current is separated from the targeted ferromagnetic layer [5].

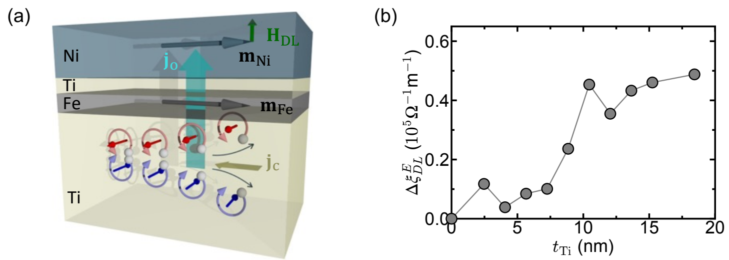

Figure 1: (a) The schematic illustration of the Ni/Ti/Fe/Ti device, (b) Ti thickness t_{Ti} dependence of current-induced torques efficiency $\Delta\xi_{\mathrm{DL}}^{E} = \xi_{\mathrm{DL}}^{E}(t_{\mathrm{Ti}}) - \xi_{\mathrm{DL}}^{E}(t_{\mathrm{Ti}} = 0\ \mathrm{nm})$.

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Magnon-mediated magnetization switching in all oxide heterostructures

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Magnon, a collective precession of magnetic moment, is an alternative spin angular momentum carrier besides the spin-polarized electron. In this work, we demonstrate the high-efficient magnon-mediated magnetization switching in all oxide epitaxial heterostructures consisted of perpendicularly magnetized $SrRuO_3$ (SRO), insulating antiferromagnetic NiO, and $SrIrO_3$ (SIO) with strong spin-orbit coupling, where the spin-polarized current generated in SIO transforms to magnon current in NiO and subsequently exerts a spin torque on the SRO. Specifically, the spin-orbit torque in the SRO/NiO(7.2 nm)/SIO trilayer is comparable to the SRO/SIO bilayer, suggesting a high charge-to-spin conversion efficiency. Interestingly, the threshold current density to generate a sufficient magnon current to manipulate the magnetization was one order of magnitude smaller than that in conventional metallic systems, which paves an avenue for the design of energy-efficient magnetic storage and logic devices.

As is schematically shown in Fig. 1, in the all-oxide heterostructure of $SrRuO_3$/NiO/$SrIrO_3$ (SRO/NiO/SIO), the spin current was generated by the spin Hall effect in the SIO layer. Then the magnon current was excited in the SRO layer, which finally leads to the switching of perpendicular magnetization in the SRO layer. Experimentally, we successfully demonstrated that the magnon current excited in the insulating antiferromagnetic layer by electronic spin current was effective to manipulate the perpendicular magnetization in a ferromagnetic layer. Furthermore, the critical electric current to enable magnetization switching was less than 1 MA cm^{-2}, about one order of magnitude smaller than in conventional metallic systems. These findings suggest that the all-oxide epitaxial heterostructure is a promising candidate for realizing magnon-mediated magnetization switching.

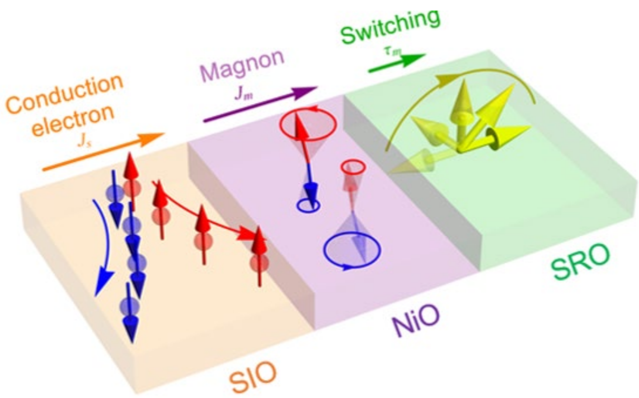

Fig. 1. Magnon-mediated magnetization switching in the SRO/NiO/SIO heterostructures.

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Electric field control of magnetization reversal in FeGa/PMN-PT

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The recent era of information technology devices largely focusses on energy and cost efficiency. Magnetoelectric (ME) materials possess huge potential to be used in these technologies due to its coupling between magnetization and electric-field induced strain which therefore consumes less power and significantly reduces heat losses [1,2]. The application of voltage generates strain at the interface and this strain transfer to the magnetic layer from the piezoelectric layer induces change in magnetic anisotropy and domain structures [3].

