HMM
CRETE 2019

12th International Symposium on

Hysteresis Modeling and Micromagnetics

May 19th – 22nd, 2019, Heraklion, Greece

ABSTRACT BOOK

PRESENTATION

HMM 2019 is the 12th in a series of biannual meetings devoted to hysteresis modeling and micromagnetics. The Symposium is organized by the University of Crete and the Institute of Applied and Computational Mathematics (FORTH). HMM 2019 comes after the previous editions held in Ashburn, USA, (1996 and 2001), Perugia, Italy (1999), Salamanca, Spain (2003), Budapest, Hungary (2005), Napoli, Italy (2007), Gaithersburg, USA (2009), Levico, Italy (2011), Taormina, Italy (2013), Iasi, Romania (2015), and Barcelona, Spain (2017).

HMM is an interdisciplinary forum for presenting and discussing recent advancements in the fields of hysteresis modeling, and computational micromagnetics. It aims to bring together scientists from a wide range of backgrounds (mathematics, physics, engineering, materials science, etc) to exchange ideas and to present and discuss methods and results. The scientific program consists of invited and contributed talks as well as posters dedicated to topics as detailed below, with no parallel sessions.

Aims and Topics

- Mathematical model of hysteresis.
- Preisach, Jiles-Atherton and vector hysteresis modeling.
- Classical and quantum spin models, random-field models and frustrated magnetism.
- Novel developments in micromagnetics, link to other physical models.
- Magnetic excitations and solitons.
- Ab-initio, atomistic and multi-scale modeling.
- Modeling of thermal effects in magnetism.
- Modeling of magnetization dynamics and spintronics.
- Modeling of individual magnetic nanostructures and their interactions.
- Modeling of magnetic systems for technological and biomedical applications.
- Experimental studies and model validation.

Website: http://users.math.uoc.gr

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Dr. Edward Della Torre

1934 - 2018

<u>IN MEMORY OF ED</u>

With deep sadness I write this reminder of the dear colleague and friend Ed.

Dr. Edward Della Torre, since 1982 Professor in the School of Engineering and Applied Science of the Department of Electrical and Computer Engineering of the George Washington University, Washington DC, passed away few months ago.

It is difficult for me to remember the long list of his titles, of the award received, of his prestigious scientific activities and merits.

Edward Della Torre earned a Bachelor of Electrical Engineering from the Brooklyn Polytechnic Institute, in 1954. He received a Master of Electrical Engineering from the Princeton University, in 1956. Thereafter, he obtained a Master of Science in physics from Rutgers, the State University of New Jersey, in 1961. In 1964, he earned a PhD from the Columbia University.

Professor Della Torre started his career in the Electrical Engineering Department at Rutgers, the State University of New Jersey, in 1956. He was also involved with the Solid State Physics Laboratory at Bell Telephone Laboratories from 1967 to 1968. Then he joined the McMaster University from 1968 to 1979, the Wayne State University from 1979 to 1982, before to move to the George Washinghton University.

A fellow of the Institute of Electrical and Electronics Engineers IEEE, and the American Physical Society, Prof. Della Torre has contributed more than 300 articles to professional journals and authored three books, “Magnetic Bubbles” in 1975, “Electromagnetic Field” in 1969, and “Magnetic Hysteresis” in 1999.

He has served IEEE as president of the Magnetic Society, as member of the board of directors, and in other many ways.

He has promoted and founded many international scientific events: among all I want to mention the first edition of the symposium “Hysteresis Modeling and Micromagnetics”, in 1996.

It is not easy for me to separate the evaluation of the qualities of man and scientist of Edward Della Torre.

Always co-operative with colleagues, available for students, Prof. Della Torre has created and directed a valuable, productive and numerous research group.

Ed, let me call him this way, as we all called him, leaves a deep and overwhelming emptiness not only in your family, but also in our scientific community: we will always remember him with affection and profound esteem.

I will miss his glances in silence, clearer and more eloquent than any word and any explanation.

Ermanno Cardelli

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HMM 2019 - Program at a glance

Time	Sunday	Monday	Tuesday	Wednesday
		Magnetic Solitons I (M. Garst)	Magnetization Dynamics (G. Finocchio)	Hysteresis Modeling III (A. Stancu)
8:15 - 8:30		In memory of Prof. Della Torre		
8:30 - 9:00		Mathias Kläui	Andrei Slavin	Vittorio Basso
9:00 - 9:15		Anne Bernand-Mantel	Elena Semenova	Ondrej Hovorka
9:15 - 9:30		Guoqiang Yu	Vito Puliafito	Marcos De Campos
9:30 - 9:45		Jonathan Leliaert	Johannes Ender	Olga Miroshkina
9:45 - 10:00		Luis Sanchez-Tejerina	Massimiliano d'Aquino	Virgil Provenzano
10:00 - 10:15		Yu Li	Alexander Chizhik	Hari Prasad Rimal
10:15 - 10:30		Pranaba Kishor Muduli	Ansaf Safin	Mikhail Vaganov
10:30 - 11:00		COFFEE BREAK		
		Hysteresis Modeling I (C. Visone)	Hysteresis Modeling II (K. Liu)	Micromagnetics and Nanoparticles II (A. Lyberatos)
11:00 - 11:15		Kai Liu	Evangelos Hristoforou	Jan Masell
11:15 - 11:30			Vladimir Sokolovskiy	
11:30 - 11:45		Joachim Gräfe	Laurentiu Stoleriu	Sergey Erokhin
11:45 - 12:00		Alexandru Stancu	Abdelahman Ghanim	Dmitry Berkov
12:00 - 12:15		Ümit Akıncı	Ciro Visone	Ruslan Rytov
12:15 - 12:30		Artur Chrobak	*Conference Picture*	Ali Oubelkacem
12:30 - 14:30		LUNCH BREAK		
		Multiscale Modeling (M. d'Aquino)	Magnetic Solitons II (C. Panagopoulos)	
14:30 - 15:00		Bertrand Dupé	Konstantin Gusliyenko	
15:00 - 15:15		Oksana Chubykalo-Fesenko	Markus Garst	
15:15 - 15:30		Haydar Kanso	Michalis Charilaou	
15:30 - 15:45		Min Yi	Nikolai Usov	
15:45 - 16:00		Cyrill Muratov	Giovanni Finocchio	
16:00 - 16:30	REGISTRATION	COFFEE BREAK		
		Micromagnetics and Nanoparticles I (D. Berkov)	Poster Session (J. Masell - O. Hovorka)	
16:30 - 17:00	Introductory Session (M. Kläui)	Daniele Pinna	POSTER SESSION	
17:00 - 17:15	Peter Fischer	Andreas Lyberatos		WINE TESTING EXCURSION
17:15 - 17:30		Yusuf Yüksel		
17:30 - 17:45		Kenan Song		
17:45 - 18:00	Christos Panagopoulos	*Panel discussion* International Credit Mobility		
18:00 - 18:15				
18:15 - 18:30				
18:30 - 20:00	WELCOME RECEPTION			
		18:45 - 20:30 TOUR OF THE CITY	19:30 - 00:00 SOCIAL DINNER	

HMM 2019

Heraklion, Greece, May 19th - 22nd, 2019

PROGRAM

SUNDAY, MAY 19th, 2019

16:00 Registration

INTRODUCTORY SESSION - Chair: **Mathias Kläui**, Johannes Gutenberg University Mainz, Germany

17:00 **Peter Fischer**, Lawrence Berkeley National Laboratory, Berkeley, CA, USA, invited
Advanced magnetic x-ray spectromicroscopy - a path towards understanding novel spin textures at fundamental magnetic length and time scales

17:45 **Christos Panagopoulos**, Nanyang Technological University, Singapore, invited
Stabilizing zero-field skyrmions in Ir/Fe/Co/Pt thin film multilayers by magnetic history control

18:30 Welcome Reception

MONDAY, MAY 20th, 2019

08:00 Registration

08:15 In memory of Prof. Edward Della Torre

MAGNETIC SOLITON I - Chair: **Markus Garst**, Karlsruhe Institute of Technology, Germany

08:30 **Mathias Kläui**, Johannes Gutenberg University Mainz, Germany, invited
Topological Dynamics – combining micromagnetic simulations and direct imaging to understand skyrmion dynamics

09:00 **Anne Bernand-Mantel**, Institut Néel, CNRS, Université Grenoble Alpes, France
The skyrmion-bubble transition in a ferromagnetic thin film

09:15 **Guoqiang Yu**, Institute of Physics, Chinese Academy of Sciences, Beijing, China
Anatomy of skyrmionic textures in magnetic multilayers

09:30 **Jonathan Leliaert**, Ghent University, Belgium
Coupling of the skyrmion velocity to its breathing mode in periodically notched nanotracks

09:45 **Luis Sánchez-Tejerina**, Politecnico di Bari, Italy
Micromagnetic and analytical descriptions of antiferromagnets

10:00 **Yu Li**, University of Manchester, United Kingdom
Investigation on Bloch point-mediated switching in magnetic skyrmions and antiskyrmions

10:15 **Pranaba Kishor Muduli**, Indian Institute of Technology Delhi, India
Skyrmion auto-oscillations in constrained ferromagnetic nanodisk

10:30 Coffee break

HYSTERESIS MODELING I - Chair: **Ciro Visone**, University of Sannio, Benevento, Italy

11:00 **Kai Liu**, Georgetown University, Washington, DC, USA, invited
Magnetization Reversal in Interconnected Nanowire Networks

11:30 **Joachim Gräfe**, Max Planck Institute for Intelligent Systems, Stuttgart, Germany
Interpreting FORC Diagrams Beyond the Preisach Model: an Experimental Permalloy Micro Array Investigation

11:45 **Alexandru Stancu**, Alexandru Ioan Cuza University of Iasi, Romania
xyFORC vectorial technique for characterization of multi-phase magnetic systems

12:00 **Ümit Akıncı**, Dokuz Eylül University, İzmir, Turkey
Hysteresis behavior of the magnetic system driven by a time-dependent magnetic field with white noise

12:15 **Artur Chrobak**, University of Silesia, Katowice, Poland
Optimization of hard magnetic properties of composites containing ultra-high coercive phases – simulations

12:30 Lunch break

MULTISCALE MODELING - Chair: **Massimiliano D'Aquino**, University of Naples "Parthenope", Italy

14:30 **Bertrand Dupé**, INSPIRE Group, Institute of Physics, Johannes Gutenberg University Mainz, Germany, invited
A multiscale approach to interfacial magnetism

15:00 **Oksana Chubykalo-Fesenko**, Institute of Materials Science of Madrid (ICMM), Spain
Atomistic modeling of temperature-dependent domain walls in ferro and ferrimagnets

15:15 **Haydar Kanso**, University of Rouen, France
Effect of grain boundaries and atomic interdiffusion on the exchange bias properties of ferromagnetic/antiferromagnetic nanodots: a Montecarlo investigation

15:30 **Min Yi**, Technical University of Darmstadt, Germany
Evaluating anisotropic exchange effect in Nd-Fe-B magnet by combined ab initio calculation, atomistic spin model, and micromagnetic simulation

15:45 **Cyrill Muratov**, New Jersey Institute of Technology, Newark, NJ, USA
Multidomain states in ultrathin ferromagnetic films with strong perpendicular magnetic anisotropy

16:00 Coffee break

MICROMAGNETICS AND NANOPARTICLES I - Chair: **Dmitry Berkov**, General Numerics Research Lab e.V., Jena, Germany

16:30 **Daniele Pinna**, TWIST Group, Institute of Physics, Johannes Gutenberg University Mainz, Germany, invited
Reservoir Computing with Random Magnetic Texture

17:00 **Andreas Lyberatos**, University of Crete, Heraklion, Greece
Dynamic coercivity of $L1_0$ FePt nanoparticles close to the Curie point

17:15 **Yusuf Yüksel**, Dokuz Eylül University, İzmir, Turkey
Effects of the particle size and shape of the magnetic nanoparticles on the magnetic hyperthermia and exchange bias properties

17:30 **Kenan Song**, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia
Spin Orbit Torque in Co/Graphene Hetero-System

17:45 Panel discussion: "*International Credit Mobility* "

19:00 Guided tour in the city

TUESDAY, MAY 21th, 2019

08:00 Registration

MAGNETIZATION DYNAMICS - Chair: **Giovanni Finocchio**, University of Messina, Italy

08:30 **Andrei Slavin**, Oakland University, Rochester, MI, USA, invited
Vector Hamiltonian Description of Hysteretic Nonlinear Dynamics in Nano-Scale Magnetic Systems

09:00 **9fŜyl· {ŜYŜyzØl·**, General Numerics Research Lab e.V., Jena, Germany
GPU-based massively parallel simulations of spin-torque-induced magnetization reversal in small nanoelements with applications to MRAM

09:15 **Vito Puliafito**, University of Messina, Italy
Spin-Hall current driven spin-wave resonance in an antiferromagnetic material

09:30 **Johannes Ender**, Institute for Microelectronics, TU Vienna, Austria
Two-Pulse Magnetic Field Free Switching Scheme for Advanced Perpendicular SOT-MRAM

09:45 **Massimiliano d'Aquino**, University of Naples "Parthenope", Italy
Analysis of switching times statistical distributions for magnetic memories

10:00 **Alexander Chizhik**, University of Basque Country, San Sebastian, Spain
New scenarios of magnetization reversal related to spiral structures in magnetic microwires

10:15 **Ansaf Safin**, Kotel'nikov Institute of Radioengineering and Electronics, Russian Academy of Sciences, Moscow, Russia
Mutual Synchronization of Coupled THz-frequency Antiferromagnetic Spin-Hall Oscillators with Hysteretic Responses

10:30 Coffee break

HYSTERESIS MODELING II - Chair: **Kai Liu**, Georgetown University, Washington, DC, USA

11:00 **Evangelos Hristoforou**, National Technical University of Athens, Greece
Hysteretic and non-hysteretic stress-dependent behavior of magnetostrictive delay line

11:15 **Vladimir Sokolovskiy**, Chelyabinsk State University, Russia
Monte Carlo simulations of hysteresis effects at the martensitic transformation

11:30 **Laurentiu Stoleriu**, Alexandru Ioan Cuza University of Iasi, Romania
Time-dependent Stoner-Wohlfarth model

11:45 **Abdelahman Ghanim**, University of Perugia, Italy
Analytical Formulation to estimate the Dynamic Energy Losses in Electrical Steels: Effectiveness and Limitations

12:00 **Ciro Visone**, University of Sannio, Benevento, Italy
Identification of a Preisach-based magneto-elastic model through its formal 'thermodynamic' constraints

12:15 Conference picture

12:30 Lunch break

	MAGNETIC SOLITONS II - Chair: **Christos Panagopoulos**, Nanyang Technological University, Singapore
14:30	**Konstantin Gusliyenko**, University of the Basque Country, San Sebastian, Spain, invited *Magnetic skyrmions in ultrathin films and dots*
15:00	**Markus Garst**, Karlsruhe Institute of Technology, Germany *Solitary wave excitations of skyrmion strings in chiral magnets*
15:15	**Michalis Charilaou**, University of Louisiana at Lafayette, USA *Dynamical pair-creation of Bloch points upon magnetization reversal in ferromagnetic nanoparticles*
15:30	**Nikolai Usov**, National University of Science and Technology MISiS, Moscow, Russia *Magnetostatic properties of assembly of magnetic vortices*
15:45	**Giovanni Finocchio**, University of Messina, Italy *Magnetic skyrmion entropy calculation based on a statistical thermodynamic approach*
16:00	Coffee break
16:30 18:30	**Poster Session** - Chairs: **Jan Masell**, University of Cologne, Germany, **Ondrej Hovorka**, University of Southampton, United Kingdom
20:00	Conference dinner at the tavern "Charilaos"

WEDNESDAY, MAY 22nd, 2019

08:00	Registration
	HYSTERESIS MODELING III - Chair: **Alexandru Stancu**, Alexandru Ioan Cuza University of Iasi, Romania
08:30	**Vittorio Basso**, INRIM National Institute of Metrological Research, Turin, Italy, invited *Magnetic refrigeration with hysteretic materials*
09:00	**Ondrej Hovorka**, University of Southampton, UK *Distributed heat production in clusters of magnetic nanoparticles*
09:15	**Marcos de Campos**, Federal Fluminense University, Volta Redonda RJ, Brazil *Hysteresis modification due to magnetostatic coupling*
09:30	**Olga Miroshkina**, Chelyabinsk State University, Russia *Thermal hysteresis modeling for Ni2.18Mn0.85Ga0.97 Heusler alloy*
09:45	**Virgil Provenzano**, National Institute of Standards and Technology, Gaithersburg, MD, USA *On the role of the leading anisotropy constant (K1) in the complex magnetic behavior of gadolinium revealed by magneto-thermal protocols*
10:00	**Hari Prasad Rimal**, University of Perugia, Italy *Modelling of dynamic losses in soft ferrite cores*
10:15	**Mikhail Vaganov**, Institute of Continuous Media Mechanics, Perm, Russia *Magnetic Hysteresis of Undermagnetized Magnetorheological Elastomers*
10:30	Coffee break
	MICROMAGNETICS AND NANOPARTICLES II - Chair: **Andreas Lyberatos**, University of Crete, Heraklion, Greece
11:00	**Jan Masell**, University of Cologne, Germany, invited *Higher order discretization schemes and artificial boundary conditions for high-accuracy simulations of the micromagnetic model*
11:30	**Sergey Erokhin**, General Numerics Research Lab e.V., Jena, Germany *Single-grain micromagnetic approach for simulations of a nanocomposite*
11:45	**5Yʎǘǌè .Ŝǌɩ2ǿ**, General Numerics Research Lab e.V., Jena, Germany *Optimization of the "energy bounce" method for determination of the switching rate of magnetic nanoelements*
12:00	**Ruslan Rytov**, National Research Nuclear University “MEPhI”, Moscow, Russia *Dynamics of superparamagnetic nanoparticle in viscous liquid in rotating magnetic field*
12:15	**Ali Oubelkacem**, Moulay Ismail University, Meknes, Morocco *The thermodynamics properties of a ferroelectric bilayer system: Effect of the size and strain induced field*
12:30	End of the symposium
17:00	Wine tasting excursion at the local winery "Lyrarakis"

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POSTERS

	TUESDAY, MAY 21th, 2019
16:30 18:30	**Poster Session** - Chairs: **Jan Masell**, University of Cologne, Germany, **Ondrej Hovorka**, University of Southampton, United Kingdom
P1	**Petru Andrei**, Florida State University, Tallahassee, USA *Efficient numerical implementation of the fast multipole method in finite element simulations*
P2	**Vittorio Basso**, INRIM National Institute of Metrological Research, Turin, Italy *Walker's modes in ferromagnetic finite hollow cylinder*
P3	**Valerio Apicella**, University of Sannio, Benevento, Italy *Stress Self-sensing in Amplified Piezoelectric Actuators through a Fully-Coupled Model of Hysteresis*
P4	**Andrey Chirtsov**, Czech Technical University in Prague, Czech Republic *Hysteresis Loops Modeling using Combined Rational and Power Functions*
P5	**Krzysztof Chwastek**, Czestochowa University of Technology, Poland *Towards a unified approach to hysteresis modeling and micromagnetics: A dynamic extension to the Harrison model*
P6	**Massimiliano d'Aquino**, University of Naples "Parthenope", Italy *Analysis of Thermal Switching and Chaotic Dynamics in ac-driven Nanomagnets*
P7	**Giovanni Finocchio**, University of Messina, Italy *Skyrmion based Random Bit Generator*
P8	**Ioana Firastrau**, Transilvania University of Brasov, Romania *Second order anisotropy contribution on magnetization dynamics in fully perpendicular spin transfer torque nano-oscillators*
P9	**Przemyslaw Gawronski**, AGH University of Science and Technology, Cracow, Poland *Micromagnetic simulation of spiral domain structures in microwires under influence of circular magnetic field*
P10	**Qihua Gong**, Technische Universität Darmstadt, Germany *Calculating coercivity at finite temperatures by micromagnetic simulations: a comparative study*
P11	**Joachim Gräfe**, Max Planck Institute for Intelligent Systems, Stuttgart, Germany *Using FORC to understand the Microstructure-Micromagnetism Relationship in Supermagnets*
P12	**Ondrej Hovorka**, University of Southampton, United Kingdom *The effects of disorder on hysteresis loops in chiral magnets*
P13	**Andrey Izotov**, Siberian Federal University, Krasnoyarsk, Russia *Micromagnetic simulation analysis of two-magnon relaxation processes in nanocrystalline thin films*
P14	**Adam Jakubas**, Czestochowa University of Technology, Poland *Modeling hysteresis loops of SMC cores with the Jiles-Atherton-Sablik description*
P15	**Gülşen Karakoyun**, Dokuz Eylül University, İzmir, Turkey *Effects of the Double Gaussian Random Field Distribution on the Hysteresis Characteristics of the Magnetic Binary Alloy*
P16	**Dimitris Kechrakos**, School of Pedagogical and Technological Education (ASPETE), Athens, Greece *Magnetic skyrmion formation on cylindrical surfaces with chiral interactions*
P17	**Yu Li**, University of Manchester, United Kingdom *Antiskyrmion-mediated phase transition in ideal and defective hexagonal skyrmion lattices*
P18	**Valentina Lucaferri**, Roma Tre University, Italy *A Neural Networks method based on Preisach model for hysteresis inverse problem*
P19	**Valentina Lucaferri**, Roma Tre University, Italy *Parallel Neural Networks system for dynamic magnetic hysteresis modelling*
P20	**Mariya Matyunina**, Chelyabinsk State University, Russia *First principles study of structural and magnetic properties in* $Fe_{100-x}Ge_x$ *alloys*
P21	**Mariusz Najgebauer**, Czestochowa University of Technology, Poland *Verification of self-similar model of hysteresis loop*
P22	**Alberto Oliveri**, University of Genoa, Italy *Asymmetric power-law model for compensating rate-dependent hysteresis in piezoresistive strain sensors*
P23	**Ioannis Panagiotopoulos**, University of Ioannina, Greece *Magnetic states and dynamics of bistable square Fe nanoislands*
P24	**Oksana Pavlukhina**, Chelyabinsk State University, Russia *Structural, magnetic and electronic properties of* $FeRh_{1-x}Pd_x$ *compounds: ab initio study*
P25	**Carl-Martin Pfeiler**, Institute of Analysis and Scientific Computing, TU Vienna, Austria *Computational studies of the nonlinear dynamics of magnetic skyrmions*
P26	**Aleksei Samardak**, Far Eastern Federal University, Vladivostok, Russia *Magnetic properties of Fe/Au barcode nanowire arrays and NdFeCoB nanoparticles studied by the FORC diagram method and micromagnetic simulations*

P27	**Takashi Shirane**, National Institute of Technology, Sendai College, Japan *Preisach and Steinmetz analyses of asymmetric hysteresis curves measured by lock-in amplifier*
P28	**Anastasios Skarlatos**, CEA-LIST, Saclay, France *Regression approach for steel characterization based on magnetic hysteresis*
P29	**Alexandru Stancu**, Alexandru Ioan Cuza University of Iasi, Romania *Typical hysterons and interactions in a multiphase flow of a ferrofluid in biological tissues*
P30	**Jan Szczygowski**, Czestochowa University of Technology, Poland *The use of quasi-static loops of magnetic hysteresis in prediction losses in non-oriented electrotechnical sheets*
P31	**Marius Volmer**, Transilvania University of Brasov, Romania *Micromagnetic modelling of reversal nucleation generated by magnetic nanoparticles on spintronic sensors*
P32	**Mikhail Zagrebin**, Chelyabinsk State University, Russia *Phenomenological modeling of thermal hysteresis in* $Ni_{2.18}Mn_{0.82}$ *Ga Heusler alloys in magnetic field*
P33	**Grzegorz Ziółkowski**, University of Silesia, Katowice, Poland *Magnetization processes of irregular dendrite structures - a Monte Carlo study*

PUBLICATION of PAPERS

A full paper related to the accepted abstract (oral and poster) can be submitted for publication in ***Physica B: Condensed Matter*** through the symposyum webpage.