In the framework of multiferroic heterostructures and their interfacial magnetoelectric interplay, here we propose to investigate the properties of Iron Gallium (FeGa)/PMN-PT heterostructures using magnetometers and magnetic imaging techniques. FeGa thin films have been deposited by sputtering on PMN-PT substrates. The study of magnetic domains using Magneto-Optic Kerr effect (MOKE) revealed the presence of in-plane magnetic domains in the samples. Under the application of voltage, a change in magnetic hysteresis shape is observed as represented in Figure 1. The hysteresis curve at the tensile state (pink curve) has the highest magnetic remanence (*Mr*) and coercive field (*Hc*). The corresponding domain images with domain walls pointing along x, are shown in Figure 1(b). The hysteresis has the lowest *Mr* and *Hc* at the compressive state (orange curve) and new the magnetic domain walls starts appearing at an angle of 45° w.r.t x. Further, when the field is decreased towards negative polarization saturation (-10 kV/cm), the strain decreases again generating a tensile strain along x. The *Mr* and *Hc* values increases and the domain structures shown in Figure 1(e) become similar to ones recorded at 10 kV/cm. In order to better understand the effect of electric field on the magnetic relaxation, the evolution of remanent magnetization with time has also been studied using a vibrating sample magnetometer (VSM).

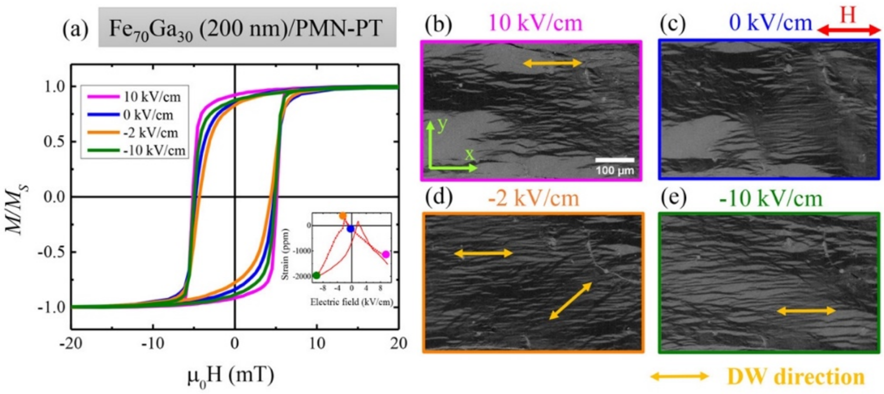

Figure 1: (a) represents the in-plane magnetic hysteresis loop for $Fe_{70}Ga_{30}$/PMN-PT (001) sample. The pink, blue, orange and green curves represent to the hysteresis recorded under applied field of 10 kV/cm, 0 kV/cm, -2 kV/cm and -10 kV/cm, respectively. The plot of strain as a function of electric field is shown in the inset. The magnetic domains near coercivity for the corresponding curves are shown by (b), (c), (d) and (e), respectively.

Acknowledgements

This work has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 861145.

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Antiferromagnetic interlayer exchange coupled $Co_{68}B_{32}$/Ir/Pt multilayers

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Synthetic antiferromagnets (SAFs) are attracting attention for new spintronic technology applications. When placing a non-magnetic spacer between two ferromagnetic materials, the ferromagnetic layers can experience interlayer exchange coupling (IEC)[1]. With a specific spacer thickness, the two magnetic layers will experience antiferromagnetic interlayer exchange coupling (AFM-IEC) due to the Ruderman–Kittel–Kasuya–Yoshida (RKKY) interaction, which is how a SAF is designed[2]–[4].

Here, we report on the properties of Pt/CoB/Ir multilayers in a SAF state promoted by the Ir spacer, as a function of temperature and repetitions. CoB is used due to reduced possibilities of pinning[5], and Ir and Pt are used to provide PMA and interfacial Dzyaloshinskii–Moriya interaction (DMI). This SAF design has the potential to expand the possibilities for SAF devices, for example, skyrmion hosting devices or multilevel memory devices, and allows for fine parameter tuning with many degrees of freedom.