Paper submission is open until May 31st.

VENUE

The Symposium takes place at Atlantis hotel, which is located in the very center of Heraklion (very close to the archeological museum) and has a view of the harbour.

INVITED CONTRIBUTIONS

Magnetic refrigeration with hysteretic materials

Vittorio Basso

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Magnetic refrigeration around room temperature is an environmentally friendly technology relying on the magnetocaloric effect (MCE) of magnetic materials. Materials with large MCE have been identified in compounds with a first order magneto-structural transition, where the large magnetic field induced entropy change is due to the presence of the latent heat of the transition. While in first order phase transition the hysteresis may represent a detrimental effect that should be either eliminated or appropriately taken into account, there are also other cases in which the hysteresis may present an advantage for achieving larger reversible entropy changes.

In this talk we first review the current status of magnetic refrigeration technology that has the objective of overcoming the limited temperature change of the magnetocaloric effect (of the order of 4 K/T). This is done by several methods as for example by using the principle of active magnetic regeneration of by cascading several stages. These permit to gain a resulting ΔT of ten times larger than the single material [1]. Next we review some of the most promising magnetic materials with large entropy change like the hydrogenated La(Fe-Si)$_{13}$-type and the Mn-Fe-P-Si-type both undergoing a first order transformation driven by the magnetic field [2]. The presence of hysteresis in the phase transition poses the problem of its description in a thermodynamic compatible way. As the hysteresis is always associated to out-of-equilibrium states, any thermodynamic approach must explicitly take into account the presence of internal production of entropy. Such a thermodynamic framework can be worked out in detail by considering energy profiles with two energy minima separated by an energy barrier, like in as the Bean-Rodbell model of magneto-volume coupling [3]. When structural disorder is taken into account, the resulting models have a Preisach-type structure and can be used to predict the details of the entropy change and the shapes of magnetic refrigeration cycles [4]. Finally we will present cases where the material hysteresis represents instead a chance of improvement for refrigeration. Indeed the reversible effect found around a remanence can be much increased by the use of large negative fields but unable to reverse the remanence state [5]. This effect is possible only in presence of large hysteresis.

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A multiscale approach to interfacial magnetism

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Magnetism at interfaces is becoming a major player in magnetic devices such as in magnetic random-access memory (MRAM) [1]. Interfaces can host a wide range of phenomena: the changes of chemical potential can induce large electric fields and the breaking of inversion symmetry allows the emergence of new transport properties or new interactions. The study of material properties at this scale requires to understand the interplay between chemical, structural and fonctional properties at the microscopic scale. This can be achieved based on atomistic simulations parametrized via density functional theory (DFT) calculations.

Recently, magnetism interfaces have been attracting lots of attention due to the presence of a chiral interfacial interaction called the Dzyaloshinskii-Moriya interaction (DMI). The DMI stabilizes chiral non-collinear magnetic textures such as domain-walls or skyrmions which can be manipulated efficiently by electrical currents and offer attractive perspectives for future spintronic applications [2].

Here, we show that density functional theory can be used to accurately describe the stability of non-collinear magnetic textures at surfaces [3] and interfaces [4]. Especially, we show that atomistic Hamiltonians parametrized via DFT calculations can be used to engineer the magnetic properties of interfaces and explain the occurance of skyrmions or explain their transport properties [5]. Our microscopic model revealed that a new type of magneto-resistance, called the non-collinear magnetoresistance (NCMR), could emerge depending on the skyrmion radius [10].

Our method further allows the exploration of the stabilization mechanisms of skyrmions. We could show that the competition between magnetic interactions can give rise to the simultaneous stabilization of both skyrmion and anti-skyrmions with peculiar dynamical properties [6]. Our findings also suggest new mechanisms to nucleate skyrmions such as magnetization quenching [7] or ultra-fast laser pulses [8]. These achievements show that Hamiltonians parametrized via DFT are a powerful tool to design materials with tuned magnetic, ferroelectric and optical properties.

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Advanced magnetic x-ray spectromicroscopy - a path towards understanding novel spin textures at fundamental magnetic length and time scales

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Spin textures and their dynamics hold the key to understand and control the properties, behavior and functionalities of novel magnetic materials, which can impact the speed, size and energy efficiency of spin driven technologies. Advanced characterization tools that provide magnetic sensitivity to spin textures at high spatial resolution, ultimately at buried interfaces and in all three dimensions [1], and at high temporal resolution to capture the spin dynamics across scales, are therefore of large scientific interest.

Magnetic soft X-ray spectro-microscopies [2] provide unique characterization opportunities to study the statics and dynamics of spin textures in magnetic materials combining X-ray magnetic circular dichroism (X-MCD) as element specific, quantifiable magnetic contrast mechanism with spatial and temporal resolutions down to fundamental magnetic length, time, and energy scales.

Current developments of x-ray sources aim to increase dramatically the coherence of x-rays opening the path to new techniques, such as ptychography [3] or x-ray photo-correlation spectroscopy (XPCS) [4] that allow unprecedented studies of nanoscale heterogeneity, complexity, and fluctuations.

I will review recent achievements and future opportunities with magnetic x-ray spectro-microscopies, specifically with full-field soft X-ray transmission microscopy and soft x-ray ptychography. Whereas the former uses Fresnel zone plate optics to form an image, the latter retrieves high resolution amplitude and phase contrast images via reconstruction algorithms of oversampled diffraction patterns.

Examples will include the static properties and dynamic behavior of magnetic skyrmion [5,6] textures with potential application to novel magnetic logic and storage devices, as well as results from an XPCS study at LCLS with a novel 2-pulse scheme that allowed to discover an unexpected and drastic change of the correlation times in nanoscale spin fluctuations near phase boundaries, i.e., in the skyrmion phase, and near the boundary with the stripe phase of a multilayered Fe/Gd system [4].

Acknowledgement

This work was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, Materials Sciences and Engineering Division Contract No. DE-AC02-05-CH1123 in the Non-Equilibrium Magnetic Materials Program (MSMAG).

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Magnetic skyrmions in ultrathin films and dots

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Magnetic skyrmion is a kind of topological soliton, a non-trivial inhomogeneous magnetization texture on the nanoscale. Skyrmions can be manipulated by spin polarized currents of extremely low density in comparison with the densities used in traditional spintronics [1]. Recently the individual skyrmions were experimentally observed at room temperature in Co/Pt, Ir/Co/Pt etc. ultrathin multilayer structures, including magnetic dots. To achieve efficient manipulation of the nanosized spin textures and implement skyrmion-based spintronic devices, it is essential to understand the skyrmion stability and dynamics in restricted geometries.

In this talk I focus on the skyrmion stability and excitation spectra in ultrathin magnetic films and cylindrical magnetic dots. The skyrmions can be stabilized at room temperature and zero external magnetic field due to an interplay of the isotropic exchange, interface Dzyaloshinskii-Moriya (DMI), perpendicular magnetic anisotropy and magnetostatic interactions. We consider Bloch- and Neel-skyrmions (see Figure 1) and calculate their stability phase diagrams and dynamics. The chiral DMI induced on the interfaces of heavy metals with ultrathin ferromagnetic layers (0.5-1 nm) is crucial for the Neel skyrmion stabilization [2]. The calculated spin wave eigenfunctions/ eigenfrequencies are classified according to the number of nodes of the dynamical magnetization in the radial and azimuthal directions [3]. The low-frequency skyrmion gyrotropic modes are in GHz frequency range and can be exploited in spin-torque nano-oscillators. The skyrmion eigenfrequencies are represented as functions of the skyrmion equilibrium radius, dot radius and the dot magnetic parameters. Recent experiments and calculations of magnetic skyrmion stabilization and dynamics in multilayer films and nanodots are discussed.

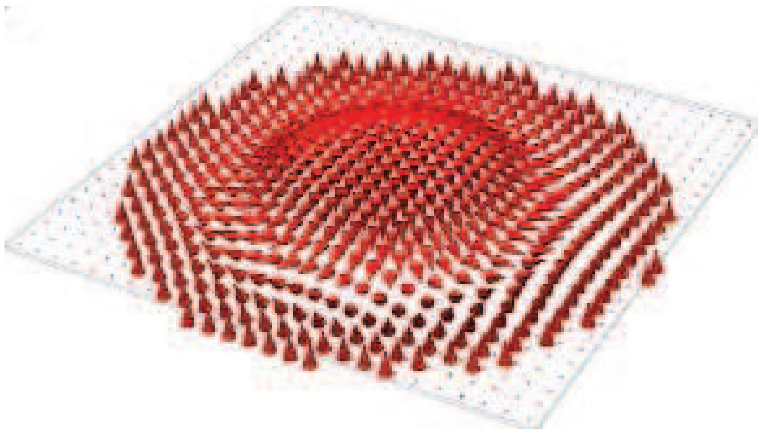

Figure 1: The magnetization texture of the Neel skyrmion in thin circular dot [3].

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Topological Dynamics – combining micromagnetic simulations and direct imaging to understand skyrmion dynamics

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Spintronics promises to be a paradigm shift from using the charge degree of freedom to using the spin degree of freedom. To this end three key requirements are: (i) stable spin structures for long term data retention; (ii) efficient spin manipulation for low power devices and (iii) understand both by comparison to micromagnetic simulations.

To obtain ultimate stability, topological spin structures that emerge due to the Dzyaloshinskii-Moriya interaction (DMI), such as chiral domain walls and skyrmions are used. These possess a high stability and are of key importance for magnetic memories and logic devices [1,2]. We have investigated in detail the dynamics of topological spin structures, such as chiral domain walls that we can move synchronously with field pulses [3]. We determine in tailored multilayers the DMI [4], which leads to perfectly chiral spin structures.

For ultimately efficient spin manipulation, spin transfer torques are maximized by using highly spin-polarized ferromagnetic materials that we develop and we characterize the spin transport using THz spectroscopy [2]. Furthermore, we use spin-orbit torques, that can transfer 10x more angular momentum than conventional spin transfer torques [4-6].

We combine strong spin-orbit torques and strong DMI so that novel topologically stabilized skyrmion spin structure emerge [5]. Using spin-orbit torques we demonstrate in optimized low pinning materials for the first time that we can move a train of skyrmions in a “racetrack”-type device [1] reliably [5,6]. We find that skyrmions exhibit a skyrmion Hall effect leading to a component of the displacement perpendicular to the current flow [6]. We study the field - induced dynamics of skyrmions [7] and find that the trajectory of the skyrmion’s position is accurately described by our quasi particle equation of motion [7]. To understand the skyrmion Hall effect origin, we use micromagnetic simulations including multiscale modelling [8] that combines Heisenberg spin model and micromagnetics. We identify 3 distinct origins of the skyrmion Hall angle depending on the creep and viscous flow regime.

The state of the the topic of skyrmions is reviewed in Ref. [9].

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Magnetization Reversal in Interconnected Nanowire Networks

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Three-dimensional arrays of nanomagnets offer exciting potentials for explorations of 3D information storage, spintronics and artificial spin ice. However, the synthesis and characterization of such nanostructures are often challenging. We have successfully realized novel, interconnected low density metallic nanowire networks, using electrodeposition into nuclear track-etched membranes etched at multiple azimuthal angles. Metallic networks with densities as low as 40mg/cm^3 have been achieved. The magnetization reversal in cobalt nanowire networks and the effects of intersections on magnetization reversal have been investigated by magnetometry and the first order reversal curve (FORC) method. Analysis alongside arrays of non-intersecting wires shows similar hysteresis dominated by demagnetizing interactions when the magnetic field is applied parallel to most wires. The magnetization reversal mechanism in the intersecting wires depends strongly on the interconnected structure and the orientation relative to the applied field. When all wires are perpendicular to the applied field, the magnetization reversal proceeds primarily by magnetization rotation. When majority of the wires are aligned with the applied field, the reversal proceeds primarily by single domain switching of the wires aided by demagnetizing dipole interactions. Finally, when planes of wires begin to be aligned with the applied field and fewer wires are parallel to that field, the dipole interaction weakens and in-plane domain wall propagation along the intersections begins to play an important role until it dominates the reversal. These results demonstrate a fascinating platform to encode information onto 3D nanomagnet arrays.

This work has been supported by the US NSF (ECCS-1611424 and DMR-1905468).

Higher order discretization schemes and artificial boundary conditions for high-accuracy simulations of the micromagnetic model

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For the description of magnetic textures on scales much larger than the lattice constant of the underlying atoms, the micromagnetic model is a simple approximation with great predictive power. The assumption of a continuous magnetization allows for both options: a rigorous analytic investigation or a numerical treatment of the equations. I will focus only on the simplified micromagnetic model in which the impact of magneto-static interactions is assumed negligible.

Unfortunately, even for the simplified case an analytic solution cannot be obtained for most problems, in contrast to results by numerical simulations. For calculating energies of the micromagnetic model and simulating its dynamics, various open-source codes are available and widely spread, the most common being MuMax3 [1] or OOMMF [2]. Usually, the simulations are performed by introducing finite distance or finite element approximations that are subject to numerical errors which usually scale quadratically in the lattice discretization, e.g., by mapping the continuous model to an effective atomistic model with only nearest neighbor interactions. These implementations have the clear advantage of being fast. However, the poor scaling properties prohibit the calculation of results with high accuracy since huge lattices would be required and demand extreme runtimes.

By using higher order discretization schemes, the scaling can be improved and exploited such that with only a few lattice sites the results become many orders of magnitude more precise while at the same time the runtime of the simulation can be reduced due to the smaller system size. An asymmetric discretization is required in the proximity of the boundaries to account for the missing discretization neighbors while pertaining the desired precision [3]. Furthermore, for infinitely large systems without magneto-static interactions, I show how half-infinite boundary conditions can be used instead of periodic boundary conditions in order to reduce the required system size and therefore the runtime tremendously. Figure 1 shows an example for the application of an 8th order discretization algorithm in combination with one half-infinite boundary condition, where the twist at the edge of a chiral magnet is calculated numerically with high accuracy while using only 10 lattice sites.

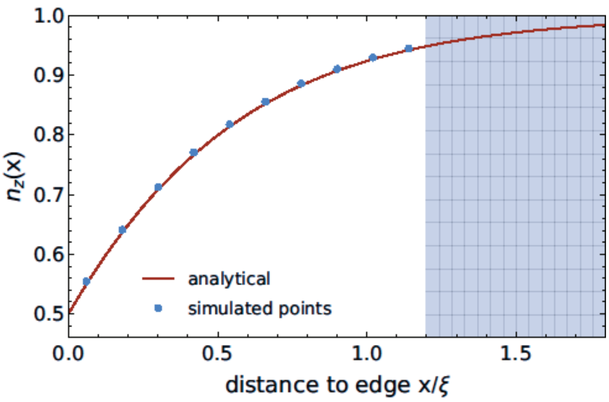

Figure 1: The magnetic profile at the edge of a system with Dzyaloshinskii-Moriya interaction twists. Comparison between the exact analytic result (red line) and the result of a simulation with 10 lattice sites (blue) with an open boundary condition (left) and a half-infinite boundary condition (right, gray area).

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Stabilizing zero-field skyrmions in Ir/Fe/Co/Pt thin film multilayers by magnetic history control

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Magnetic skyrmions are topologically charged spin textures, which resist external perturbations and are thus appealing as potential information carriers for spintronic technology. Recently, it has been shown that thin film multilayers comprising ferromagnets and heavy metals are suitable candidates to host stable skyrmion phases. In these materials, additively enhanced Dzyaloshinskii-Moriya interactions from neighbouring interfaces within the multilayers enable spin-winding (and hence, skyrmion formation) to occur even at room temperature. I will present a study of the stability of room-temperature skyrmions in [Ir/Fe/Co/Pt] thin film multilayers, using the First Order Reversal Curve (FORC) technique and magnetic force microscopy (MFM). FORC diagrams reveal irreversible changes in magnetization upon field reversals, which can be correlated with the evolution of local magnetic textures probed by MFM. Using this approach, we identified two different mechanisms - (1) skyrmion merger and (2) skyrmion nucleation followed by stripe propagation - which facilitate magnetization reversal in a changing magnetic field. Analysing the signatures of these mechanisms in the FORC diagram allows us to identify magnetic “histories” - i.e. precursor field sweep protocols – capable of enhancing the final zero-field skyrmion density. Our results indicate that FORC measurements can play a useful role in characterizing spin topology in thin film multilayers, and are particularly suitable for identifying samples in which skyrmion populations can be stabilized at zero field.

Reservoir Computing with Random Magnetic Textures

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The topologically protected magnetic spin configurations known as skyrmions offer promising applications due to their stability, mobility and localization. Thanks to their many nanoscale properties, skyrmions have been shown to be promising in many applications ranging from non-volatile memory and spintronic logic devices, to enabling the implementation of unconventional computational standards such as Stochastic computing and Reservoir Computing. Particularly, Reservoir Computing is a type of recursive neural network commonly used for recognizing and predicting spatio-temporal events. Its basic functioning does not require any knowledge of the reservoir topology or node weights for training purposes and can therefore utilize naturally existing networks formed by a wide variety of physical processes.

In this talk we will discuss how a random skyrmion "fabric" composed of skyrmion clusters embedded in a magnetic substrate can be effectively employed to implement a functional reservoir. This is achieved by leveraging the nonlinear resistive response of the individual skyrmions arising from their current dependent anisotropic magneto-resistance effect (AMR). Complex time-varying current signals injected via contacts into the magnetic substrate are shown to be modulated nonlinearly by the fabric's AMR due to the current distribution following paths of least resistance as it traverses the geometry. By tracking resistances across multiple input and output contacts, we show how the instantaneous current distribution effectively carries temporally correlated information about the injected signal. This in turn allows us to numerically demonstrate simple pattern recognition. We argue that the fundamental ingredients for such a device to work are threefold: i) Concurrent probing of the magnetic state; ii) stable ground state when forcings are removed; iii) nonlinear response to input forcing. Whereas we demonstrate this by employing skyrmion fabrics, the basic ingredients should be general enough to spur the interest of the greater magnetism and magnetic materials community to explore novel reservoir computing systems.

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Vector Hamiltonian description of hysteretic nonlinear dynamics in nano-scale magnetic systems

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A vector variant of a classical Hamiltonian formalism is developed for the theoretical description of nonlinear magnetization dynamics in nano-scale magnetic systems. The formalism is based on a specific version of a Lambert azimuthal equal-area projection that maps three-dimensional magnetization dynamics on a unit sphere on a two-dimensional Hamiltonian dynamics on a plane. The developed method uses a hybrid approach, where the linear eigenvalue problem for a nano-scale magnetic system is solved numerically, while the nonlinear dynamics is described analytically using the numerically calculated frequencies and spatial profiles of the magnetic eigenmodes. The developed hybrid approach is illustrated on two examples.

The first example is the description of the nonlinear properties of dynamic modes in an unbiased flat nano-scale NiFe element (80 nm x 40 nm x 5 nm). The lowest dynamic modes in the element are a pair of "edge modes" (symmetric and anti-symmetric) having amplitude maxima at the "length" edges of the element. Our calculations have shown that the "edge modes" demonstrate a hysteretic behavior in the nonlinear regime, and have a nonlinear frequency shift of the opposite sign and a much larger magnitude compared to the quasi-uniform "ferromagnetic resonance" mode of the same element (see Fig.1).