Two SAF systems were investigated, stack 1: $[\text{CoB}(7\ \text{Å})/\text{Ir}(4\ \text{Å})/\text{Pt}(6\ \text{Å})]_{\text{xN}}$, with AFM-IEC between each layer, and stack 2: $[\text{CoB}(6.5\ \text{Å})/\text{Ir}(6\ \text{Å})/\text{Pt}(6\ \text{Å})]_{\text{x4}}$/CoB(6.5 Å)/ Ir(4 Å)/Pt(6 Å)/$[\text{CoB}(6.5\ \text{Å})/\text{Ir}(6\ \text{Å})/\text{Pt}(6\ \text{Å})]_{\text{x5}}$., with two ferromagnetically coupled multilayers of CoB/Ir/Pt with five repetitions, coupled together antiferromagnetically with an iridium layer. Designing the stack in this way allows the magnetic textures to be observed more easily with various imaging techniques, such as Kerr microscopy.

With stack 1, we observed individual switching for each CoB layer up to 7 repetitions via superconducting quantum interference device (SQUID) measured hysteresis loops (Figure 1a). It was also shown that the AFM-IEC remained between the layers down to 10 K. In the case of stack 2, we observed two switches in the hysteresis loop (Figure 1b), which is a clear feature of a SAF structure. When measuring the Kerr microscopy signal, domain patterns were observed at each switching field during a hysteresis loop. Unlike stack 1, the AFM-IEC was maintained only until 250 K.

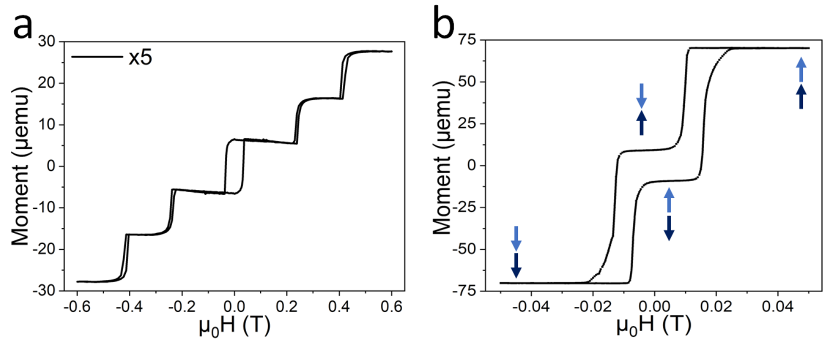

Figure 1: a) shows the stack 1 with N=5, showing one switch for each layer. b) shows the hysteresis loop of the stack 2 with two separate wasp-like switches. The data was taken by SQUID-VSM.

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Magnonic properties of 3D Nickel Gyroid Networks

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[1] Adam Mickiewicz University, Poznań, Poland
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[3] Technische Universität Kaiserslautern-Landau, Kaiserslautern, Germany
[4] Tohoku University, Sendai, Japan

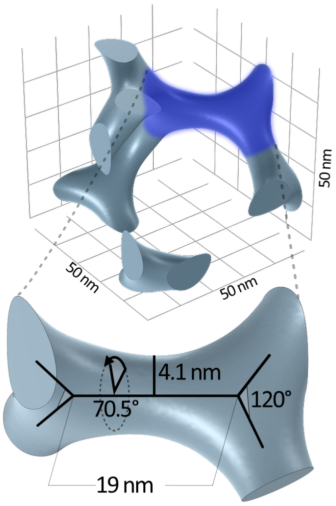

Figure 1: A geometric model of the gyroid unit cell.

New possibilities for the manipulation of spin waves may be offered by topological or non-uniform geometric media. New phenomena can be studied in 3D networks, which allow interactions and collective effects in all dimensions [1]. Gyroids are one of the most promising but still largely unexplored structures in the field of magnetism. They are defined by chiral triple bonds and periodicities along all three spatial directions (see fig. 1).

We have fabricated the nickel gyroid nanostructures by thermal annealing of a block copolymer template, selective dissolution of one of the gyroid-forming blocks, and electrodeposition of nickel into the voided right-handed gyroid network. The orientation of the gyroid network with respect to the static magnetic field axis appeared to be a critical factor in broadband ferromagnetic resonance measurements, as we observed a strong influence of crystallography on the spectral signals. Using the finite element solver – *tetmag* [2], we performed micromagnetic simulations of the gyroid systems (fig. 2) to understand better the experimental results.

Ferromagnetic resonance measurements and micromagnetic simulations showed that the spin-wave spectra of nm-scale gyroids depend on the orientation of the external magnetic field with respect to the crystallography. The presented findings on the properties of gyroids suggest their great potential in the development of magnonic 3D nanomaterials.

The research that led to these results has received funding from the National Science Centre of Poland, project No. UMO-2020/39/I/ST3/02413, JSPS KAKENHI 21K04816, and the Graduate Program for Spintronics (GP-Spin), Tohoku University.

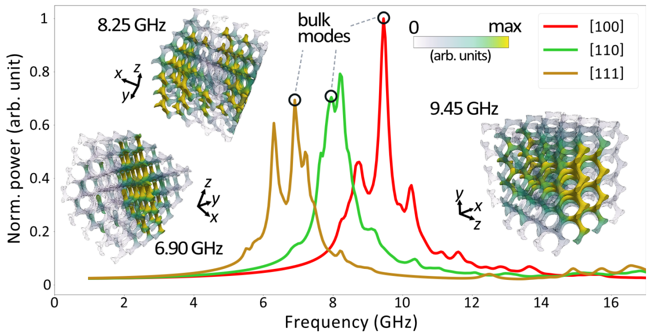

Figure 2: The resonance frequency spectra obtained from micromagnetic simulations. Different colors indicate the crystallographic direction along which the 300 mT field is applied, while circles indicate volumetric ferromagnetic resonance. The color scale corresponds to the amplitude modulus of the dynamic magnetization component.

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Growth mechanism of the spin current source forming the interface with the $L1_0$ FePt layer

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Spin-orbit torque (SOT)-induced magnetization switching is an essential phenomenon for developing electronic devices with high energy efficiency and fast speed. On the other hand, ferromagnets with strong perpendicular magnetic anisotropy, such as $L1_0$ FePt become the mainstream of magnetic data storage media because of their thermal stability. Therefore, it is important to utilize the strong PMA materials for SOT-based spintronic devices.

In this presentation, we discuss the crystallinity and magnetic properties of the $L1_0$ FePt with Pt and Ta contacts which generate spin currnet via spin hall effect. In particular, the growth mechanism of each material is analyzed in a thermodynamic point of view. In addition, the Pt contact showed island-growth, while a smooth surface was made with the Ta contact. We found that the surface roughness of the Pt contact was improved when the oxide was added during growth of the FePt layer.

Design and functional properties of SmCo films for MEMS devices

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Riccardo Bertacco

Politecnico di Milano, Milan, Italy

High remnant magnetizations, large coercive field, extremely strong uniaxial magnetocrystalline anisotropy and storage of high magnetic energy are the main features attracting great interest to permanent magnet. An active study of SmCo and NdFeB films for MEMS devices has been carried out in the last ten years [1]. Various methods for creating high-coercivity SmCo films are used. However, deposition conditions, phase composition, fine-grained structure and their influence on the magnetic properties in SmCo nanostructures are still under review. Understanding of interphase interaction is also important for the prediction of their magnetic properties and practical applications.

This work is aimed at designing heterostructures based on SmCo films and tuning their magnetic properties suitable for MEMS platforms. W/SmCo/W/Si was grown by RF sputtering. The films showed good stability and low roughness. Lithography and passivation of the SmCo film also showed good results (Fig.1 a). As grown amorphous samples were annealed in vacuum at temperatures of 650–750 C. We have distinguished the contribution of the grains of the soft and hard magnetic phases to the total magnetization. Increase of annealing temperature results in dispersion of the magnetic phases and corresponding increase of the interphase coupling, decreasing the switching field of the hard phase (Fig.1 b).