The second example is the description of the nonlinear properties of a magnonic Bose-Einstein condensate (BEC) observed at room temperature in a thin ferrite film. This BEC is double-degenerate, i.e. it is formed in two spectral minima corresponding to the lowest-energy magnons propagating in opposite directions. Our calculations have shown that the attractive self-interaction between the magnons residing in each of the spectral minima is very weak, so the magnon gas in the minimum is, practically, ideal. In contrast, the interaction between the magnons residing in different minima is relatively strong and repulsive, leading to a repulsive (positive frequency shift) total inter-magnon interaction (see Fig.2).

In both cases the results of the proposed semi-analytical vector Hamiltonian approach are in good quantitative agreement with the results of micromagnetic simulations or/and the results of a laboratory experiment.

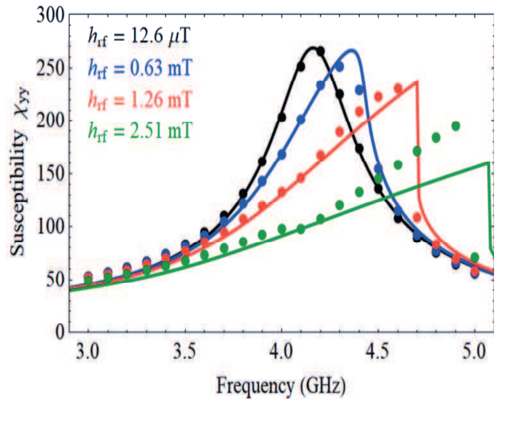

Figure1: Resonance curves for the dynamic "edge" mode of a rectangular NiFe element for different driving microwave fields h_{rf} . Points – full scale micromagnetic simulations, lines –semi-analytical calculations using vector Hamiltonian approach.

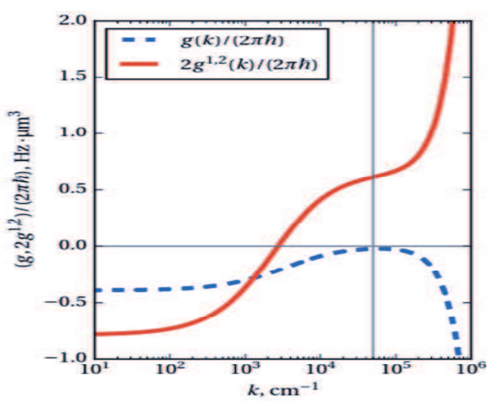

Figure 2: Nonlinear frequency shift coefficients for the self-interaction of magnons within a single magnon BEC (g(k), dashed line) and cross-interaction between two magnon BECs corresponding to opposite directions of the magnon wave vector k ($g^{1,2}$ (k), solid line.

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ORAL CONTRIBUTIONS

Hysteresis behavior of the magnetic system driven by a time-dependent magnetic field with white noise

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Random fluctuations in interested quantity can be defined by noise and it occurs almost everywhere. We cannot get rid of the noise completely and this limits the performance of our devices. On the other hand, external noise can result in some interesting phenomena such as noise-induced transition [1] and Stochastic resonance [2]. The noise-induced transition is a different type of nonequilibrium phase transition and can be investigated by theoretical methods. For instance, the effect of noise on Ising-like models is investigated by the Langevin equation and noise-induced phase transition has been observed [3].

Dynamical response of the magnetic systems (spin systems) to the time-dependent magnetic field has attracted attention both theoretically and experimentally. The relation between the relaxation time of the spin system and period of the driving periodic external magnetic field determines the dynamic phase of the system. Dynamic phase transition in these systems come from the competition between these two time scales [4]. Of course, the driving field is noisy in real life. Tuning the level of noise may induce some interesting behavior such as noise-induced dynamical phase transition, which mentioned above. Apart from this, in principle, dynamical hysteresis characteristics could be altered by tuning the level of noise.

The aim of this talk is to present the results about the effect of the white noise in the time-dependent periodic magnetic field on the spin-S Ising system. The method is an effective field theory based on Glauber type of stochastic process. Recently we investigate the behavior of the dynamical order parameter of the spin-1/2 Ising system. We conclude that the rising noise level can induce phase transition [5]. The generalization of the work to higher spin models results in the same phase transition. Besides, interesting behaviors related to the dynamical hysteresis characteristics obtained.

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GPU-based massively parallel simulations of spin-torque-induced magnetization reversal in small nanoelements with applications to MRAM

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We present a new micromagnetic methodology for parallel simulation of a large number of small-sized nanoelements. The proposed method is based on the specific cut-off of the magnetodipolar interaction kernel and allows to fully exploit the potentially high acceleration rate provided by modern GPUs only for large systems. The major target of the method is the study of magnetization dynamics in elements with sizes up to 100 nm, which are of the primary interest for, e.g., designing in-plane and perpendicular MRAM cells.

We apply our method to the spin-torque-induced magnetization switching of elliptical elements for two cases: the constant *total current* and the constant *current density* through the MRAM cell. By computing simultaneously the reversal of up to 1000 nanoparticles, we obtain the switching time distributions in dependence on the element size with a high statistical accuracy (Fig. 1). We show that results for the two simulation protocols mentioned above are qualitatively different.

For comparison, we perform the same simulations for the macrospin approach and demonstrate that full-scale micromagnetic simulations are essential for nanoelement sizes $> 40 \times 50\,\mathrm{nm}^2$. Switching times obtained by full-scale simulations largely exceed those of the macrospin model, and the difference rapidly growths with the element size. Analysis of the switching process has shown that for elliptical elements with the short axis $b = 40\,\mathrm{nm}$ and long axes $a < 90\,\mathrm{nm}$ the magnetization switches via the nucleation and growth of small reversed regions. For larger sizes ($a > 90\,\mathrm{nm}$) reversal occurs via the domain wall formation near the edge of an element and its propagation.

We also discuss in detail the relation between the switching time and the number and intensity of 'active' eigenmodes which naturally increases with the nanoelement size.

Financial support by the Deutsche Forschungsgemeinschaft (DFG project BE2464/17-1) is greatly acknowledged.

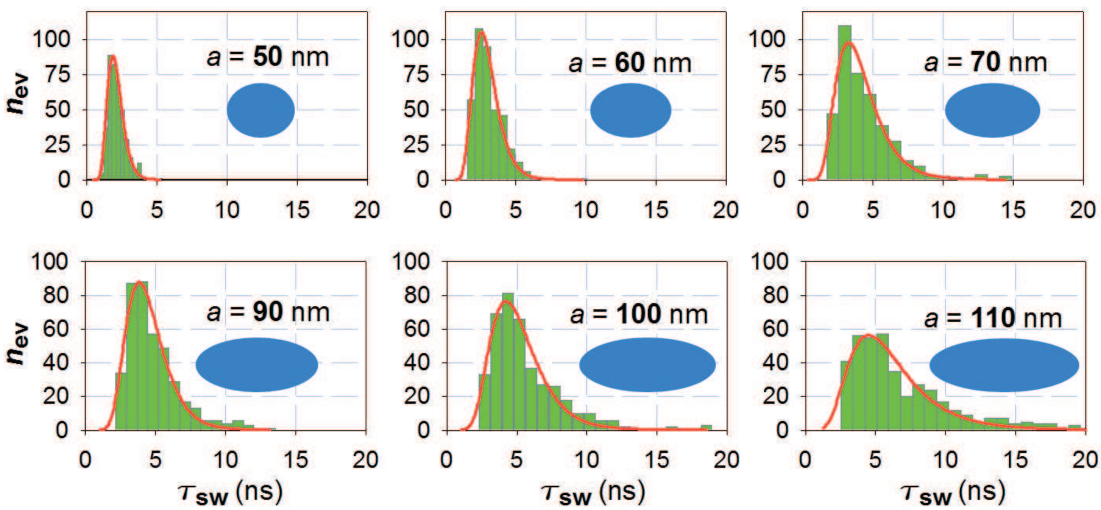

Figure 1: Distribution densities of the switching time τ_{sw} for 400 independent elliptical nanoelements for current desity $j = 9 \times 10^{11}\,\mathrm{A/m^2}$.

The skyrmion-bubble transition in a ferromagnetic thin film

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Magnetic skyrmions and bubbles, observed in ferromagnetic thin films with perpendicular magnetic anisotropy, are topological solitons which differ by their characteristic size and the balance in the energies at the origin of their stabilisation. However, these two spin textures have the same topology and a continuous transformation between them is allowed. The nanoscale size and non-trivial topology of skyrmions make them particularly attractive for information technologies. The recent observations of skyrmions at room temperature and their fast displacement with low electrical currents [1], has triggered a revival of the quest for a memory based on topological solitons, taking the form of a skyrmion racetrack memory [2]. Magnetic bubbles and skyrmions are close relatives as they can share the same topology. However, their characteristic size differs and while classical bubbles present a long lifetime at room temperature, much shorter lifetimes were found for skyrmions of a few nanometers in recent experimental and theoretical. The case of intermediate-size solitons is more favorable, as stable room-temperature topological solitons with sizes of a few hundred to a few tens of nanometers have been reported in multilayers and even in a single ferromagnetic layer. These topological solitons are sometimes called skyrmion bubbles when the demagnetising energy plays a role in their stabilization. In this context, the necessity to clarify whether a fundamental difference exist between skyrmions and bubbles appears. In previous works, the difference between magnetic bubbles with a large number of collinear spins in their center and skyrmions with a compact core has been described [3]. In the present work [3], we have developed an analytical topological soliton model containing expressions of the long range demagnetising and exchange curvature energies, two key ingredients to stabilize bubbles and skyrmions in ferromagnetic thin films. This allowed us to construct a skyrmion and bubbles phase diagram and explore quantitatively the possible transitions between them. The observed skyrmion-bubble transition present similarities with the liquid-gaz transition, in particular a critical point is present above which the transformation between both spin textures becomes continuous. While distinct characteristics of skyrmions and bubbles remain, their common nature as topological solitons is emphasised. In a second part we will discuss the role of long range dipolar interactions in the stabilization of compact skyrmions.

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Dynamical pair-creation of Bloch points upon magnetization reversal in ferromagnetic nanoparticles

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In magnetic particles with dimensions comparable to fundamental magnetic length scales, i.e., beyond the Stoner-Wohlfarth regime, competing magnetic forces lead to curling. We show, using high-resolution micromagnetic simulations, that the curling in ferromagnetic nanoparticles with uniaxial symmetry leads to the formation of smooth topological defects in the form of 2π domain-walls, i.e., skyrmion lines [1]. In order to accomplish magnetization reversal, the skyrmion lines have to break, consequently creating a pair of Bloch points, topological point-defects, which propagate rapidly through the solid. In fact, we find that these Bloch points move with speeds of several kilometers per second, faster than any other known magnetic object, and their linear motion generates a substantial emergent electric field with magnitude on the order of MV/m. Our findings show that topological concepts play a crucial role in magnetization processes in a wide range of materials, sizes, and shapes, and that the hysteretic behavior of ferromagnetic particles is closely associated with the generation of dynamic emergent fields.

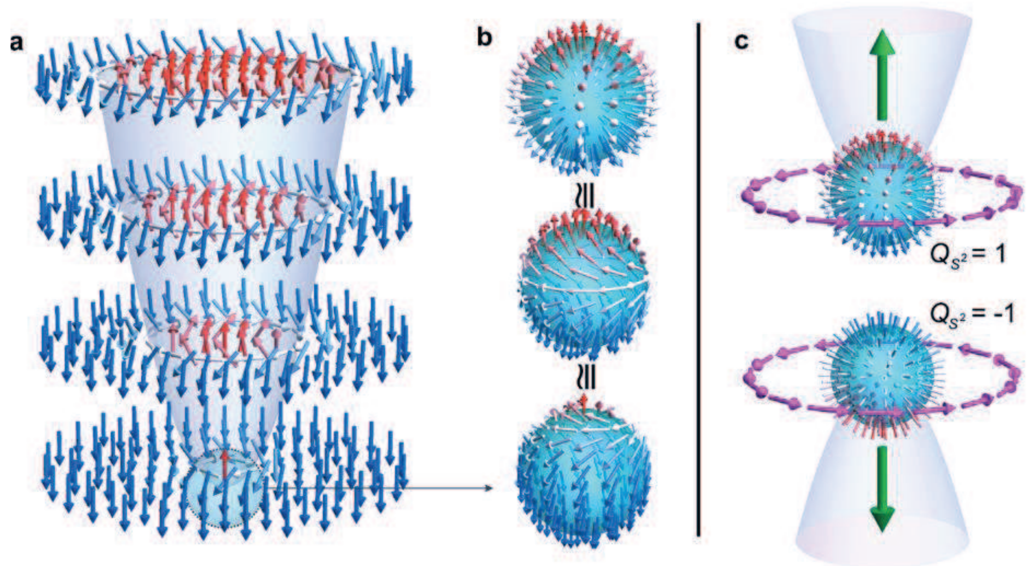

Figure 1: Schematic representation of (a) how the end of a broken skyrmion line is a topological point-defect (Bloch point), (b) how radial or chiral Bloch points are equivalent, and (c) how the motion of Bloch points generates a solenoidal emergent electric field. (Figure taken from [1])

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New scenarios of magnetization reversal related to spiral structures in magnetic microwires

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Identification and characterisation of novel and unusual magnetization states and scenarios of magnetization reversal is a topic of research in modern magnetism. Here we present the results of the study of spiral domain structure discovered earlier in magnetic glass covered microwires [1] and the scenarios of magnetization reversal related to this structure.

Imaging of the magnetic domains and hysteresis loops on the surface of microwires were performed via optical polarizing microscopy in the reflective mode using the longitudinal magneto-optical Kerr effect geometry. A mechanical torsion stress was applied to the studied microwire.

The surface magnetization reversal process began with the formation of wedge-like inclined domains, and at the second stage the wedge-like domains moved along the wire surface in such a way as to form a quasi-periodic structure (Fig. 1a). The magnetization reversal is determined basically by the effect of sporadic migration of spiral solitary domain at the surface and inside the microwire.

A theoretical analysis of the obtained results was performed on the basis of the assumption that, for a magnetostrictive microwire, the cylindrical symmetry of the wire limits the stress to radial, circumferential and axial components.

Using the simulations we demonstrated the spiral character of the obtained structure (Fig. 1b). This image clearly exhibit a structure radically different from the inclined ellipse helical structure studied earlier. The peculiarities of the calculated spiral structure reflect in calculated hysteresis loops. The effect of the surface domain migration finds its confirmation in the calculations realized in a series of dips and jumps on the hysteresis loops.

We have to note that an external torsion stress induced a variation of the type of surface magnetic structure giving preference to the spiral or elliptic structures depending on the value and direction of the stress. The decisive factor for realization of different scenarios of the magnetization reversal was the internal stress distribution inside the microwire.

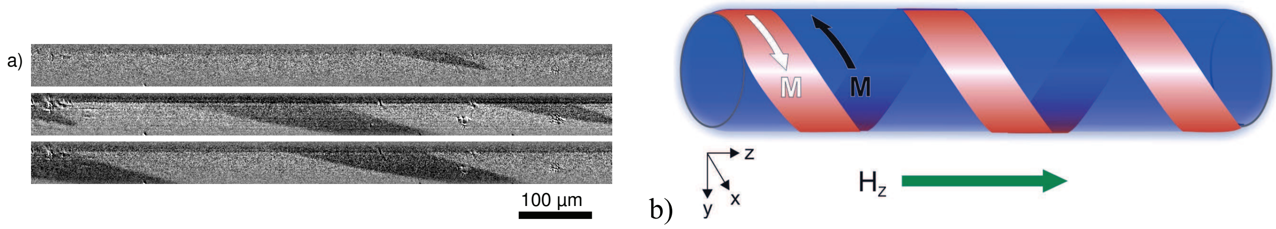

Figure 1: Experimental (a) and calculated (b) images of surface spiral domain structure. H_z is the external magnetic field induced magnetization reversal.

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Optimization of hard magnetic properties of composites containing ultra-high coercive phases – simulations.

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Hard magnetic materials are very important in modern technologies including automotive industry, energetics as well as different kind of sensors and actuators. Perfect permanent magnets should have high magnetic remanence, high coercive field and high value of the so-called energy product $|BH|_{max}$ (related to the energy of magnetic field outside a sample). In the family of hard magnetic materials a special meaning have those containing rare earth (RE) as well as transition metals. For example, the system of Nd-Fe-B sintered powders is considered as the best permanent magnets due to their high value of $|BH|_{max}$ and coercive field H_c. Unfortunately, resources of the rare earths are restricted, and therefore, findings of new hard magnetic materials without or with reduced RE content are of great importance. One of possible research directions is related to a possibility of coupling magnetically hard and soft phases in the so-called spring-exchange magnets where the hard part is a source of magnetic anisotropy and the soft phase should increase magnetic remanence. Recently, we have reported ultra-high coercivity of Fe-Nb-B-Tb bulk alloys prepared by vacuum suction technique [1]. It was shown that for the $(Fe_{80}Nb_6B_{14})_{0.88}Tb_{0.12}$ alloy the coercive field exceed 7 T in the room temperature that, in the case of bulk alloys, is a unique feature. In this system (Tb-Fe) Tb and Fe magnetic moments are coupled antiferromagnetically which is responsible for relatively low magnetic remanence and in consequence $|BH|_{max}$. However, the Fe-Nb-B-Tb bulk alloys can be considered as material with extremely high resistance to external magnetic field and can be a source of magnetic anisotropy in powders as well as bulk composites.

The presentation refers to simulations of magnetization processes of the spring-exchange magnetic composites containing magnetically soft and ultra-high coercive phases. In order to modeling hysteresis loops a special disorder-based Monte Carlo procedure, suitable for irregular geometry of the composites, was introduced [2]. The idea is based on the fact that disorder of some physical properties may affect clusterization of the system. The proposed modification of the method enhances effectiveness of the energy minimization during the Monte Carlo step, which is especially important in simulations of magnetization processes of irregular multiphase systems. The obtained results indicate a possibility to optimization of hard magnetic properties of the tested systems, regarding either enhancement of the $|BH|_{max}$ parameter, important for the modern permanent magnets, or decrease of the hard magnetic phase content.

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Atomistic modeling of temperature-dependent domain walls in ferro and ferrimagnets

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Evaluation of temperature-dependent micromagnetic parameters is an essential part of the finite-temperature micromagnetics within the multi-scale approach [1]. Within this framework one starts with ab-initio parameterization of the Heisenberg Hamiltonian and using the temperature-dependent atomistic modeling evaluate the temperature-dependent macroscopic parameters. Those can be used for large-scale micromagnetics: at relatively low temperatures - the standard micromagnetics based on the Landau-Lifshitz-Gilbert equations [2] while at high temperatures - the micromagnetics - based on the Landau-Lifshitz-Bloch equation [3]. Typically all micromagnetic parameters are scaled with temperature-dependent magnetisaiton with characteristic material-dependent exponent. This multi-scale scheme provides a simple possibility to evaluate the temperature-dependent dynamics for example, the dependence of the skyrmion radius on temperature [2]. This approach also predicts that the domain wall width typically increase with temperature due to a slower temperature dependence of the exchange parameter with respect to the anisotropy.

In the present work we investigate the temperature-dependence of domain wall width in ferromagnets (on the example of Cobalt) and ferrimagnets (on the example of FeGd). The on-site RKKY-type exchange parameters for these materials are evaluated by ab-initio models. While the domain wall width has a pronounced temperature dependence in ferromagnets with the scaling exponent following predicted theoretical behavior [4], in ferrimagnets this dependence is slow (see Fig.1). Moreover, the two sublattices in ferrimagnet share the same domain wall width (except for a very negligible value of antiferromagnetic coupling) at all temperatures. Furthermore, we did not find any peculiar behavior of the domain wall width in the vicinity or at the magnetization compensation point Tm. This shows that ferrimagnets cannot be treated as ferromagnets in this respect since the macroscopic parameters do not scale with the net magnetization (or the value of the Neel vector). The results are important for understanding recent results of temperature-dependent domain wall dynamics in ferrimagnets [5].

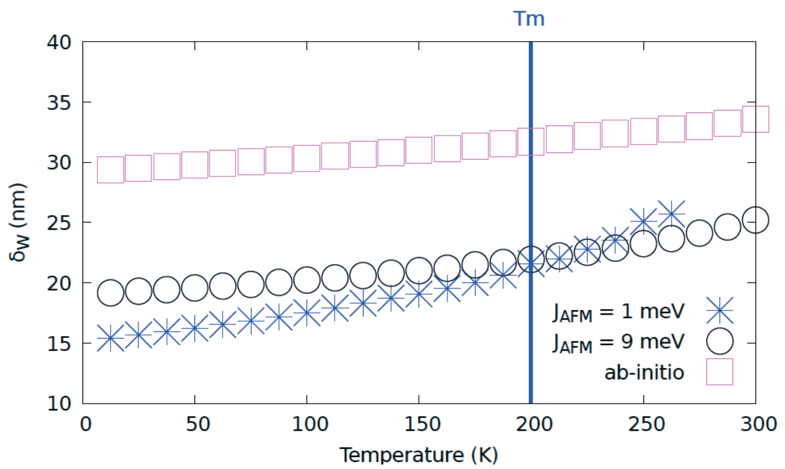

Figure 1: The temperature-dependence of ferromagnetic domain wall width for several exhcnage parameters modes.

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Analysis of switching times statistical distributions for magnetic memories

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Magnetization switching in nanomagnets is the fundamental issue to deal with in order to obtain high speed and energy-efficient recording devices[1].

To realize fast magnetization switching with greater efficiency, strategies as microwave-assisted switching[2] and precessional switching[3] have been proposed. In particular, the latter occurs by applying a field transverse to the initial magnetization and yields much smaller switching times than conventional switching. However, extremely precise design of the field pulse is required for successful switching. Then, the equilibrium magnetization is reached after quasi-random relaxation from a high-to low-energy state. This mechanism is probabilistic even when thermal fluctuations are neglected, but the stochasticity is much more pronounced when the latter are considered[3]. On the other hand, magnetic recording devices must fulfill strict reliability requirements in terms of very low write-error rates, which can be realized at expense of the write process speed.

In this paper, we theoretically analyze the magnetization switching for a single magnetic bit cell subject to applied field/spin-polarized current pulses and room temperature thermal fluctuations. By using analytical techniques, we derive expressions for the switching times distribution functions in terms of material, geometrical and external field properties[4]. Numerical simulations (macrospin and full micromagnetic) are performed to validate the analytical predictions. Fig. 1 reports an example of comparison between analytical approach, numerical macrospin and full micromagnetic simulations in the case of a perpendicular recording magnetic grain.

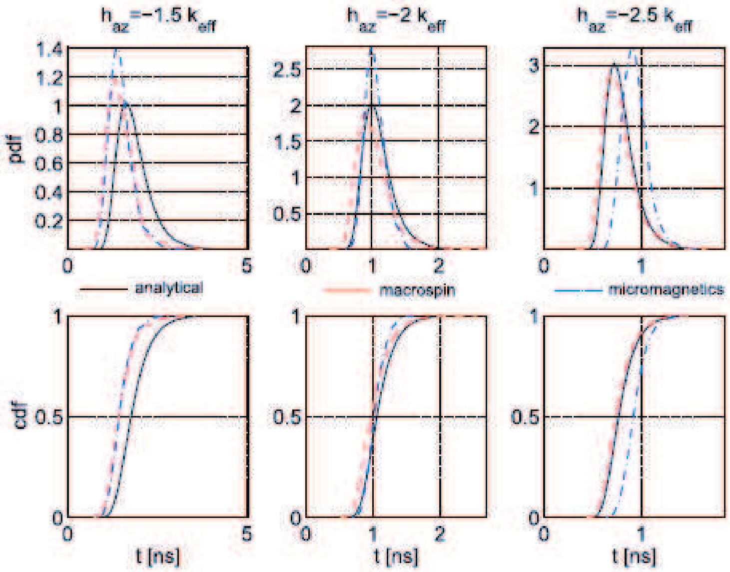

Figure 1: Switching times probability and cumulative distributions as function of applied field pulse amplitude (normalized by the critical switching field k_{eff}). Solid black, dashed red, dash-dotted blue lines refer to analytical theory, macrospin and micromagnetic simulations, respectively.

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Hysteresis modification due to magnetostatic coupling

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Effects of magnetostatic coupling between different phases can affect the hysteresis shape. The magnetostatic coupling can be taken into account by a mean field. In this study, it is described how the model of Callen-Liu-Cullen [1] can be interpreted as a model describing magnetostatic coupling between two phases, one magnetically hard and another magnetically soft.

Two situations will be discussed: One is the system found in SmCoFeCuZr magnets, with two main phases: Sm(CoCu)5 (1:5) and $Sm_2(FeCo)_{17}$ (2:17), where 2:17 is the hard phase and 1:5 is the soft phase here, due to large amount of copper replacing cobalt. The other situation is that of significant practical interest, the coupling between $Nd_2Fe_{14}B$ and alpha-iron phase, where $Nd_2Fe_{14}B$ is the hard phase and alpha-iron is the soft phase. The two situations are very different because 1:5 and 2:17 are crystallographically coherent in SmCoFeCuZr magnets, whereas for the second case the crystalline structures are different: $Nd_2Fe_{14}B$ is tetragonal , with Space Group (SG) number 136 and lattice parameters a=b=8.77 Å and c= 12.1 Å , however alpha-iron is bcc (SG=229) a=2.87 Å.

As consequence of magnetostatic coupling, there is a limitation for phase dimensions: both the hard and the soft phases need to be below the single domain particle size. With basis on the existence of magnetostic coupling, ideal nanostructures for obtaining high BHmax (maximum energy product) are discussed.

Henkel plots [2] may provide evidence of magnetostatic coupling. The Henkel plots [2] were formulated considering the Wohlfarth model of interaction between particles [3]. Here it is discussed how the Callen-Liu-Cullen model can be combined with the Wohlfarth model [3] for providing an estimate of the volume fraction of the soft phase directly from measured hysteresis curves.

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Two-Pulse Magnetic Field Free Switching Scheme for Advanced Perpendicular SOT-MRAM

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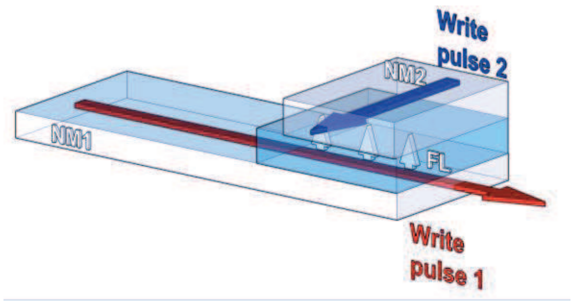
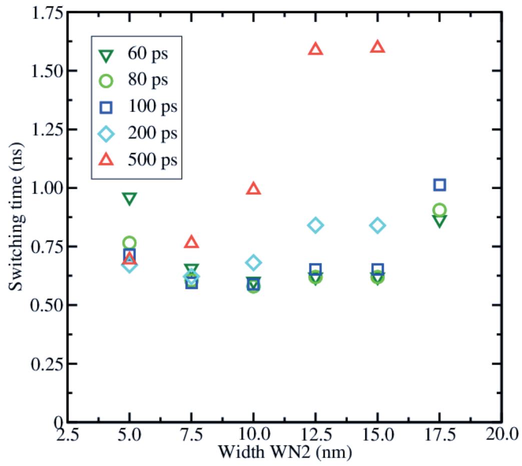
The continuous increase in performance and speed of modern integrated circuits is steadily supported by miniaturization of CMOS devices. However, a rapid increase of stand-by power due to leakages becomes a pressing issue. To reduce the energy consumption particularly in CPUs, one can replace the SRAM in hierarchical multi-level processor memory structures with a non-volatile memory. The development of an electrically addressable non-volatile memory combining high speed and high endurance is essential to achieve this goal [1]. Spin-orbit torque magnetoresistive random access memory (SOT-MRAM) combines non-volatility, high speed, and high endurance and is thus perfectly suited for applications in caches. However, its development is still hindered by the need of an external magnetic field for deterministic switching of perpendicularly magnetized layers [2].

We demonstrate that a magnetic field free two-pulse switching scheme previously suggested to accelerate switching of afree layer (FL) of a rectangular form [3] is also suitable for switching of symmetric perpendicularly magnetized layers. The memory cell is shown in Fig.1a: It includes a perpendicularly magnetized FL on top of a heavy metal wire (NM1). Another heavy metal wire (NM2) overlaps partly and serves to apply the second consecutive perpendicular current pulse of the same current density, with a duration T_2. The first pulse puts the magnetization in-plane, while the second pulse running under a part of the free layer tilts the magnetization in this part to create an in-plane stray magnetic field. This in-plane magnetic field acts on the rest of the free layer and completes the switching deterministically

Fig.1b shows the switching time averaged over 20 realizations as a function of the second pulse duration T_2 when the first pulse is 100ps short as a function of the overlap of NM2 with a 25nm×25nm FL. The fast (~0.5ns), deterministic, and magnetic field free switching of a perpendicularly magnetized recording layer is achieved for non-complete overlap between 20% to 70%. The switching scheme is extremely robust with respect to pulse duration fluctuations and pulse synchronization failure as it yields a large confidence window with respect to T_2 fluctuations (Fig.1b). The optimal overlap NM2 with the free layer is found to be around 30-50%



(a)



(b)

Figure 1: (a) Two-pulse switching scheme applied to the perpendicularly polarized square magnetic FL; (b) Switching time averaged over 20 realization as function of the overlap, for several second pulse

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Single-grain micromagnetic approach for simulations of a nanocomposite

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Micromagnetic analysis of magnetization reversal process is a powerful tool for the development of novel materials based on magnetic nanocomposites. The overall magnetic performance of these materials strongly depends of their microstructure, so that for straightforward simulations of their magnetization reversal, simulation volumes $\sim 1\,\mu\mathrm{m}^3$ should be used, requiring enormous computational resources [1]. To overcome this problem, we present in this talk a methodology based on a single-grain approach that allows to obtain quantitatively accurate results on systems with a typical grain sizes exceeding several tens of nanometers; this grain size would make direct micromagnetic simulations of a system having a statistically relevant number of composing elements unfeasible.

On the example of ferrite-based nanocomposites [2] containing magnetically soft grains embedded in a hard matrix, we demonstrate how micromagnetic simulations using individual soft grains can be tailored in order to obtain an upper size limit of the single-domain state of such grains in a nanocomposite. In this study, we concentrate our efforts on systems with the low volume fraction of a soft phase, what represents the most important case for permanent magnet materials. Due to this assumption and relatively large dimensions of soft grains, the system size to be simulated would be too large (both from the memory and computational time considerations) to allow modeling of a truly multigrain sample.

The approach for simulations of soft/hard nanocomposites in the single-particle formalism presented here takes into account the exchange interaction with adjacent hard crystallites by the introduction of the additional surface 'exchange anisotropy' of a soft grain. Further, the magnetodipolar field of both the hard matrix and other soft grains are included. In particular, we show that the magnetodipolar interaction between soft grains even at small concentration of this phase plays an important role in the magnetization reversal process of a nanocomposite and should be quantitatively determined. Several models of this effect are provided.

Financial support of the EU Horizon-2020 project "AMPHIBIAN" (720853) is gratefully acknowledged.

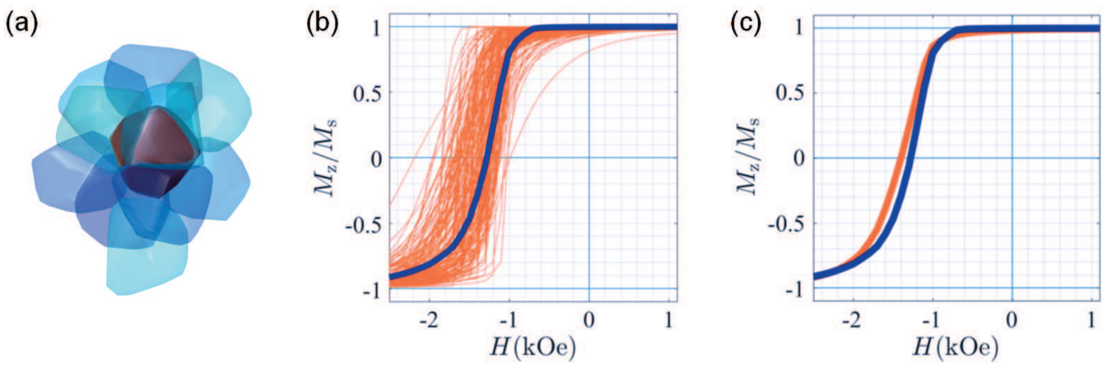

Figure 1: (a) An example of a soft grain (dark red) surrounded by a hard matrix grains (blue) used in simulations. (b) Upper part of the soft phase partial hysteresis loop (blue line) obtained for the 'full' multigrain model and 'single particle' loops (orange lines) for different realizations of single soft grains (taking into account an **average** magnetodipolar field from other soft grains). (c) Upper parts of the soft phase loop for the 'full' model (blue line) and obtained by averaging of 'single particle' loops shown in (b) (orange line).

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Magnetic skyrmion entropy calculation based on a statistical thermodynamic approch

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Magnetic skyrmions have a leading role in low-dimensional magnetic systems for their suitable physical properties and potential applications. New techniques in ferrimagnets and micromagnetic simulations show that skyrmions exhibit changes of size and deformations with time [1]. The purpose of this study is thus the determination of configuration entropy due to skyrmion changes of size and deformations as observed in micromagnetic simulations using a statistical thermodynamic approach. This approach is different from the ones of previous studies based on classical thermodynamics [2,3].

The method is based on two main ansatz: 1) the skyrmion energy is fitted via a parabola in the vicinity of the minimum and 2) the skyrmion diameters population follows a Maxwell-Boltzmann (MB) distribution. Concerning 1), the skyrmion energy is written as $E = a\,(D_{\mathrm{sky}} - D_{0\mathrm{sky}})^2 + b$ and has a parabolic dependence on skyrmion diameter D_{sky}, with $D_{0\mathrm{sky}}$ the equilibrium diameter, a the curvature and $b = E_{\mathrm{min}}$ the minimum energy. Regarding 2), from the comparison between micromagnetic and analytical results, we have found that the skyrmion diameters distribution is of the form: $dn/dD_{\mathrm{sky}} = C\,D_{\mathrm{sky}}^2 \exp(-a(D_{\mathrm{sky}} - D_{0\mathrm{sky}})^2/k_B T)$ with C a constant, k_B the Boltzmann constant and T the temperature. This has allowed us to make a strict analogy between the skyrmion diameters population and the MB distribution of particles in an ideal gas and to calculate the skyrmion entropy $S = -k_B H_0$ from the Boltzmann H_0 order function at thermodynamic equilibrium. In the special case, the configuration entropy of a magnetic Néel skyrmion in a Co circular nanodot with out-of-plane magnetization of radius $R_d = 200$ nm and thickness $t = 0.8$ nm has been computed.

Figure 1 shows the analytically calculated skyrmion configuration entropy as a function of T using the following parameters at $T = 0$ K: saturation magnetization M_S=600 kA/m, exchange stiffness A=20 pJ/m, *i*-DMI parameter D=3.0 mJ/m^2, uniaxial anisotropy constant K_u=0.60 MJ/m^3, Gilbert damping coefficient α =0.01. Magnetic parameters are scaled with T [4]. S increases with increasing T and decreases with increasing the external bias field at fixed temperature.

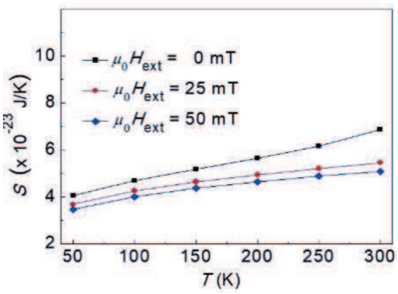

Figure 1: Skyrmion entropy vs. T at three different external bias fields.

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Solitary wave excitations of skyrmion strings in chiral magnets

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Chiral magnets possess topological line excitations where the magnetization within each cross section forms a skyrmion texture. We study analytically and numerically the low-energy, non-linear dynamics of such a skyrmion string in a field-polarized cubic chiral magnet, and we demonstrate that it supports solitary waves. Theses waves are in general non-reciprocal, i.e., their properties depend on the sign of their velocity v, but this non-reciprocity diminishes with decreasing $|v|$. An effective field-theoretical description of the solitary waves is derived that is valid in the limit $v \to 0$ and gives access to their profiles and their existence regime. Our analytical results are quantitatively confirmed with micromagnetic simulations for parameters appropriate for the chiral magnet FeGe. Similarities with solitary waves found in vortex filaments of fluids are pointed out.

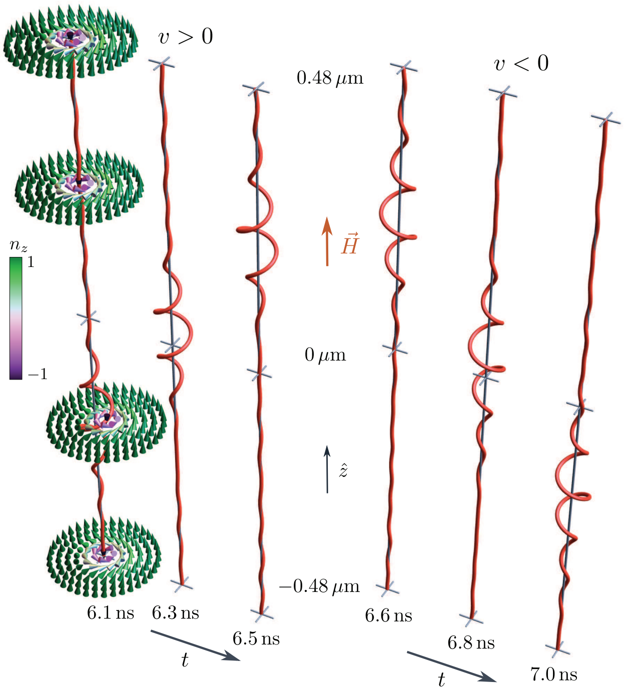

Figure 1: Solitary wave excitation of an isolated skyrmion string in a field-polarized cubic chiral magnet. The string is aligned with the magnetic field $\vec{H} = \hat{z}H$, and the solitary wave is propagating in a direction parallel ($v > 0$) and antiparallel ($v < 0$) to $\vec{H}$. The figure is produced by micromagnetic simulations with parameters typical for the chiral magnet FeGe. The magnetic field is $\mu_0 H \approx 0.8$ T resulting in a skyrmion string radius of approximately 5 nm. Solitary waves with amplitude $R_0 \approx 5.8$ nm are created at time $t = 0$ and propagate with velocity $|v| \approx 1$ km/s.

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Analytical Formulation to estimate the Dynamic Energy Losses in Electrical Steels: Effectiveness and Limitations

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The paper proposed deals with the characterization and the modeling of the dynamic energy losses for laminated electrical steels in use for the magnetic components in power electronics applications, where the voltage and current wave forms are highly distorted and not-sinusoidal. In these conditions it is critical to estimate with accuracy the dynamic energy losses.

The predictive methods for the dynamic energy losses for soft ferromagnetic materials can be divided into two main categories. On one hand, analytic formulas, eventually based on the “loss separation criterion” [1], are used: they compute the dynamic energy losses as a function of the frequency, of the amplitude of the magnetic induction, or of the first derivative in time of the magnetic induction, and in function of some other geometrical and physical parameters. On the other hand, the dynamic energy losses can be estimated using a FEM formulation in time domain to solve the diffusion equation, where the hysteretic constitutive law has to be modeled in proper way. In this case a more correct modeling of hysteresis and eddy current is made, but the component of the dynamic energy losses, usually named as *excess losses* in not considered. It has been extensively proved that the modeling of magnetic hysteresis via the Preisach approach is reliable and generally accurate, although it needs for an experimental identification of its parameters and is rather expensive from the computational point of view.

In this paper a grain oriented GO electrical steel M3T23 grade, and a not grain oriented NGO electrical steel 35H270 grade are considered as test materials. The experimental analysis is carried out via an Epstein frame, where an efficient feedback algorithm is implemented to control the magnetic induction waveform.

The materials under test are excited with suitable non-sinusoidal magnetic induction waveforms at 400 Hz as a fundamental frequency superimposed with 3rd harmonics, and the results got from the different approaches are compared with the measurements.

Fig. 1 shows some preliminary results found. A detailed discussion will be given in the extended version of the paper.

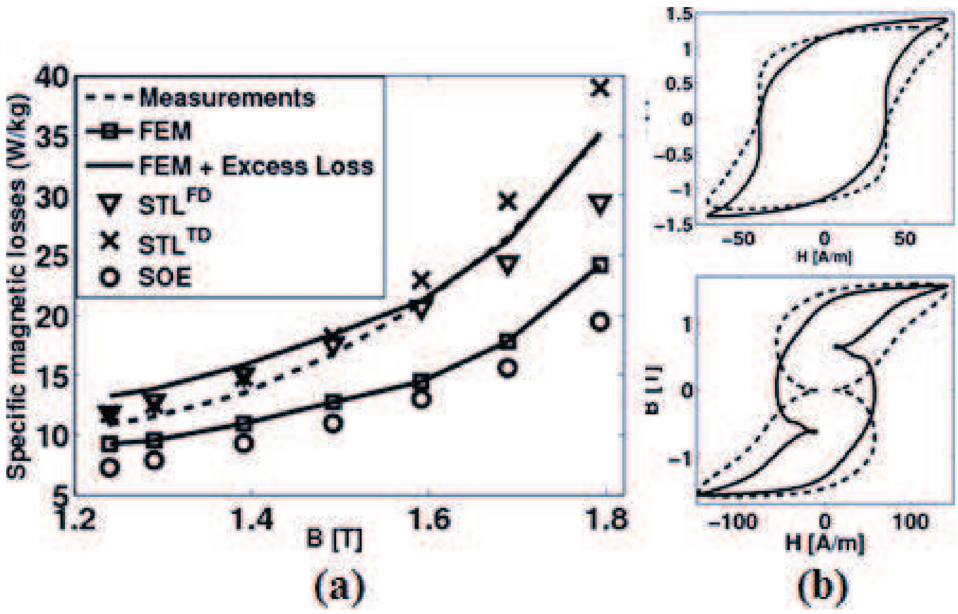

Figure 1: (a) Core Loss as a function of the magnetic induction and (b) hysteresis loops (the Dotted line is the measurements while the solid line is the simulation results.