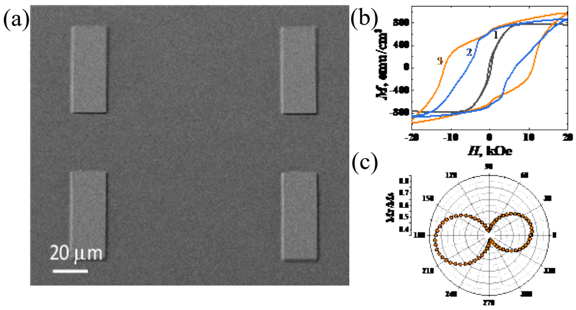

Figure 1: (a) SEM image of W/SmCo/W/Si micromagnet; (b) Hysteresis loops *M(H)* recorded in magnetic field lying in plane of samples before (1) and after annealing at 650 ºC (2) and 750 ºC (3); (c) Angular dependence of the normalized remnant magnetisation.

The magnetocrystalline anisotropies strongly depend on the ratio of the $SmCo_5$ and Sm_2Co_{17} phases after annealing (Fig.1 c). Identification of phase contribution to out-of-plane and in-plane remnant magnetization was performed. We have shown the possibility of creating stable SmCo thick films and tuning the switching field, intergrain interaction and phase contributions to the magnetization after annealing.

This research is part of the EU project M&MEMS [2]

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Revealing the spin texture of the 2D vdW $Cr_2Ge_2Te_6$

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Two-dimensional magnetism is an emerging area of research with potential for the development of magnetic materials and device applications ranging from magnetic storage devices to spintronics [1,2]. Magnetic properties of these materials can be tuned via, e.g. the number of layers, strain, doping. Magnetic coupling between individual layers in vdW heterostructures can lead to the emergence of exotic magnetic phases such as skyrmion or other non-collinear magnetic configurations [3].

Here, we employ nanometer-scale magnetic imaging to shed light on the magnetic behavior, magnetic anisotropy, spin texture, and magnetic domain structure of a 2D magnetic material. We investigate few-layer $Cr_2Ge_2Te_6$ using our recently developed scanning SQUID-on-lever probe. By performing micromagnetic simulations, we are able to reproduce the magnetic behavior of the material and reveal the magnetic spin textures that appear in it. More specifically, simulations show that when the material breaks into domains, spiral spin textures should form (figure 1a). Using the simulated magnetization, we reconstruct the expected gradient of the out-of-plane magnetic field, which is shown in figure 1b and matches our experimental data in figure 1c. Simulations also reveal the formation of skyrmions before the material transitions to the fully saturated state, indications of which we also observe in our experimental data. Finally, we find a layer dependence in the flake's magnetic behavior. We see changes in the shape of the simulated magnetic hysteresis loop going from very thin layers (soft ferromagnetic behavior) to thicker layers (bow-tie hysteresis), which agree with our experimental results.

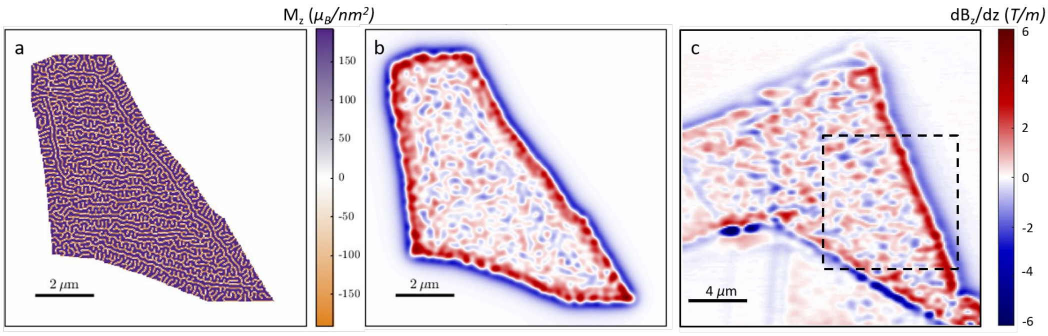

Figure 1: (a) The simulated z-component of magnetization of a few-layer $Cr_2Ge_2Te_6$ under an externally applied field of 13 mT along the z-axis and (b) the resulting gradient of magnetic field along z-axis at a height of 200 nm above the flake. The chosen geometry represents part of the experimentally studied sample. (c) Magnetic field gradient along z-axis measured with our SQUID-on-lever. Inset shows the part of the flake that was used for the simulation.

[1] C. Gong et al. Nature **546** (2017), 265–269.

[2] B. Huang et al. Nature **546** (2017), 270–273.

[3] Y. Xu et al. Nature Nanotechnology **17** (2022), 143–147.