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Interpreting FORC Diagrams Beyond the Preisach Model: an Experimental Permalloy Micro Array Investigation

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First-order reversal-curves (FORCs) are a powerful tool, which is increasingly used in material science and nano-magnetism [1-4]. Ideally, it can access microscopic interactions and coercive fields without the need for lateral resolution [5]. Unfortunately, most real systems violate the Mayergoyz criteria that are requirements for straightforward interpretation of FORC diagrams [6]. Thus, additional tools, like magnetic microscopy, are needed for proper interpretation of FORC diagrams beyond a mere fingerprint [1, 2]. It would be desirable to push the interpretability of FORC diagrams beyond these limitations.

We artificially designed systems that violate the Mayergoyz criteria in order to create features in the FORC density, which are not part of the classical interpretation. These multi-component systems consist of 150 µm permalloy (Py, Ni80Fe20) stripes of alternating size (inset in Fig. 1) which experience a considerable interaction field from their neighbors. An exemplary FORC density is shown in Fig. 1: Peak A corresponds to the wider stripes, peak B to the narrow ones. The additional peak pair (C) is a pure consequence of the interaction between two components with different intrinsic coercivities and does not correspond to a physical component of the system.

By varying spacing and width of the stripes, we show that the volume of the double peak C corresponds to the interaction in the system. Furthermore, a dipole approach is used to model these interactions. Each stripe was approximated as a superposition of up to 4500 dipoles. Plotting the interaction peak volume over the interaction extracted from the model for two different big stripe widths (w = 30, 50 µm) we find a linear relation for these two quantities (Fig. 2).

Systematically investigating alternating microarrays, we found that hard and soft magnetic components within one structure can lead to extra peaks in the FORC density [7]. This can be used to extract additional quantitative information not provided by the conventional interpretation approach and is a thorough step towards a more general and quantitative interpretation of FORC diagrams.

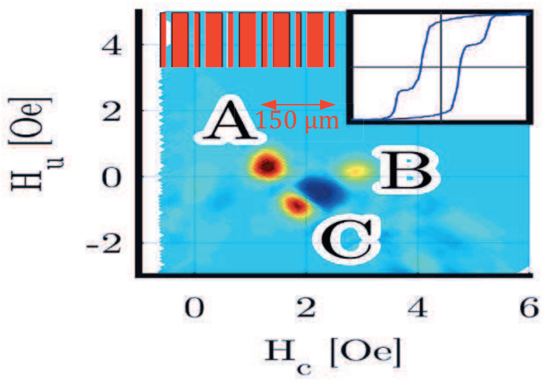

Figure 1: FORC density of alternating stripes.

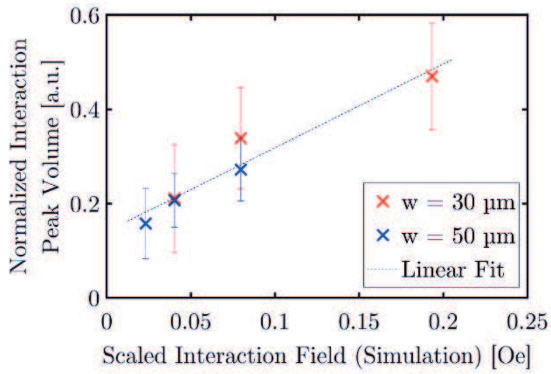

Figure 2: Interaction peak volume plotted over simulated interaction field.

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Distributed heat production in clusters of magnetic nanoparticles

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We address the issue of quantifying the heat produced by a single magnetic nanoparticle (MP) embedded within an interacting MP cluster. This is relevant for MP hyperthermia considered as a modality for enhancing cancer therapies, where it becomes necessary to understand the distribution of heat production across a MP aggregate inside a living cell. The heat produced by MPs subject to the time-varying external magnetic field can be determined from the area of the hysteresis loop. However, at the single-particle level of description, the magnetization of a MP undergoes a fluctuating stochastic process and the meaning of the hysteresis loop becomes ambiguous, as suggested also experimentally [1]. It is then unclear how to quantify the heat production, especially if the interactions between MPs cannot be neglected.

We use the modern stochastic thermodynamics [2] in combination with the Néel-Arrhenius theory of thermal relaxation of MPs to establish the relationship between the fluctuating work and entropy (heat) produced along the fluctuating magnetization trajectories of MPs. By considering the dipolar chains of MPs, we demonstrate a practical recipe for quantifying the heat produced by a single MP embedded within a chain, which then allows to map heat production distributions along the chains (Fig. 1).

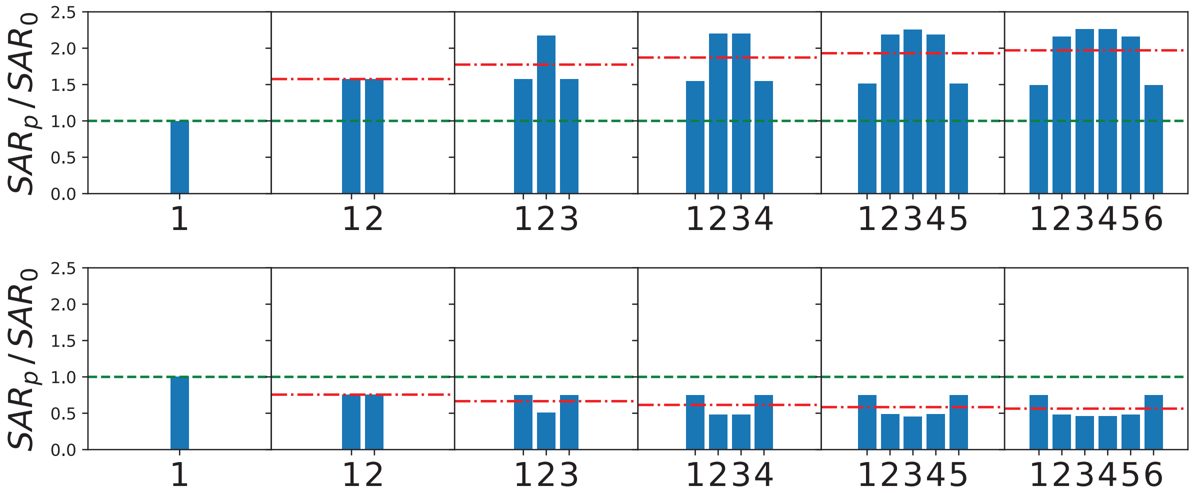

Figure 1: Calculations of specific heat rates (SAR_p) of individual particles along particle chains of length increasing from 1 (left subfigure) to 6 (right subfigure). Normalisation is by the non-interacting case SAR_0. Green dashed line corresponds to equivalent chains with interactions turned off. Red dash-dotted line is the heat per particle, i.e. average heat determined from a total hysteresis loop of a chain normalised by the number of particles in the chain. **(Top row)** Anisotropy axes of particles aligned along the chain axis and parallel with respect to applied field. **(Bottom row)** Anisotropy axes of particles aligned perpendicular to the chain axis but parallel with respect to applied field. The simulation parameters were: Particle diameter 11 nm, sinusoidal field of amplitude H_0 = 24 kA/m and frequency f = 300 kHz, anisotropy K = 4e4 J/m3 and saturation magnetisation Ms = 446 kA/m of magnetite.

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Hysteretic and non-hysteretic stress-dependent behavior of magnetostrictive delay lines

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Magnetostrictive delay lines (MDL for short) can be considered as geometrical shapes of magnetostrictive materials with uniform cross section, where elastic waves can be inductively generated by magnetic fields, propagate along their length due to their uniform cross-section, and then detected by inductive or acoustic methods. The waveform of the generated elastic waves depends on the λ(H) function at the volume of microstrain generation and therefore on the biasing and time-varying magnetic fields at this point, thus permitting microstrain time-variation λ(t). These elastic waves can propagate through the magnetostrictive material in a longitudinal or transverse mode, because of their uniform cross section, allowing them to act as acoustic waveguides. The inductive detection of these signals is due to the inverse magnetostriction effect, causing a time varying voltage output dependent on the amplitude of the propagating elastic pulse and the biasing field at the detection point. The time delay between the generation and the detection of the elastic pulse is due to either the longitudinal or the transverse sound velocity of the material, dependent on the mode of elastic wave generation. The MDL cross section can have any uniform shape, like a rod of circular, elliptic, or rectangular shape. It can also be a tube with uniform cross section, while the generation of elastic waves can be achieved in a volume including either a small part or the whole cross section of the MDL.

The above-mentioned λ(H, t) functions also depend on the localized residual stresses and the level of plastic deformation at the volumes where elastic waves are generated, propagate and detected. Concerning the volumes of elastic wave generation and detection, the λ(H, t) functions depend on the λ(σ) and M(σ) functions respectively, where σ represents the summary of residual stresses and plastic deformation. The propagation of elastic waves depends on the localized longitudinal or transverse Young's modulus of the MDL, provided that the mode of propagation is longitudinal or transverse respectively, which in turn are dependent on the localized residual stresses and the level of plastic deformation σ. This formulation permits the study and modeling of the MDL response dependence on the amount of localized stresses σ, accumulated in their infinitesimal volumes.

For simplicity reasons, in this paper we consider generation of elastic waves in cylindrical rods, where elastic waves are generated at a volume including the whole MDL cross section. Amorphous $Fe_{78}Si_7B_{15}$ wires of 0.15 mm diameter have been used as reference un-hysteretic materials. Experiments have been performed in polycrystalline low carbon wire steels of the same diameter, which have been tested after hot and cold rolling, followed by heat annealing for stress relief process. Hysteresis effects have been observed for the as-prepared tested low carbon steel wires without stresses, attributed to the hysteresis of the λ(H) and M(σ) functions. The level of localized dependence of the MDL response on hydraulic stresses has also been studied, illustrating a monotonic MDL dependence on stress. However, performing quasi-static minor loops of stresses, the amount of hysteresis was dependent on the amount of induced stresses: the larger the stress cycle, the larger the hysteresis effect, thus limiting the accuracy of stress determination. Work is under way for the modeling of the MDL response, which will permit the use of the method in stress monitoring along the length of magnetostrictive steels.

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Effect of grain boundaries and atomic interdiffusion on the exchange bias properties of ferromagnetic/antiferromagnetic nanodots: a Monte Carlo investigation

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This work focuses on exchange bias (EB) properties of ferromagnetic/antiferromagnetic (F/AF) nanodots which are used in read heads and magnetic random access memory [1]. The originality of our model is to consider an atomic approach which includes grain boundaries. Indeed, the combination of the presence of grain boundaries with magnetic frustration can result in complex magnetic configurations in the AF layer at the interface (magnetic domains) which can significantly alter the EB properties [2,3]. In addition, we have investigated the effect of the atomic interdiffusion in the AF layer. To that purpose, we use the Heisenberg model where the spins $\vec{S}_i$ can take any orientation in the space. Our magnetic Hamiltonian is given by:

$$H = -\sum_{<i,j>} J_{ij}\, \vec{S}_i.\vec{S}_j - \sum_i D_i\, (S_i^y)^2 + \mu_0\mu_B \vec{H}.\sum_i g_i\, \vec{S}_i$$

where J_{ij} represents the exchange interactions, D_i the anisotropy constants for the F spins or the AF spins and $\vec{H}$ is the applied magnetic field. In Fig. 1.a and Fig. 1.b, we show two configurations of the AF moments at the F/AF interface for a weak and a high frustration. Due to the presence of grain boundaries and magnetic frustration, we can see that the magnetic configurations exhibit domains. We have investigated the effect of these magnetic configurations on the exchange field H_E. The variation of H_E versus the interfacial coupling J_{int} is plotted in Fig. 1.c. It is clearly seen that the presence of noncollinear AF moments at the F/AF interface decreases H_E. In addition, the vanishing of H_E which comes from the reversal of the AF layer with the F one occurs for a lower value of J_{int} as the magnetic frustration increases evidencing that the AF layer becomes less stable. The temperature dependence of H_E is drawn in Fig. 1.d. As expected, a decrease of H_E is observed as the temperature increases due the thermal fluctuations of the interfacial AF moments. Whereas, the AF layer remains stable for all studied temperatures when there is no frustration, it reverses at $T \approx 50$ K when the frustration is high confirming its lower stability. Finally, the study of the atomic interdiffusion in the AF layer at the interface evidences a significant decrease in H_E leading to simulated values which are in good agreement with the experimental ones.

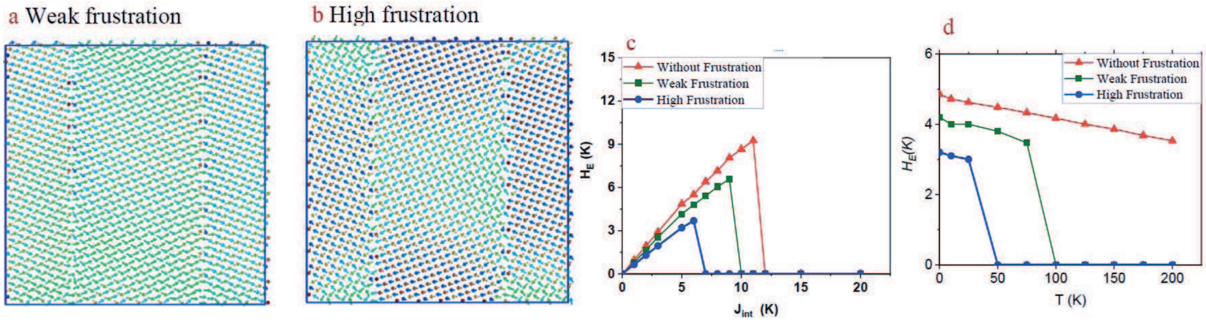

Figure1: Noncollinear magnetic configurations close to the F/AF interface in the AF layer for a weak (a) and a high (b) frustration, and the variation of H_E versus the interfacial coupling J_{int} (c) and temperature dependence of H_E (for J_{int} = 5 K) (d).

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Coupling of the skyrmion velocity to its breathing mode in periodically notched nanotracks

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A thorough understanding of the skyrmion motion through nanotracks is a prerequisite to realize the full potential of spintronic applications like the skyrmion racetrack memory[1]. One of the challenges is to place the data, i.e. skyrmions, on discrete fixed positions, e.g. below a read or write head. In the domain-wall racetrack memory, one proposed solution to this problem was patterning the nanotrack with notches[2]. Following this approach, we present the skyrmion mobility through a nanotrack with periodic notches (constrictions) made by changing the chiral Dzyaloshinskii-Moriya interaction strength[3]. We observe that such notches induce a coupling between the mobility and the skyrmion breathing mode (see figure), which manifests itself as velocity-dependent oscillations of the skyrmion diameter and plateaus in which the velocity is independent of the driving force.

Next, we present an analogous study on domain wall motion and, surprisingly found even larger plateaus of constant velocity, despite the fact that domain walls are far more rigid objects than skyrmions. For both systems it is straightforward to tune the velocity at these plateaus by changing the design of the notched nanotrack geometry, e.g. by varying the distance between the notches. Therefore, the notch-induced coupling between the excited modes and the mobility could offer a strategy to stabilize the velocity against unwanted perturbations in racetrack-like applications.

Finally, we focus on the low-current mobility regimes, whose very rich dynamics at nonzero temperatures are very similar to the operating principle of recently developed probabilistic logic devices[4]. This proves that the mobility of nanomagnetic structures through a periodically modulated track is not only interesting from a fundamental point of view, but has a future in many spintronic applications.

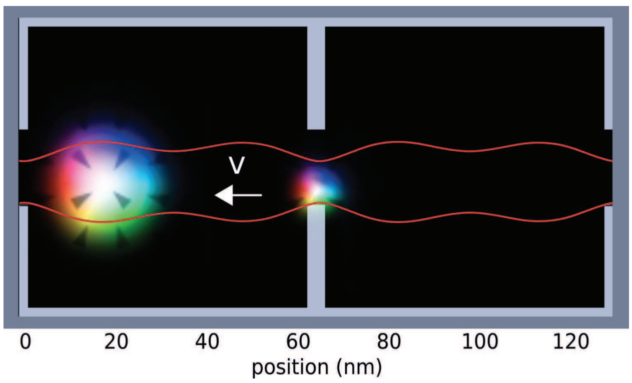

Figure 1: Skyrmion diameter (red lines) as function of position (using periodic boundaries) during its motion through the notched nanotrack at the resonances corresponding to 2 skyrmion breathing periods, in between two consecutive notches.

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Investigation on Bloch point-mediated switching in magnetic skyrmions and antiskyrmions

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Magnetic skyrmions are chiral spin textures with spins in the centre pointing up, and gradually whirling down along the radius direction. By virtue of the antisymmetric Dzyaloshinskii-Moriya interaction (DMi) [1], skyrmions and derivative skyrmionic textures, including antiskyrmions[2] and skyrmioniums, can be topologically protected and stably exist in the magnetic materials. Recent advances highlight their room-temperature existence and current-driven motion in racetrack-based structures [3], which suggests skyrmionic-based devices to become promising candidates on high-density and high-stability storage devices, and also the potential use on neuromorphic computing.

In our work, using GPU-accelerated micromagnetic simulation tool Mumax^3 [4], we numerically show a general nucleation/annihilation switching process in various thin-film skyrmionic textures, including skyrmions (Fig. 1b), anti-skyrmions (Fig. 1c) and skyrmioniums. During field-induced annihilation (Fig. 1d-g), asymmetric unwinding of skyrmionic textures is associated by Bloch point(s) nucleating from one surface (eg. bottom surface in Fig. 1d), propagating through the whole layer, and annihilating to the opposite surface (eg. top surface in Fig. 1g). The mechanism is proved to be determined by the DMi energy distribution through the layer.

We systematically investigate the dependence of Bloch-point mediated mechanisms on materials parameters. We directly demonstrate that various transition modes and the Bloch point dynamics can be effectively tuned by magnetic parameters. Then we take a step further, in order to elucidate the asymmetric Bloch point mediation process and control it by inducing artificially engineered defects, which are able to compensate and even reverse the DMi-induced asymmetric energy distribution through the layer. By virtue of this artificial "symmetry-breaking" design, a new deterministic nucleation and annihilation phase transition mode can be proposed.

Our work provides an explanation of the underlying Bloch-point mechanism mediating the nucleation and annihilation of skyrmionic textures, and also proposes a design for controlling this process. It is expected to contribute to the industrially-relevant research and development of future skyrmion-based storage and nanocomputing devices.

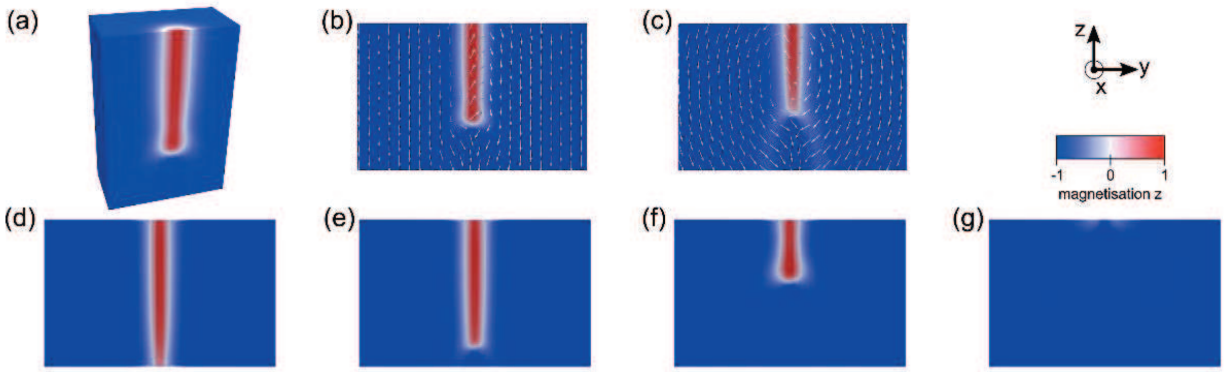

Figure 1: (a) Schematic of 3D skyrmion. (b-c) Bloch-point mediated annihilation in skyrmion and antiskyrmions textures. (d-g) Asymmetric annihilation in single skyrmion.

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Dynamic coercivity of $L1_0$- FePt nanoparticles close to the Curie point

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The dynamic coercivity of $L1_0$-ordered FePt nanoparticles in the critical regime close to the Curie temperature, is studied using an atomistic model based on an effective classical spin Hamiltonian [1]. The spin dynamics is simulated using the LLG-Langevin equation. The magnetization reversal at elevated temperatures of FePt granularthin films with high perpendicular anisotropy is of current interest to optimize the magnetic and thermal properties of the media used in heat-assisted magnetic recording (HAMR) [2]. At temperatures close to but below the Curie point, the intrinsic coercive field H_o where the energy barrier vanishes can be determined from the probability distribution of the magnetization component in the direction of the easy axis. The time dependence of the dynamic coercivity does not show a clear transition from the dynamic to thermoactivated regime, below the Curie point. The activation volume of an FePt grain was deduced from the field dependence of the mean first passage time (Fig.1) and found to be smaller than the physical volume of the grain, as a result of the formation spin clusters [3]. The numerical results will be compared with theoretical predictions for the dynamic coercivity using Landau-Lifshitz-Bloch dynamics [4,5].

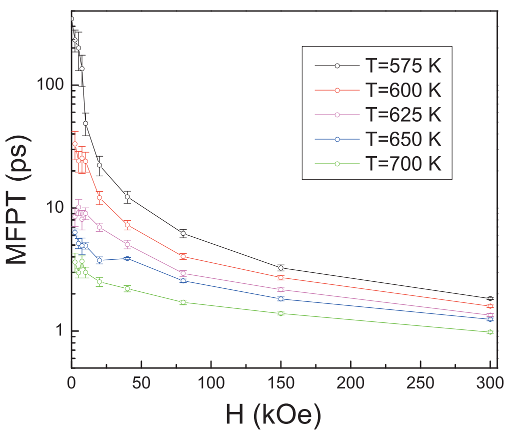

Figure 1: Mean first passage time of a 5 nm cubic FePt nanoparticle as a function of applied field (H) at different temperatures. Curie temperature is $T_c = 600$ K, smaller than the bulk $T_c \approx 750$ K of FePt as a result of the finite grain size and the truncation of the long range anisotropic Fe-Fe exchange interaction.

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Thermal hysteresis modeling for $Ni_{2.18}Mn_{0.85}Ga_{0.97}$ Heusler alloy

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Ni-Mn-Ga Heusler alloy demonstrated merged magnetic and structural phase transitions is of considerable interest among scientific community. In this work, the statistical model for the magnetic and structural phase transitions description is proposed. The thermal hysteresis for heating and cooling calculated with the help of this model for $Ni_{2.18}Mn_{0.85}Ga_{0.97}$ alloy is presented in comparison with the experimental data. Our model takes into account the coexistence of martensitic (*m*) and austenitic (*a*) structural domains in the vicinity of the structural phase transition point. For the calculation of strains, the following equation for the free energy density was used: $F = \xi^m F_m + (1 - \xi^m) F_a$, where ξ^m is the volume fraction of martensite [1], σ is the external stress, and E is the strain. The expression for the free energy density of the α phase (austenite (*a*) or martensite (*m*)) includes the magnetic, elastic, and magnetoelastic parts:

$$F_\alpha = F_\alpha^{el} + F_\alpha^{m} + F_\alpha^{me},$$

where $F_a^{el} = C_a E^2/2 - \zeta C_a E(T - T_m) + \rho c T(1 - lnT/T_m)$,

$F_m^{el} = C_m(E + E_b)^2/2 - \zeta C_m(E + E_b)(T - T_m) + \rho c(1 - \ln T/T_m) - Q(1 - T/T_m)$,

$F_\alpha^m = -A_\alpha y^2/2 - HM_{0\alpha} y - R\rho T S_\alpha/\mu$, $\quad F_\alpha^{me} = B_\alpha y^2 E/2$, $\quad F_{m,p}^{me} = B_m y^2(E + E_b)/2$,

where C_α are the elastic moduli of α domain, ζ is the thermal expansion coefficient, ρ is the density of alloy, c is the specific heat, A_α is the exchange constant, $M_{0\alpha}$ is the magnetization saturation, y is the normalized magnetization, R is the gas universal constant, μ is the molar mass, S_α is the magnetic entropy, B_α is the magnetostriction constant.

Minimization the free energy function gives the expression for estimation of E. The result of the modeling is presented in Fig. 1. One can seen the pronounced thermal hysteresis under heating and cooling. The results of theoretical modeling are in good agreement with the experiment [2].

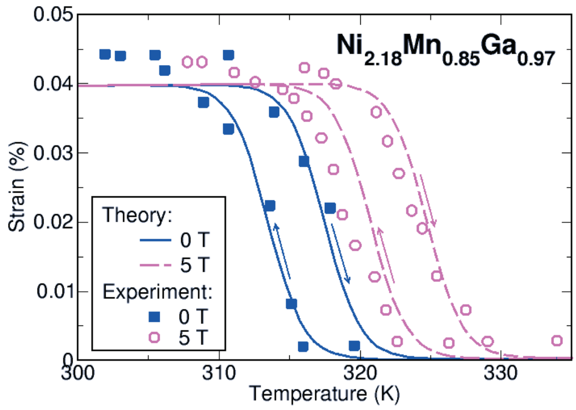

Figure 1: The calculated strain as a function of temperature in the magnetic field of 0 and 5 T for $Ni_{2.18}Mn_{0.85}Ga_{0.97}$ in comparison with the experiment [2].

This work was supported by Grants of Russian Science Foundation No. 17-72-20022 and Russian Foundation for Basic Research No. 18-32-00507.

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Skyrmion auto-oscillations in constrained ferromagnetic nanodisk

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Magnetic skyrmions are topological nanoscale magnetization configurations which are stabilized in materials with the Dzyaloshinskii-Moriya interaction (DMI). The dynamics of skyrmions was recently proposed to be exploited for an spin torque nano-oscillator (STNO), as this can offer nearly two orders of magnitude lower threshold current than conventional STNOs[1-2]. The auto-oscillations of skyrmions are so far established by using a non-uniform spin torque, by either employing a vortex state reference layer [1] or by using a nano-contact geometry with spatially varying current density[2]. In this study, we numerically demonstrate magnetization auto-oscillations due to sustained rotation of the skyrmion, by using a much simpler uniform spin torque which is easier to realize. We consider a disc-shaped magnetic element of a material with DMI originating in the interface with a heavy-metal layer. We use values for the material parameters similar to those measured for the Co_2FeAl Heusler alloy[3]. We apply spin torque uniform in space and time and observe numerically that the skyrmion is set in steady rotational motion [Fig. 1]. We give a theoretical description of the emerging auto-oscillation dynamics based on the coupling of the rotational motion to the breathing mode of the skyrmion and to the associated oscillations of the in- plane magnetization. Using Thieles formulation[4], we analytically calculate the velocity of the skyrmion and we find excellent agreement with the numerical simulation results [Fig. 2]. The present set-up may be the simplest that has been proposed to-date in order to produce oscillations based on a localized magnetic soliton. This makes the system interesting for experimental realization and also quite appealing for a detailed theoretical study.

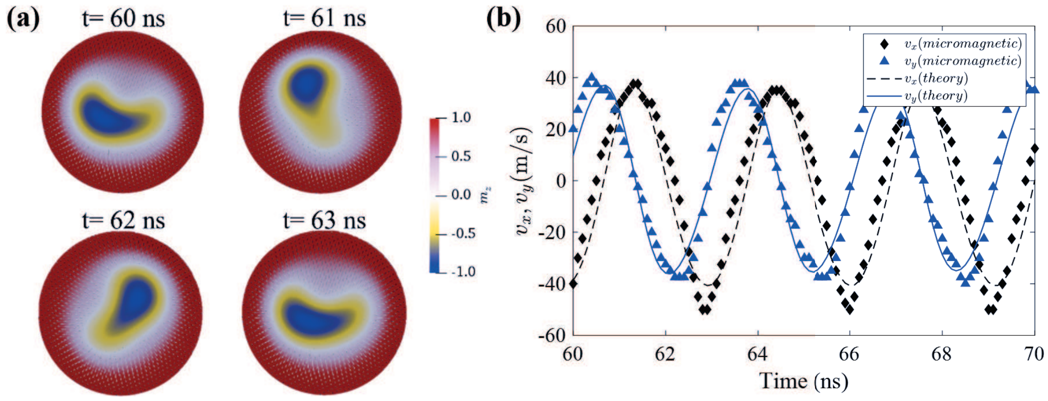

Figure 1: (a) Snapshot of the skyrmion inside nanodisk at different time instants (b) Plot of skyrmion core velocity in x and y direction as a function of time. The markers show the simulated velocity while the solid and dashed lines show the analytically calculated values

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Multidomain states in ultrathin ferromagnetic films with strong perpendicular magnetic anisotropy

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This talk summarizes a rigorous mathematical study of the ground state energy and optimal domain patterns in thin ferromagnetic films with strong uniaxial anisotropy and the easy axis perpendicular to the film plane. Starting from the full three-dimensional micromagnetic model, we identify the critical scaling for which the transition from single domain to multidomain ground states such as bubble or maze patterns occurs as the film thickness goes to zero and the lateral extent goes to infinity. In the multidomain regime, we derive the scaling of the minimal energy and deduce a scaling law for the typical domain size.

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The thermodynamics properties of a ferroelectric bilayer system: Effect of the size and strain induced field

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Using the Monte Carlo simulation technique (MCs) and the Effective Field Theory (EFT) with a probability distribution technique, we apply the transverse Ising model in the presence of the strain induced field to study the ferroelectric bilayer system with a ferroelectric interfacial coupling. We investigate in detail the effects of the size and the strain induced field on the thermodynamics properties such us the pyroelectric, dielectric properties and the internal energy of the system. The effects of the temperature and the transverse field on the hysteresis loops are also discussed. It is found that the pyroelectric and dielectric properties and the hysteresis loops of the ferroelectric bilayer will be strongly influenced by the strain. The EFT results are compared to those obtained by using the MCs. However, EFT predicts the same topology of the dielectric properties as the MCs.

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On the role of the leading anisotropy constant (K_1) in the complex magnetic behavior of gadolinium revealed by magneto-thermal protocols

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The magnetic properties of gadolinium (Gd) have been extensively studied because of its unique and interesting magnetic behavior and its various technological uses, including as the leading refrigerant for near-room temperature magnetic refrigeration applications. Gadolinium has a close-packed hexagonal crystal structure that gives rise to its uniaxial anisotropy, characterized by the anisotropy constants, K_1 and K_2. It is known that the phenomenon of spin reorientation transition in Gd is directly related to the temperature dependence of K_1 and K_2; specifically it occurs near 240 K (The spin reorientation transition temperature, T_{SR}), when the leading anisotropy constant K_1 changes sign and becomes negative. In a previous study, we reported that the systematics of the complex magnetic behavior of Gd, including the spin reorientation and related features, were revealed by subjecting polycrystalline Gd bulk samples to a magneto-thermal (M-T) protocol, using both dc SQUID and VSM magnetometries [1]. The M-T protocol developed in the previous study (herein referred as the "the standard M-T protocol") consisted on cooling the Gd samples from 300 K to 5 K under a negative field of 50 mT and then measuring the temperature dependence of the magnetization (*M*) at a positive field in the range of +2.5 mT to + 50 mT, first on warming from 5K to 380 K then on cooling a second time to 5 K and on warming a second time to 380 K. We respectively designated these three sequential *M* versus *T* sweeps (plots), as W1, C2, and W2. When the Gd samples are cooled under the negative field, a fraction of the magnetization becomes frozen in the negative direction leading to a reduced value of the magnetization in W1 compared to W2. The closeness of the C2 and W2 results reflects that there is a threshold for the cooling field to be effective on reducing the magnetization on warming [2]. The dependence of the W1 on the measuring field, permits the extraction of the fraction of the magnetization that is frozen. We have attributed the frozen fraction to the build up of magnetic charge density at the polycrystalline grain boundaries, which, like the susceptibility, is quite different for positive and negative K_1. The fraction frozen below T_{SR} is easily unfrozen on warming, while the fraction frozen above T_{SR} persists almost to T_C. Our most recent data, wherein we apply the cooling fields over different temperature ranges, clarifies these conclusions.

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Spin-Hall current driven spin-wave resonance in an antiferromagnetic material: a comparison between micromagnetic simulations and analytical calculations

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Terahertz (Thz) oscillations typical of antiferromagnetic (AFM) materials turn out to be very promising for the development of AFM-based oscillations [1]. Here, the effect of spin-Hall current on spin-wave resonance in an AFM material is studied. This is accomplished by using a full micromagnetic solver based on the numerical solution of two coupled Landau-Lifshitz-Gilbert-Slonczewski (LLGS) equations [2] and by developing an analytical theory of spin-wave excitations in an AFM. Two cases are considered: 1) easy axis along the in-plane direction of the sublattice magnetization (x-direction) and 2) xy easy plane with hard axis along z-direction. In both cases the spin-Hall current term is described via a spin-Hall field depending on the polarization. For the easy axis case with polarization along y, for small spin-Hall current densities (J_{DC} < 2 A/cm^2), the dynamics can be described in the linear regime and the AFM resonance frequency takes the form $f_{AFMR} = \pm \gamma_0 M/(2\pi(1+\alpha^2))[(2\sigma\beta - \alpha^2\sigma^2 - d_J^2(1+\alpha^2))^{1/2} + i\alpha\sigma]$ with $\sigma = 4A_{AFM}/(\mu_0 M^2 a^2)$, $\beta = 2K_U/(\mu_0 M^2)$ and $d_J = g\,\mu_B\,\theta_{SH}\,J_{DC}/(2\gamma_0\, e\, M^2 d)$. f_{AFMR} shows a quadratic decreasing dependence on J_{DC}. Here, γ_0 is the gyromagnetic ratio, M is the magnetization of each sublattice, α is the Gilbert damping, A_{AFM} is the AFM stiffness constant, μ_0 is the vacuum permeability, a is the lattice constant, K_U is the uniaxial anisotropy constant, g is the Landè factor, μ_B is the Bohr magneton, θ_{SH} is the spin-Hall angle, e is the electron charge and d is the AFM thickness. For J_{DC} > 2 A/cm^2, the precession cone angle dramatically increases leading to a nonlinear dynamics and the analytical f_{AFMR} strictly depends also on the resonance amplitude [3].

For the easy-plane case, both micromagnetic simulations and analytical calculations predict the existence of an acoustic mode (in-phase precession) and an optical mode (out-of-phase precession) whose frequencies tend to merge crossing each other at a given value of the spin-Hall current density, corresponding to the threshold current for self-oscillations. Also in this case, for J_{DC} > 2 A/cm^2 the dynamics becomes nonlinear and is analytically described in terms of the spin-wave amplitude.

Figure 1 shows the AFM resonance frequency typically in the THz range calculated micromagnetically as a function of spin-Hall current density in the easy axis case for A_{AFM} = 5.0 × 10^{-12} J/m, K_U = 1.0 × 10^5 J/m^3, M = 350 kA/m, α = 0.05, θ_{SH} = 0.2, a = 0.5 m and d = 5 nm.

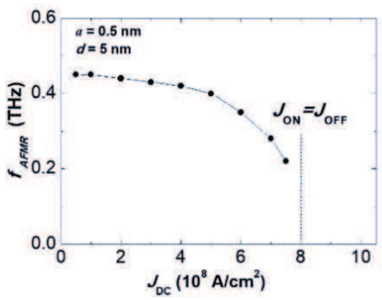

Figure 1: Micromagnetic AFM resonance frequency vs. spin-Hall current density.

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Modelling of Dynamic Losses in Soft Ferrite Cores

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Soft ferrite cores are widely used in power electronic components and filters. Usually they are modelled as linear devices, and the hysteresis is not accounted for. On the other hand, the accurate estimation of the dynamic energy losses in soft ferrite cores is important, because the temperature rise and the related change in the equivalent inductance and resistance of the device can change the output of the power system where the device is connected.

This paper deals with the modelling of the energy losses in soft ferrite cores up to 1 MHz. Two different approaches are taken into account. The first one is based on the ideas of Saotome [1] [2], who has proposed the decomposition of the total magnetic field intensity in three components: The first one is individuated by the an-hysteretic curve, the second one by the energy losses measures at low frequency, the third one by the dynamic losses measured for triangular magnetization at a given first derivative of the magnetic induction respect to the time.

The second approach is based on the paper [3] of Muhlethaler and has an almost different methodology. The original Steinmetz equation [4] is extended in time domain. The magnetic induction vs time is used to estimate the dynamic energy losses. The experimental parameters are evaluated in the frequency domain. The effect of the minor hysteresis loops is therefore accounted for.

In this paper, a toroidal core of soft ferrite is used to experimentally test the results of the application of the two different methodologies.

The fig. 1 shows a preliminary result of the computed and measured dynamic loop at 400 kHz.

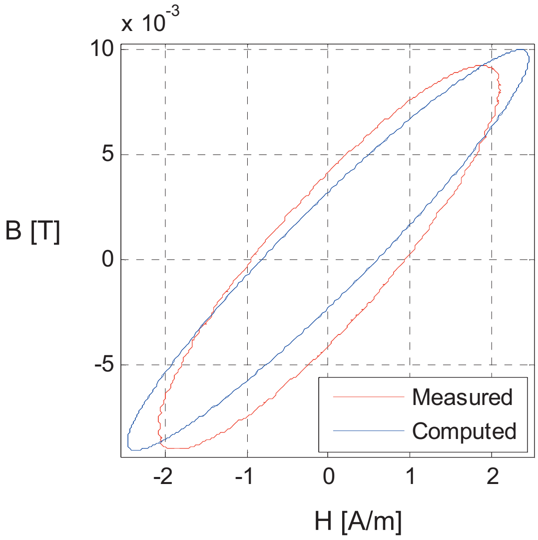

Figure 1: Computed and the measured dynamic hysteresis loops for Mn-Zn Ferrite (©EPCOS N30 material).

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Dynamics of superparamagnetic nanoparticle in viscous liquid in rotating magnetic field

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The dynamics of a spherical uniaxial magnetic nanoparticle in a viscous fluid under the influence of a rotating magnetic field (RMF) was studied using the Landau – Lifshitz stochastic equation. In contrast to the case of an alternating magnetic field (AFM) [1], in the magneto- dynamic limit three stationary modes of motion of a unit magnetization vector *m*, and a director of a particle *n*, were found, depending on the RMF frequency and amplitude. Figs. 1a - 1c show the behavior of the vector *m* in the various stationary modes on the assumption that the RMF rotates in the XZ plane. In viscous mode, Fig. 1a, at sufficiently low frequencies, the vectors *m* and *n* move in unison in the plane of the RMF rotation, the Y components of these vectors being close to zero. In the intermediate, perpendicular mode, Fig. 1b, which occurs when the RMF frequency is sufficiently high, $f > f_{cr}$, the vectors *m* and *n* move almost perpendicularly to the plane of RMF rotation, their Y components are close to unity in absolute value. Finally, in magnetic mode, Fig. 1c, which occurs when the field amplitude increases, both vectors rotate again in the plane of RMF rotation, but with a reduced frequency, and the vector *m* periodically jumps between magnetic potential wells. The areas of implementation of modes a) - c) on the plane (*H*, *f*) are shown in Fig. 1d. Fig. 1e compares the specific absorption rate (SAR) of a dilute assembly of nanoparticles in RMF and AMF fields, respectively, depending on the nanoparticle diameter. One can see that in the case of RMF SAR of assembly reaches values of the order of 250–300 W/g over a wider range of nanoparticle diameters.

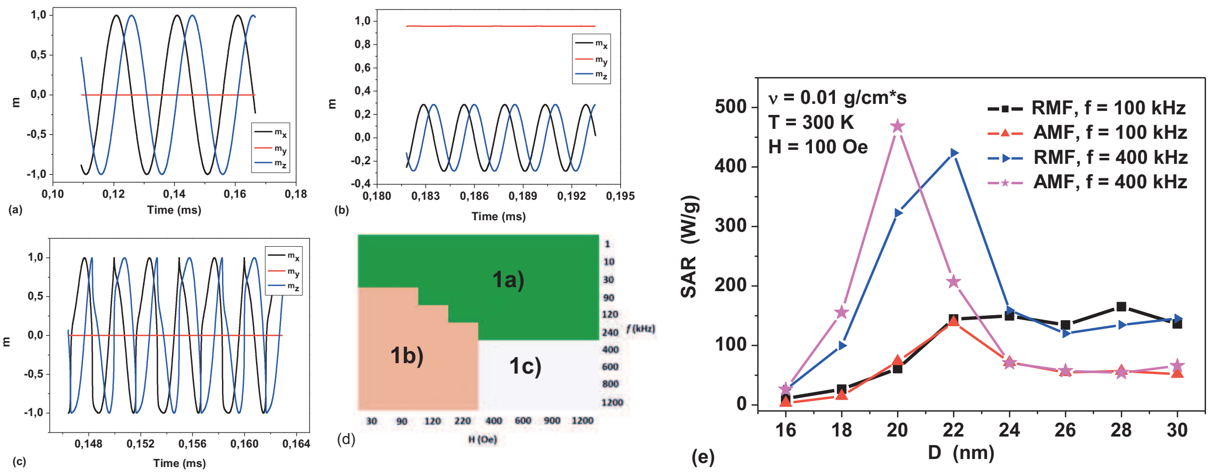

Figure 1: (a) – (c) The dynamics of the vector *m* in RMF for three different stationary modes in the magneto- dynamic limit; (d) the area of existence of modes a) - c) depending on the RMF frequency and amplitude; (e) comparison of SAR in AMF and RMF as a function of particle diameter.

The authors wish to acknowledge the financial support of the Ministry of Science and High Education of the Russian Federation in the framework of Increase Competitiveness Program of NUST «MISIS», contract № K2-2017-008.

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Mutual Synchronization of Coupled THz-frequency Antiferromagnetic Spin-Hall Oscillators with Hysteretic Responses

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The terahertz (THz) frequency range is receiving a lot of interest from researchers because of its many applications, such as ultra-high speed communication, THz-frequency imaging and sensing, etc. The development of efficient and compact THz sources and detectors is one of the important technical problems of modern wireless technology. The existing ways to generate THz-frequency signals, such as the use of quantum cascade lasers, free-electron lasers, and superconducting Josephson junctions either lead to rather bulk devices or require low temperatures, which limits their applicability in practice.

Spintronics of antiferromagnets (AFMs) has a great potential to generate THz-frequency signals [1], because, due to the presence of a very strong internal exchange field, the magnetization dynamics in AFMs is ultra-fast, and there are no stray magnetic fields of a dipolar origin. The output power of a single AFM-based THz-frequency spin-Hall oscillator (SHO), was theoretically calculated in [2], where it was shown that this power increases with the increase of the generation frequency. However, the output power of a single AFM SHO was evaluated to be of the order of nanowatts, which is not sufficient for most applications. To answer this challenge it is possible to use synchronized (or phase-locked) arrays of multiple AFM SHO.