Layer dependent magnetization in 2D vdW $Cr_2Ge_2Te_6$

K. Bagani[a], A. Vervelaki[a], D. Jetter[a], M. Doan[c], T. K. Chau[a], D. Christensen[c], P. Boggild[c] and M. Poggio[a,b]

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Magnetism in reduced dimensions is a fascinating area of research with important implications for the development of magnetic materials and device applications ranging from magnetic storage devices to spintronics. In contrast to bulk materials, 2D materials exhibit intriguing magnetic properties due to the reduced dimensionality. After he realization of long-range ferromagnetic ordering in bilayer $Cr_2Ge_2Te_6$ and monolayer CrI_3, enormous research effort has been devoted to the family of 2D vdW magnetic materials [1,2]. Magnetic properties of these materials are strongly dependent on the number of layers and magnetic coupling between individual layers in vdW heterostructure can lead to the emergence of exotic magnetic phases like skyrmions or other non-collinear magnetic configurations [3].

Here, we employ nanometer-scale magnetic imaging to shed light on the magnetic behavior, magnetic anisotropy, spin texture, and magnetic domain structure of a layered magnetic material. We investigate few-layer $Cr_2Ge_2Te_6$ using our recently developed scanning SQUID-on-lever probe (Figure 1a). With simultaneous topographic and magnetic imaging, we determine the number of layers and study the layer-dependent magnetization down to bilayer limit (Figure 1b). Nanoscale spatial resolution allows us to investigate domain formation and magnetic length-scales as a function of layer number. By studying local magnetic hysteresis (Figure 1c), we find a layer-dependent magnetic anisotropy in $Cr_2Ge_2Te_6$.

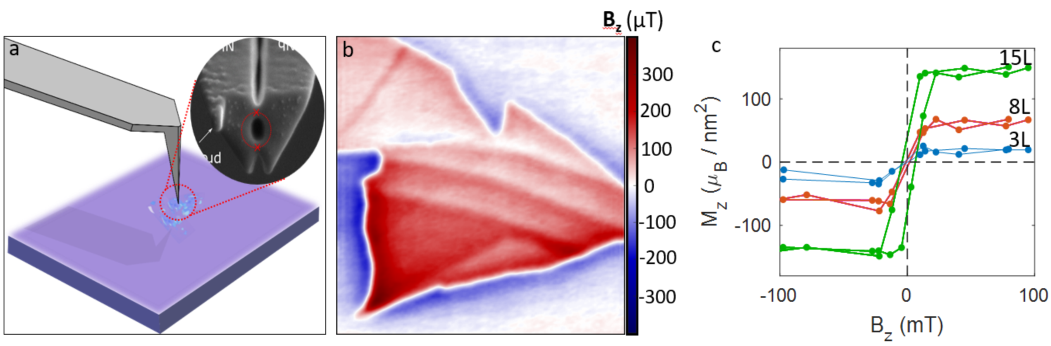

Figure 1: (a) Schematic of scanning SQUID-on-lever. Inset shows SEM image of the SQUID on the tip of the cantilever. (b) Magnetic stray field image of a single $Cr_2Ge_2Te_6$ flake with regions of different layer thicknesses. (c) Magnetic hysteresis of regions with different layers thicknesses (color-coded).

[1] C. Gong et al. Nature **546** (2017), 265–269.

[2] B. Huang et al. Nature **546** (2017), 270–273.

[2] Y. Xu al. Nature Nanotechnology **17** (2022), 143–147.

Magnetic anisotropy alteration by shock-compression of single grain flux-grown icosahedral AlCuFe quasicrystal

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Quasicrystals are highly structurally ordered solids characterized by long range orientational order of constituting atoms leading to the presence of forbidden symmetry axes, such as the five fold axis in the case of icosahedral lattice. However, the long-range magnetic coupling arising in these structures was rarely observed and not well understood. Works of Tamura *et al.* [1] and Watanabe [2] recently proven this possibility. Effects of shockwave propagation on quasicrystalline structure were investigated by Roth [3] using molecular dynamics approach. The work specifies intermediate shockwave velocities that are strong enough to introduce plastic lattice distortion without the occurrence of phase transition. The defects include stacking faults, flips of atoms between different sites, phason walls and formation of rotated crystallites from a monocrystal. In the current study, we explore how magnetocrystalline anisotropy is affected by these lattice inconsistencies.