In this work, we present a theoretical study of the dynamics of a pair of AFM SHOs that are mutually coupled by a common electrical current. We assume that the phases φ_n of the AFM Neel vectors in the coupled SHOs are phase-locked if both average and oscillating frequencies of their rotation are equal over a certain time. We demonstrate numerically, that for typical parameters of a NiO SHO by variation of a DC electrical current it is possible to find both phase-locking interval and hysteretic interval for non-identical SHOs (see Fig.1). We also demonstrate that the spectral linewidth of the output oscillations inside the phase-locking interval decreases even in the presence of an additive Gaussian noise. These results could be used to construct large arrays of mutual coupled THz-frequency SHOs.

Authors acknowledge the financial support from the Government of the Russian Federation (agreement No. 074-02-2018-286) within the laboratory "Terahertz spintronics" of the Moscow Institute of Physics and Technology (State University), RFBR through the grants 18-57-76001, 18-37-20048, 18-29-27020, 18-29-27018, 18-07-00485, and by the grants EFMA-1641989 and ECCS-1708982 from the NSF of the USA.

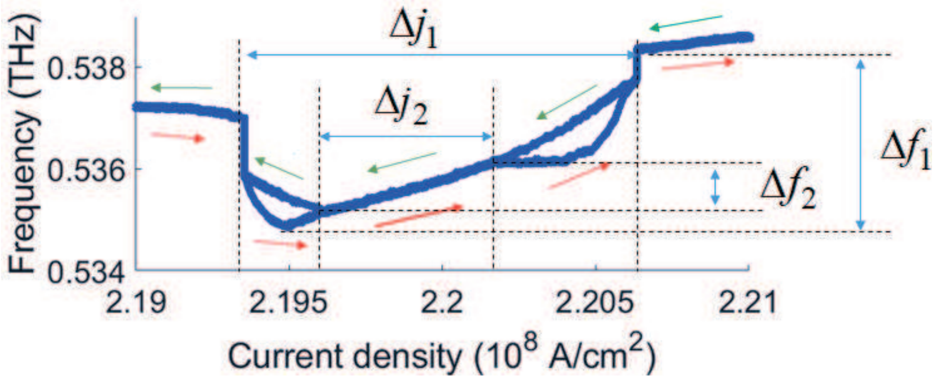

Figure 1: Free-running frequency of a system of mutually coupled antiferromagnetic oscillators as a function of the current density with hysteretic and phase-locked regions.

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Micromagnetic and analytical descriptions of antiferromagnets

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The study of antiferromagnets (AFMs) [1] is growing due to the potential applications ranging from sensors, memories, etc [2-4]. When these materials are driven out of equilibrium, their dynamic is governed by the large exchange interaction that governs the antiferromagnetic order. This exchange interaction is the main ingredient that gives rise to resonance in the range of THz [5], making AFMs promising for the development of THz spintronics.

A full micromagnetic framework (μMag) for the simulations of AFMs has been developed. Modeling of AFMs is performed by considering two different sublattices [4]. The temporal evolution of these two sublattices is assumed to be described by two Landau-Lifshitz-Gilbert (LLG) equations, augmented with a Slonczewski-like torque [6]. Those two equations, however, are coupled through the exchange field which accounts for the exchange contributions due to both, intra-sublattice and inter-sublattice neighbors [3].

Here we develop a one dimensional model (1DM) in a similar way as in ferromagnets [7] to describe domain walls in AFMs. The results depicted by such a model are compared with the full μMag simulations, showing a rather good agreement, as can be checked in Figure 1. Besides, the proposed model will be compared with a previous one based on the temporal evolution of the Nèel order parameter [8]. Finally, we perform a systematic study on the effect of the three exchange constants under play, the intra-sublattice, the homogeneous inter-sublattice and the inhomogeneous inter-sublattice constants. This analysis shows that domain wall velocity does not depend on the homogeneous inter-sublattice exchange but it depends on both, intra- and inter-sublattice inhomogeneous exchanges, due to the domain wall width dependence on these parameters, $\Delta \approx \sqrt{\left(2A - A_{AFM\text{-}nh}\right)/\left(2K_u - \frac{1}{2}\mu_0 M_e^{\,2}\right)}$

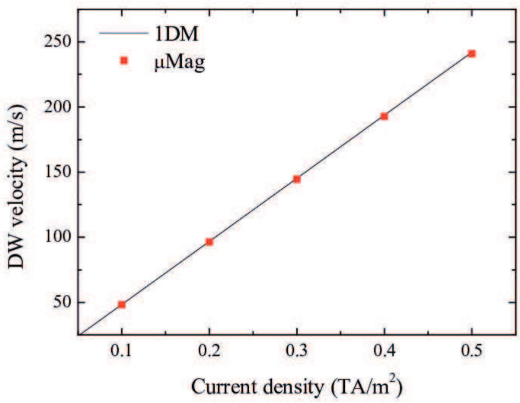

Figure 1: Antiferromagnetic domain wall velocity as a function of the applied current density computed by means of full micromagnetic simulations (red dots) and one dimensional model (solid line).

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Optimization of the ’energy bounce’ method for determination of the switching rate of magnetic nanoelements

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Prediction of the long-time stability of magnetic memory cells (MRAM) is highly important tasks for technical applications. For system with high energy barriers ΔE direct simulation of the transition over these barriers using the Langevin dynamics (LD) is impossible, as the simulation time exponentially growths with $\Delta E/kT$ according to the Arrhenius law [1]. A few years ago a so called ’energy bounce’ method [2] was suggested to overcome this difficulty. This algorithm uses the Langevin dynamics, simulating the transition between energy minima in several ’stages’; at each simulation stage it does not allow that the system energy drops below some ’bounce energy’ $E_{\rm bn}$. This parameter increases after each stage, until the region near the saddle point is reached and thus transitions between the minima become fast enough to be simulated within a reasonable time.

Here we present the detailed analysis of this method, showing how its performance can be optimized using two especially important parameters. The first parameter is the overlapping $\kappa = S_{\rm over}/S_{\rm tot}$ of probability distributions (PD) for subsequent $E_{\rm bn}$ levels defined as the ratio of the overlapping area of two subsequent PDs to the total area of the PD for the lower $E_{\rm bn}$ (Fig.1a). Increasing the overlapping κ, we improve the accuracy of the determination of the corresponding probability ratios for subsequent $E_{\rm bn}$ values, but increase the simulation time. The second crucial parameter is the simulation time $t_{\rm walk}$ for each $E_{\rm bn}$. This parameter can depend on $E_{\rm bn}$, because for small $E_{\rm bn}$ the duration of LD simulations should merely ensure the accurate sampling of energy histograms, whereas for higher $E_{\rm bn}$ we have to accumulate a sufficiently large number of switching events.

We have applied this method for the determination of the switching time $\tau_{\rm sw}$ for macrospins with parameters equivalent to thin elliptical nanoelements (thickness 3 nm) with the short axis 40 nm and varying long axes $a = 50 - 100\,{\rm nm}$, made of Permalloy. Corresponding dependence $\tau_{\rm sw}(a)$ is shown in Fig. 1b; as it can be seen from Fig. 1c, the Arrhenius law overestimates $\tau_{\rm sw}$ by 2 to 8 times.

In the last part of our talk we discuss the application of this method to full-scale micromagnetic simulations, where a nanoelement is properly discretized.

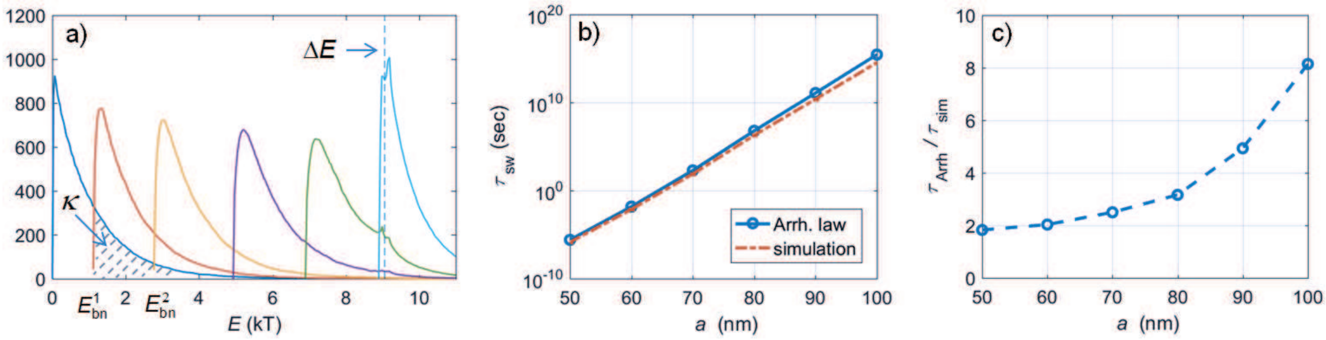

Figure 1: a) Energy distributions for simulations with increasing ’bounce energies’ and the definition of the overlapping parameter κ; b) Comparison of the switching time dependence on the long ellipse axes a obtained via the energy bounce method with the Arrhenius law; c) ratio of the dependencies shown in plot (b)

Financial support by the Deutsche Forschungsgemeinschaft (project BE2464/17-1) is greatly acknowledged.

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Monte Carlo simulations of hysteresis effects at the martensitic transformation

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Nowadays, intermetallic NiMn-based Heusler alloys are of great interest due to the unique magnetic, magnetomechanic, and magnetocaloric properties observed in the vicinity of magnetic and structural (martensitic) transitions between cubic austenite (A) and tetragonal martensite (M) structures [1]. In this work, we present a theoretical study of the thermal hysteresis that takes place across the first order martensitic transition as a function of temperature for Heusler alloys. To simulate the structural phase transitions, we propose the degenerate three-state Blume-Emery-Griffiths (BEG) Hamiltonian with account the temperature-dependent lattice entropy expansion. The original BEG model used frequently to discuss properties of the martensitic transformation between cubic phase ($\sigma = 0$) and tetragonal phase with two variants ($\sigma \pm 1$) of a given compound [2, 3]. Generally, the martensitic transition is driven by the entropy difference $\Delta S(T) = S_A(T) - S_M(T)$ between structures. Besides, the temperature-dependent entropy difference can be written as: $\Delta S(T) = \Delta S(T_m) + k_B\sigma_T(T - T_m) + ...$ [4], where the index T indicates that the coefficient σ_T may be different below and above the martensitic transition temperature T_m, k_B is the Boltzmann's constant. The total Hamiltonian interaction terms in the cubic austenite and tetragonal martensite phase as follows:

$$H = H_M + H_A,$$

$$H_M = -J\sum_{<i,j>}\sigma_i\sigma_j - k_BT\left(4 - 3\ln\left(\frac{\Theta_D^M}{T}\right) + \frac{3}{40}\left(\frac{\Theta_D^M}{T}\right)^2\right) - k_BT\sigma_T^M\xi^M\ln\xi^M,$$

$$H_A = -K\sum_{<i,j>}(1-\sigma_i^2)(1-\sigma_j^2) - k_BT\ln(p)\sum_i(1-\sigma_i^2) - k_BT\left(4-3\ln\left(\frac{\Theta_D^A}{T}\right) + \frac{3}{40}\left(\frac{\Theta_D^A}{T}\right)^2\right) - k_BT\sigma_T^A\xi^A\ln\xi^A.$$

Here the variable σ_i defines the deformation state at each lattice site; $\xi^M = \sum_i(\sigma_i^{(+1)} + \sigma_i^{(-1)})/N$ and $\xi^A = \sum_i(\sigma_i^{(0)})/N$ are the volume fraction of martensite and austenite, respectively; J and K are the exchange coupling constants in martensite and austenite, respectively; p is the degeneracy factor, which shows the number of martensitic variants; Θ_D^M and Θ_D^A are the Debye temperatures for martensite and austenite, respectively; k_BT-like terms are lattice entropy contributions for austenite and martensite phases [4, 5].

In order to simulate the austenite-martensite phase transition, we calculate the deformation order parameter $\epsilon = \sum_i \sigma_i/N$ as a function of temperature upon heating and cooling protocols. Where, $\epsilon = 1$ and 0 corresponds to martensite and austenite phase, respectively. The model lattice that contains a real fcc unit cell of Heusler alloys includes ≈ 4000 atoms with periodic boundary conditions. The Monte Carlo simulations are performed using Metropolis algorithm and 5×10^5 Monte Carlo steps. We show that the hysteresis width depends on both J/K ratio and the difference between σ_T^M and σ_T^A variables.

This work was supported by Grants of Russian Science Foundation No. 17-72-20022.

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Spin-Orbit Torque in Graphene/Co Hetero-system

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Due to the growing demand of low-power, fast data processing, non-volatile magnetic random access memories are being considered as powerful alternative to current semiconducting technology[1]. In this context, the spin-orbit torque (SOT) technique has opened new horizons for the development of innovative magnetic devices beyond memories and data storage[2]. The emblematic mechanism underlying the SOT technique is the interfacial Rashba effect that emerges at interfaces in the presence of strong spin-orbit coupling. This effect is particularly efficient at the interface between transition metal ferromagnets and topological insulators [3,4]. In conventional SOT devices, a heavy materials (Pt, W or Bi_2Se_3) adjacent to the magnetic layer is used to provide large spin-orbit coupling. Alternatively, it is also possible to exploit the spin-orbit coupling of the magnetic material itself by interfacing it with, e.g., a non-magnetic insulator [5].

We investigate interfacial spin texture and SOT at the interface between Co (001) and a graphene monolayer, a system that has recenlty been predicted to display large Rashba effect [6, 7], see Fig. a. When graphene is attached to the surface of Co (001), the inversion symmetry is broken, which results in the onset of a built-in perpendicular electric field. As a result, in the presence of the large SOC of Co, Rashba effect emerges at the interface. Therefore, a spin density driven by a net current can be achieved at the interface, bringing SOT into such a heterostructure [8]. Using first principles calculations, we compute the band structure and project it onto Wannier orbitals to obtain the tight-binding Hamiltonian. Non-equilibrium properties then are derived by the Kubo formula. We show that Co atoms at the interface exhibit spin-momentum locking, which is line with the phenomenological picture presented above. Close to the Fermi level, the graphene Dirac cones couple with the Co 3*d* states around the K and K' points (Fig. c), resulting in a spin texture odd in momentum k (Fig. *d*). This special spin texture promotes current-driven SOT. Our results show that the SOT can be used to electrically control the magnetization of the Co layer and to realize fast non-volatile data reading and writing.

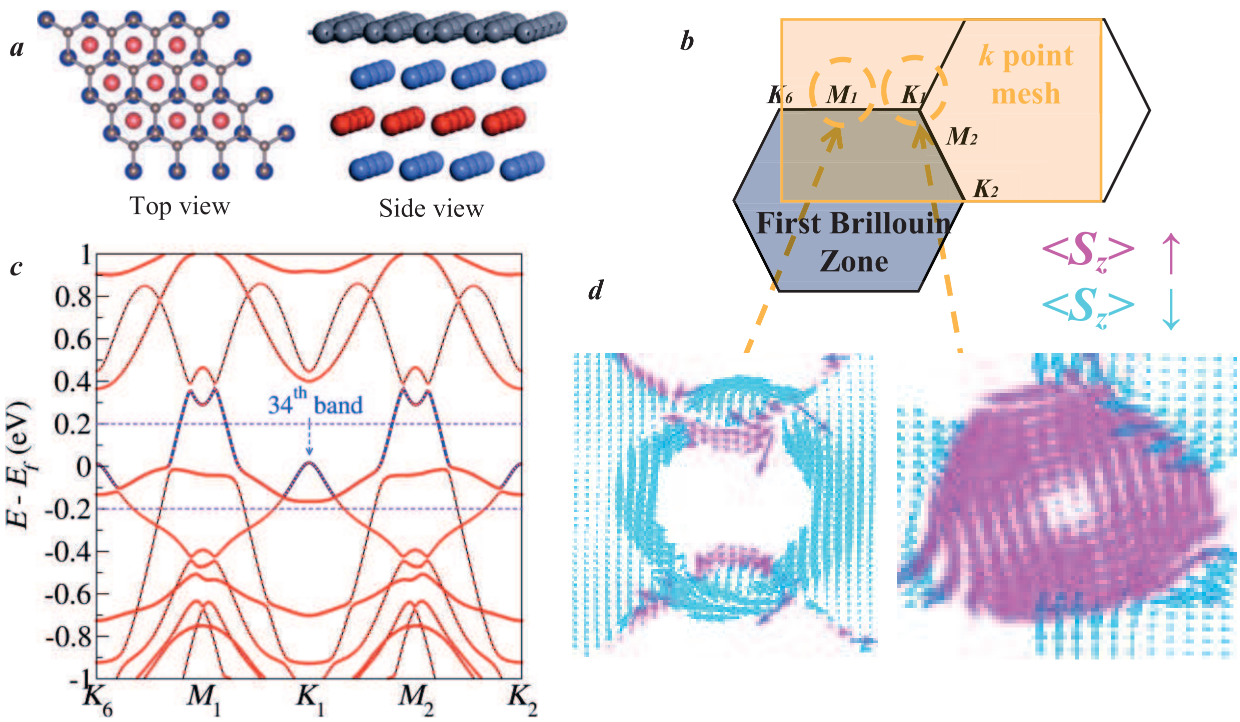

Figure 1: SOT in the graphene/Co heterostructure. *a* – theoretical model; *b* – first Brillouin zone with k-point mesh : for the spin texture calculation; *c* – band structure (red colour: contribution of Co); *d* – top view of the spin texture on of the 34th band.

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xyFORC vectorial technique for characterization of multi-phase magnetic systems

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The magnetic characterization technique based on the measurement of a special category of minor hysteresis loops named first-order reversal curves (FORC) covering the surface of the major hysteresis loop attracted a lot of interest from both experimentalists and theoreticians in the last decade. One important line of research is the extension of the method from an essential scalar characterization towards a vectorial one. As typically a Vibration Sample Magnetometer (VSM) has a scalar measurement procedure the FORC method was tailored for this type of experiment. Essentially, the reversible component in the scalar FORC is a consequence of the scalar treatment of a vectorial process [1].

A number of vectorial FORC versions have been proposed but for the moment none is sufficiently easy to implement on the VSMs [2], [3], [4].

The work we present is basically a proposal for an experimental technique which it adds not too much complexity in the experimental area and offers results really valuable in the case of some magnetic systems. We mention here especially the mixtures of magnetic phases in interaction. In a recent publication [5] we have shown the advantage of the use of the measurement of the major loop with both xy detection coils available in some VSM configurations. This time we would like to argue for a step further, that is to use the detection coils available to measure a set of two FORCs and consequently to get two FORC diagrams. We shall call this technique *xyFORC* diagram technique.

We show in Fig.1 a set of experimental x and y FORCs measured for a system of two magnetic phases with perpendicular easy axes, measured along the bisector of the two easy axes directions. We show that in the scalar measurement (the xFORC) we cannot trace the existence of the two phases while the yFORC is giving a clear image of two distinct magnetic phases.

In the presentation we shall discuss the technique and the main theoretical framework for this new experimental approach.

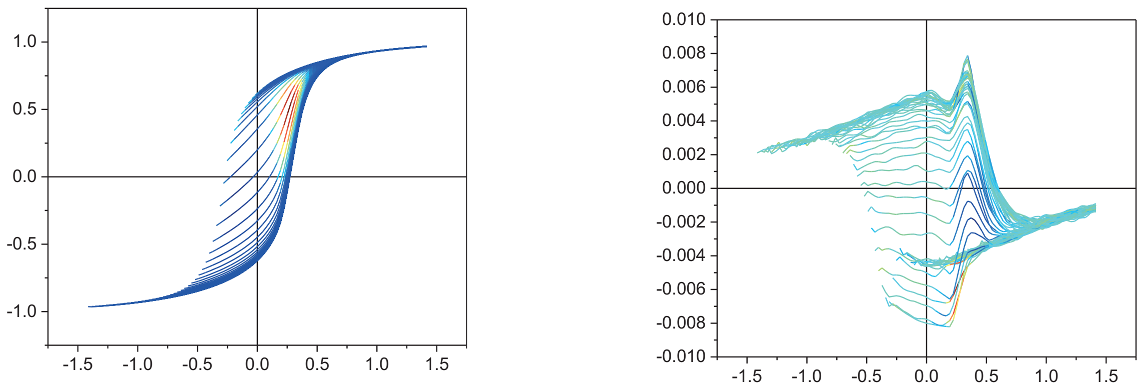

Figure 1: Experimental xFORC and yFORC for a system of two magnetic phases

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Time-dependent Stoner-Wohlfarth model

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The simulation of dynamical processes that occur in magnetic materials at the mesoscopic scale can be done using Landau-Lifschitz (LL) [1] type differential equations that describe the behavior of the magnetization when an external applied field acts on the system. Despite its efficiency, the LL model exerts a strain on the computational performance when it's used to describe a system with lots of particles. To combat this problem, we propose a new dynamic model derived from the rotational coherent model, also known as the Stoner-Wohlfarth model [2, 3].

This new model is based on calculating the time it takes the magnetization vector to reach equilibrium given certain initial conditions (Fig.1-left). Using this approach, we were able to approximate the moment's trajectories and the major hysteresis loops of a single domain particle for different applied field frequencies (Fig.1-right).

This approach, although approximative, gives very good results for times significantly longer than the Larmor period while decreasing the computation time with at least an order of magnitude compared to the differential equation solving. This opens, for example, the opportunity of studying complex systems with several components having a wide range of relaxation time values.