Single phase of Al-Cu-Fe quasicrystal was obtained by flux-growth technique that involves Canfield crucible set with decanting above Al-flux melting temperature. Single-stage propellant gun with a 20 mm diameter bore, previously used in the first documented shock-compression synthesis of quasicrystal [4], was used in this study to introduce defects into the quasicrystal lattice. Projectile velocity before impact of 1.22 km/s, determined from multiple laser-beam interrupt times, situates the impact regime in the intermediate region described by Roth [3]. Single grains of as-grown and shock-treated samples with physical dimensions of about 1x1x1 mm were isolated and mechanically cleaned. The structure was confirmed by single crystal and powder X-ray diffraction, which allowed to compare changes in quasilattice constant after the shock event. Grain orientation was determined by Electron Backscatter Diffraction (EBSD) analysis.

Temperature dependency of FC-ZFC magnetization and hysteresis loops for different temperatures recorded on commercial SQuID revealed three magnetic regimes: ferromagnetic up to 8 K, weakly ferromagnetic from 8 to 250 K and diamagnetic above 250 K. Cantilever torque magnetometry was employed to study the magnetic anisotropy of single grains rotated from 0 to 360^{o} with respect to external magnetic field vector perpendicular to rotation axis. The measurements performed at T = 2 K and H = 5 mT – 9 T. According to Fig.1 angle-dependent magnetization–proportional to torque–could be grouped into four field regimes: I: 5–75 mT, II: 100–500 mT, III: 1–5 T and IV: 6–9 T. The equivalent angular positions are α+180^{o}. Additional harmonic of Fourier series is present for moderately low (II) and high (IV) field regimes.

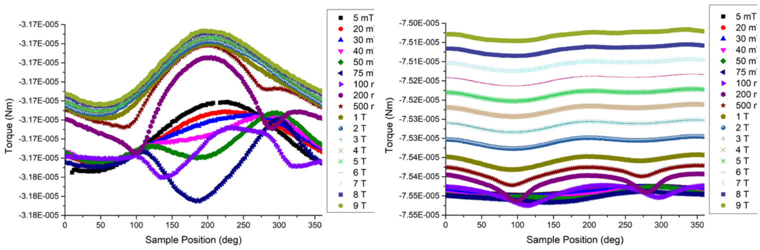

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Figure 1: Cantilever torque [Nm] versus sample position [deg] for as-prepared (left) and shock-compressed (right) single grain of AlCuFe quasicrystal, recorded for external fields up to 9 T

The research described was funded by the National Science Centre, Poland (NCN) within the research grant No. 2020/36/C/ST5/00007.

Magnetic field-induced phase transition and weak ferromagnetism in nonsuperconducting optimally doped PrBCO cuprate

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A detailed study of an optimally (OP) doped $PrBa_2Cu_3O_{6+x}$ sample with x = 0.95 (henceforth referred to PrBCO for simplicity) was reported recently [1 and references therein]. Based on the specific heat, thermal expansion, magnetic susceptibility and magnetization measurements, anomalies are observed below the Néel temperature T_N = 14 K of the Pr^{3+} antiferromagnetic (AFM) ordering, at the spin reorientation transition temperature T_2 = 10.5 K K and at the low-critical point T_{cr} = 4-5 K. However, the unsaturated behavior observed in the magnetization at 1.5 K in the limited strength of field of 2.1 T, point towards the AFM/Weak Ferromagnetic (WFM) nature of the magnetic properties of this OP doped ceramic sample for which the structural characterizations are also given in [1].

Overall, earlier reports on PrBCO compounds [2, 3] have suggested complex magnetic ordering of Pr^{3+} and Cu^{2+} spins within the CuO_2 planes at low temperatures and the high magnetic field magnetization properties of these insulating and nonsuperconducting cuprates have not yet investigated.

We report in this work, several isothermal-magnetization measurements M(H) performed at low temperatures using DC external magnetic fields H up to 16 T. After a slightly curved part, the M(H)-curves behave linearly with H and increase without any visible anomaly up to a saturation field H_S of order to 1 T at 1.35 K and before a first critical field H_{cr1}, well-identified in the differential susceptibility dM(H)/dH obtained by numerical differentiation: by a peak at 3.3 T in decreasing H and by a small inflection point at 4 T in increasing H. The linear part of the M(H) curves are described as $M_S + \chi_d H$, where M_S = 206.39 emu mol^{-1} and χ_d = 511.90 emu mol^{-1} T^{-1} are at 1.35 K, the projection on the field H of the spontaneous magnetization and the differential magnetic susceptibility of the initial WFM phase, respectively. We observe that the saturation regime extends up to temperatures until 20 K, i.e., above T_N and the trend expected is not that of the case of field-induced phase transition (FIPT) of the WFM of the Cu^{2+} spins within the CuO_2 plane of an AFM system such the undoped cuprate La_2CuO_4 where the magnetic moment goes to zero close to T_N. Above H_{cr1}, we observe at 1.35 K another critical field H_{cr2} at about 7 T which seems more marked in the curve H.[dM(H)/dH] versus H. Arrott plots $M(H)^2$ versus H/M(H) are used to observe the high field effects on these FIPTs, especially in the vicinity of the three critical points, T_N, T_2, and T_{cr}. All results are discussed in terms of the hindrance of the Pr AFM order due to some frustration effects and compared with earlier magnetization measurements performed with H up to 4.8 T on an OP doped PrBCO single crystal [4] and with some investigations based on X-ray magnetic circular dichroism which provided evidence of a field-induced out-of-plane spin moment in doped cuprates [5].

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Ultrafast laser-induced spin dynamics in van der Waals 2D antiferromagnets $NiPS_3$ and $FePS_3$

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Van der Waals materials represent a promising foundation for the development of low-dimensional electronic, spintronic, and photonic devices due to their layered structure [1]. In this diverse family of compounds, magnetically ordered transition metal thiophosphates MPS_3 (M = Fe, Ni, Mn, Co, etc.) are of particular interest as suitable objects for experimental investigation of 2D magnetism [2] both at equilibrium [3,4] and beyond [5,6].

Van der Waals crystals $NiPS_3$ and $FePS_3$ possess antiferromagnetic ordering with Néel temperatures of T_N=155 K and 118 K, respectively. In MPS_3 metal atoms are arranged in a honeycomb lattice within a monolayer. In the ordered state in $NiPS_3$ and $FePS_3$ magnetic moments within a monolayer form ferromagnetic zigzag chains coupled to each other antiferromagnetically [2]. Owing to different anisotropy, antiferromagnetic vector in $NiPS_3$ and $FePS_3$ is aligned in the plane or perpendicular to it, respectively. Correspondingly, magnetic ordering of these compounds is described by the 2D XY and 2D Ising models.

Here we perform a comparative experimental study of the laser-induced magnetic dynamics in $NiPS_3$ and $FePS_3$ with emphasis put on similarities and differences in critical behaviour close to T_N. We used exfoliated flakes of $NiPS_3$ and $FePS_3$ deposited on silicon substrates covered by 285 nm layers of SiO_2. The average thickness of the samples was 180 nm, the lateral size was ~85 µm. The measurement of laser-induced dynamics was carried out using the pump-probe technique with pulse duration of 170 fs. Transient changes of the exchange linear dichroism in reflection [7] as a function of the time delay between the pump and probe pulses were detected to trace the laser-induced dynamics of antiferromagnetic ordering in $NiPS_3$ and $FePS_3$. The temperature of samples was controlled in the range from 78 to 295 K.

The experiment results revealed that the laser pulse excitation causes an ultrafast heating-induced partial decrease of the antiferromagnetic vector (demagnetization). The numerical simulation based on the experimental data allowed us to determine the values of the critical exponents and the spin-lattice coupling constants in $NiPS_3$ and $FePS_3$. The critical behaviour of demagnetization was found to be in a good agreement with the type of magnetic ordering. Further, the characteristic demagnetization times in $NiPS_3$ and $FePS_3$. were measured. In $FePS_3$ the significant spin dynamics slowdown was observed in the vicinity of the T_N in agreement with earlier studies [5]. In contrast, demagnetization dynamics in $NiPS_3$ did not demonstrate such a pronounced critical behavior. We associate this difference to the distinct temperature dependence of spin heat capacity in these compounds.

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