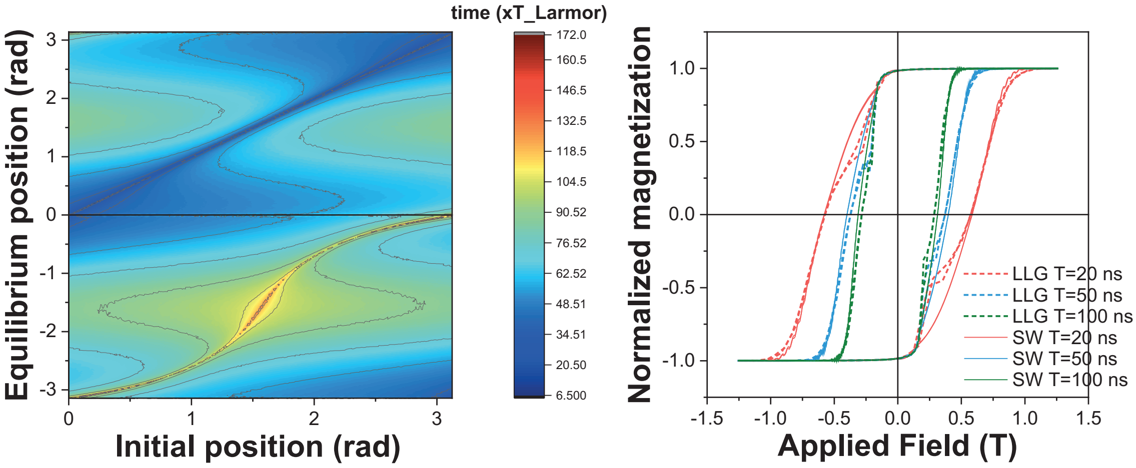

Figure 1: Time to reach equilibrium in LL formalism (left) and dynamic MHLs using the dynamic SW model (right).

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Magnetostatic properties of assembly of magnetic vortices

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It was shown recently [1] that magnetic vortices existing in soft magnetic nanoparticles with sizes larger than the single-domain diameter can provide sufficiently high specific absorption rate in alternating magnetic field of moderate amplitude. The properties of submicron nanoparticles being in magnetization curling state are still poorly investigated at present. In this work the magnetostatic properties of an assembly of FeCo nanoparticles with characteristic sizes D = 400 – 600 nm and aspect ratios $1.5 \leq L/D \leq 2.0$ have been studied both experimentally and theoretically. The particles were prepared by means of cavitation destruction of a macroscopic FeCo sample in methyl methacrylate. The XRD measurements proved that submicron FeCo particles obtained by cavitation have the same perfect crystalline structure as initial FeCo sample. In Fig. 1a curve 1 shows the experimentally measured hysteresis loop for magneto-composite sample containing submicron FeCo particles. The saturation magnetization of the particles is estimated to be M_s = 242 emu/g. Thus, it is close to that of $Fe_{73}Co_{27}$ macroscopic samples with perfect crystal structure. On the other hand, it is surprising to see in Fig. 1a that for a dilute assembly of magnetically soft FeCo particles the magnetization saturation is achieved in a very high magnetic field, $H \geq 8.0$ kOe. This fact can be explained taking into account that submicron FeCo particles should be in vortex states with very low average magnetization. Fig. 1b shows the vortex magnetization distribution in a FeCo nanoparticle with a transverse diameter D = 120 nm and length L = 180 nm in zero applied magnetic field obtained by means of the numerical simulation. The variational calculations are used to study the vortex structure in particles of larger diameters. Curves 2, 3 in Fig. 1a show the calculated hysteresis loops for dilute assemblies of FeCo nanoparticles with aspect ratios L/D = 1.5 and 2.0, respectively. Taking into account an experimentally observed distribution of particle sizes and aspect ratios it is possible to describe qualitatively the measured hysteresis loop of dilute assembly of submicron FeCo particles shown in Fig. 1a, curve 1.

The authors wish to acknowledge the financial support of the Ministry of Science and High Education of the Russian Federation in the framework of Increase Competitiveness Program of NUST «MISIS», contract № K2-2017-008.

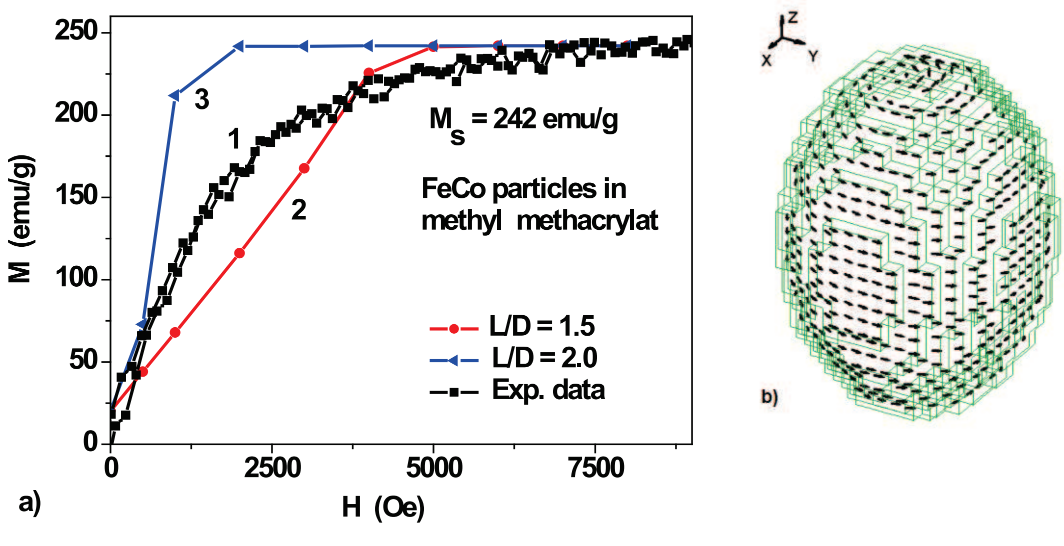

Figure 1: a) Upper part of the hysteresis loop of magneto-polymer sample based on submicron FeCo particles: 1) experimental data, 2) computer simulation for assembly of FeCo particles with aspect ratio L/D = 1.5, 3) the same for particles with aspect ratio L/D = 2.0. b) vortex magnetization distribution in FeCo nanoparticle with transverse diameter D = 120 nm and length L = 180 nm.

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Magnetic Hysteresis of Undermagnetized Magnetorheological Elastomers

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Magnetorheological elastomers (MREs) belong to a class of smart materials, whose physical properties can be controlled via application of an external magnetic field. A soft MRE sample is produced by embedding magnetic particles into a polymer matrix with an elasticity of tens of kPa. Consequently, magnetic properties of such materials highly depend on characteristics of separate particles, their interaction with each other and with the applied field, and on the level of particle mobility inside the matrix. The filler can consist not only of magnetically soft or hard particles but also of a mixture of the both types.

Rapidly solidified powders of NdFeB particles serve as a prospective filler for MRE samples thanks to their acceptable Curie temperature about 600 K, large energy product and high coercivity. The origin of their coercive force lies in a strong uniaxial magnetocrystalline anisotropy of $Nd_2Fe_{14}B$ grains constituting the particles. The anisotropy field of $Nd_2Fe_{14}B$ single domain crystallites is estimated at about 7.3 T [1], that is much higher than what a typical magnetometer can produce nowadays. Because of that, the particles are usually undermagnetized during an experiment, meaning that the applied field is not strong enough to magnetize a sample close to its saturation state.

In order to investigate and understand the magnetization process of MREs under the described conditions, we have developed a model that takes into considiration the anisotropy energy of the particle grains, the Zeeman enery of their interaction with the magnetic field inside an MRE, energy of their pairwise dipole-dipole interaction and the elastic energy of the surrounding matrix being deformed during rotation of the microparticle. By minimizing the function of this total energy with respect to the magnetic moments of the grains and to the mechanical declination of the particle from its initial state, one can obtain magnetization value of a sample at a given field.

The modelled hysteresis loops reproduce three main features of experimental magnetization curves shown in Figure 1, where h is normalized by the anisotropy field of $Nd_2Fe_{14}B$. One feature is the evident discrepancy between two first magnetiation loops. The second feature is that the curves are shifted to the negative area of the field axis with respect to the origin. As for the third feature, there is a slight difference in magnetization at positive maximal field between these two consecutive loops.

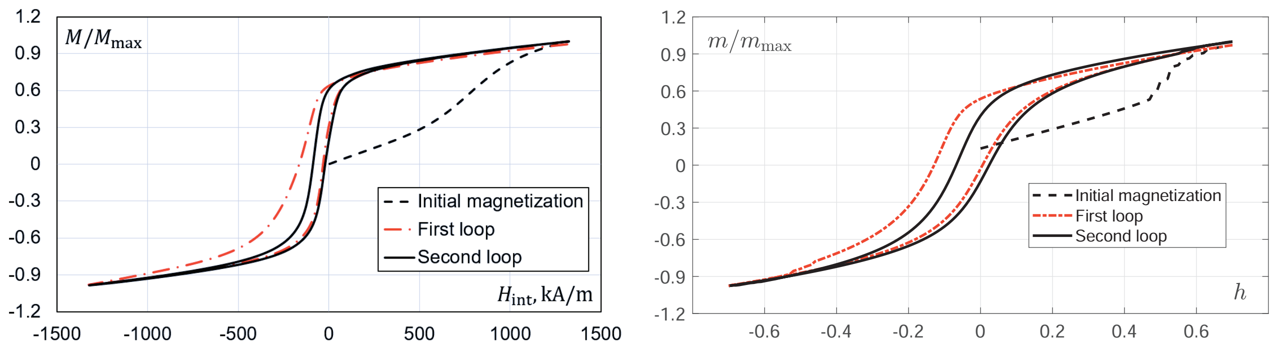

Figure 1: Measured (left) and modelled (right) magnetization curves of an MRE sample filled with NdFeB spherical particles and based on a matrix with shear modulus $G = 6.65$ kPa.

Acknowledgement: Support by RFBR projects 18-32-00817 and 19-52-12045 as well as by DFG project Bo 3343/2-1 within SPP1681/PAK907 is gratefully acknowledged.

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Identification of a Preisach-based magneto-elastic model through its formal 'thermodynamic' constraints

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Nowadays the interest to materials able to respond with a physical variable to the stimulus of second variable of different nature, i.e. *multi-functional* or *smart* materials, [1],[2], spread out well beyond the limits of a pure scientific interest, as the growth of companies specialized in the production of these materials, and their employment into specific devices.

In a general "macroscopic" frame, multi-functional materials can be considered as *energy converters* for their ability to convert work of different nature (i.e. mechanical, thermal, electromagnetic, etc.). In this respect, several of them attracted the attention of research for energy harvesting applications, [3].

The most of these materials show irreversible behaviors due to dissipation phenomena taking place inside the material and arising as hysteresis at the macroscopic scale. This parasitic processes that usually limits the performances of the devices making use of smart materials, present a further and more serious problem, since reduce the capabilities of the models to effectively describe the conversion process in terms of converted energy and efficiency of the harvesting device.

To this aim, the definition of new, fully coupled hysteresis models defined in a coherent thermodynamic framework is necessary. A contribution along this route has been proposed in [4], in which a Preisach operator $\mathcal{P}$ is associated to a second operator $\mathcal{U}$, referred to as *Potential*, defined such that the constraint, formally equivalent to the *Duhem inequality*, is fulfilled:

$$u\dot{\mathcal{P}}[u] - \dot{\mathcal{U}}[u] \geq 0, \tag{1}$$

being u, the input. Such *inequality* defines the $\mathcal{U}$ operator, which results as a Preisach operator with *Distribution Function* (PDF) linked to the PDF of the $\mathcal{P}$ operator, by a simple relation (cfr. [4]). However, the identification of this operator requires some effort that this paper aims to address. In particular, in [4], an analytical PDF is assumed for $\mathcal{P}$ allowing to identify the potential operator $\mathcal{U}$, through the link between PDFs ruled by eq. (1). Conversely, in this paper, through an experimentally driven approach, it is proposed to exploit the link between PDFs to reconstruct the Everett integrals of both operators by employing only one set of first order reversal curves (either measured on the magnetic or the magneto-elastic characteristic). This would increase the modeling accuracy without sensibly increasing the complexity of the identification procedure.

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Evaluating anisotropic exchange effect in Nd-Fe-B magnet by combined *ab initio* calculation, atomistic spin model, and micromagnetic simulation

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In the viewpoint of predicting coercivity of Nd-Fe-B magnets by micromagnetic simulations, input parameters are magnetocrystalline anisotropy constant (K), saturation magnetization (M_s), and exchange constant (A_e). The spatial distribution of K, M_s, and A_e represents the microstructure. In the micromagnetic study of Nd-Fe-B permanent magnets, K and M_s have been widely explored to show their critical role in the determination of coercivity in both sintered and hot-pressed magnets. However, less attention is paid to the role of A_e. The experimental measurement of temperature-dependent A_e of the $Nd_2Fe_{14}B$ main phase is not easy. The interface exchange between the main phase and subphases is even more difficult to be quantitatively measured. In most cases, micromagnetic simulations take assumed values of A_e. How to predict A_e still deserves more efforts.

In this contribution, we carry out multiscale simulations to identify the effect of A_e in Nd-Fe-B magnets by integrating first-principles calculations [1], atomistic spin model simulations [2,3], and micromagnetic simulations [4,5]. By using the results from first-principles calculations, atomistic spin model simulations of $Nd_2Fe_{14}B$ main phase predict the temperature-dependent values of A_e, and it is found that A_e in $Nd_2Fe_{14}B$ is anisotropic. A_e along c axis is smaller than along a(b) axis due to the tetragonal crystal structure. Moreover, from first-principles results, we find that the interface exchange coupling strength is also anisotropic in the grain boundary/main phase (i.e. $Fe_xNd_{1-x}/Nd_2Fe_{14}B$) interface structure with different Fe content. By using the results from first-principles calculations and atomistic spin model simulations, we further perform micromagnetic simulations to reveal the remarkable effect of anisotropic exchange both in the bulk phase and the interface on the magnetic reversal and coercivity in Nd-Fe-B magnets.

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Anatomy of skyrmionic textures in magnetic multilayers

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Room-temperature magnetic skyrmions in magnetic multilayers are considered as information carriers for future spintronic applications. Currently, a detailed understanding of the skyrmion stabilization mechanisms is still lacking in these systems. To gain more insight, it is first and foremost essential to determine the full real-space spin configuration. Here, we apply two advanced X-ray techniques, based on magnetic circular dichroism, to investigate the spin textures of skyrmions in $[Ta/CoFeB/MgO]_n$ multilayers[1]. First, by using ptychography, a high-resolution diffraction imaging technique, we determined the two-dimensional out-of-plane spin profile of skyrmions with a spatial resolution of 10 nm. Second, by performing circular dichroism in resonant elastic X-ray scattering, we demonstrate that the chirality of the magnetic structure undergoes a depth-dependent evolution. This suggests that the skyrmion structure is a complex three-dimensional structure rather than an identical planar texture throughout the layer stack. The analyses of the spin textures confirm the theoretical predictions that the dipole-dipole interactions together with the external magnetic field play an important role in stabilizing sub-100-nm-diameter skyrmions and the hybrid structure of the skyrmion domain wall. Our combined X-ray-based approach opens the door for in-depth studies of magnetic skyrmion systems, which allows for precise engineering of optimized skyrmion heterostructures.

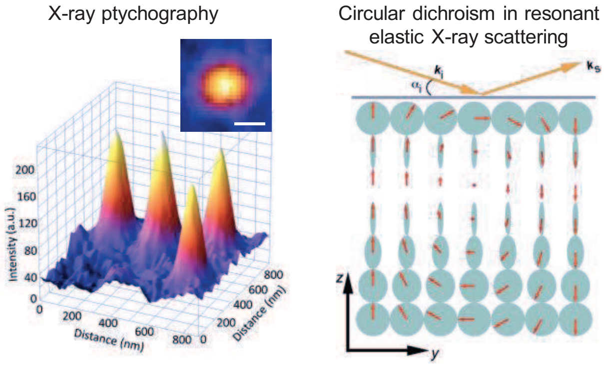

Figure 1: The spin textures of magnetic skyrmions in magnetic multilayers are determined using two advanced X-ray techniques. First, the highly resolved two-dimensional out-of-plane spin profile of skyrmion is captured using ptychography. Second, by performing circular dichroism in resonant elastic X-ray scattering, the chirality of the magnetic structure is directly demonstrated to undergo a depth-dependent evolution. This combined X-ray-based approach opens the door for in-depth studies of magnetic skyrmion systems.

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Effects of the particle size and shape of the magnetic nanoparticles on the magnetic hyperthermia and exchange bias properties

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The use of nanoscale materials in health and life sciences has been a topic of particular interest in recent times. Magnetic nanoparticles are nanomaterials that are distinguished by application areas such as technological and biomedical because of the controllable size, shape and chemical properties. Magnetic hyperthermia is one of the promising cancer treatment methods based on the injection of biocompatible nanoparticles into the cancerous region [1,2]. Core / shell nanoparticles with an appropriate specific absorption coefficient (SAR) are preferred for this treatment method to be effective [3]. In this manner, the production of nanoparticles with the ideal SAR parameter has recently become important. From the theoretical point of view, there are a few studies focusing on the SAR parameters of the nanoparticles. In first part of this presentation, the relationship between shape, size and surface anisotropy of the core/shell nanoparticles and the SAR parameter will be investigated by means of advanced numerical techniques. It is aimed to theoretically show the suitable nanoparticle shape and size for the SAR parameter to be improved.

On the other hand, when an antiferromagnetic (AFM) material is in contact with a ferromagnetic (FM) material, exchange bias (EB) effect, known as shift in hysteresis loops is observed under certain special conditions. Systems which exhibit exchange bias have current applications in magnetic recording read heads and also, they have a great potential for the development of magnetic sensor systems and non-volatile memory chips devices, for example, magnetoresistive random-access memory for computers. Thin films and magnetic nanoparticles are some of systems in which the EB phenomenon is observed. Exchange bias effect was firstly observed in FM core/AFM shell Co/CoO nanoparticles [4,5] and up to day, it has been studied in many multi-component core/shell nanoparticle systems. The second part of the presentation is devoted to the investigation of EB in nanoparticles exhibiting different shapes.

The classical Heisenberg model which is one of atomic spin models will be used for the theoretical design of core/shell nanoparticles with different geometries in the direction of the above mentioned targets. Monte Carlo simulation technique will be used for this aim. Core/shell nanoparticles with different geometries, such as sphere and ellipsoid, will be designed. In order to improve the SAR parameter and EB properties, it is aimed to identify the nanoparticle type with appropriate shape and size.

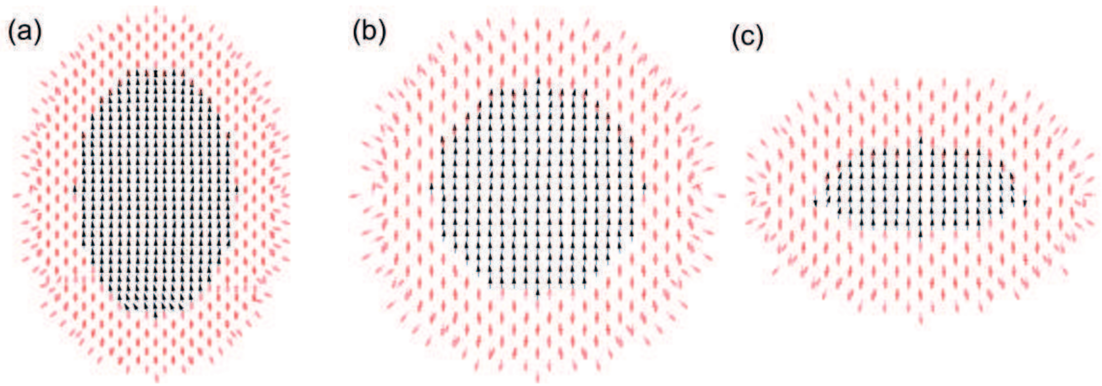

Figure 1: Simulated particles of different shapes with the same shell thickness: (a) prolate (b) spherical (c) oblate.

Acknowledgements This work was supported by the Scientific and Technological Research Council of Turkey (TUBITAK) under the Research Project No. 118F316. The numerical calculations reported in this paper were performed at TUBITAK ULAKBIM High Performance and Grid Computing Center (TR-Grid e-Infrastructure).

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POSTER CONTRIBUTIONS

Efficient numerical implementation of the fast multipole method in finite element simulations

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The Fast Multipole Method (FMM) [1] has been called one of the "ten most significant algorithms" in scientific computation discovered in the 20th century [2]. The method allows the evaluation of the product of dense matrices (having some particular structure) with a dense vector in $\mathrm{O}\left[(N+M)\ln(N+M)\right]$ operations, whereas direct multiplication requires $\mathrm{O}(NM)$ operations, where N and M represent the dimensions of the matrices. The proportionality factor in the above equation depends on the type of the problem that is solved. In magnetics, the FMM was used in many applications such as the computation of the magnetic fields produced by nonuniformly distributed magnetic charges (diploes) [3], demagnetizing fields [4,5], and micromagnetics [6-8]. The magnetic potentials or fields are usually expanded in series as a function of Legendre polynomials P_{lm} and then truncated to a maximum number of terms $l_{\max}$. The number of operations required to compute the magnetic field is proportional to $\mathrm{O}\left[f(l_{\max})\times(N+M)\ln(N+M)\right]$, where $f(l_{\max})$ is an increasing function of $l_{\max}$ and depends on the procedure used to evaluate the coefficients of the series expansions. If these coefficients are evaluated by direct translation (see [3]), then $f(l_{\max}) \sim l_{\max}^4$. For relatively small values of $l_{\max}$ (e.g. $l_{\max} < 7$), the computation time of the FMM is fairly low, however, for larger values of $l_{\max}$ this computation time becomes inefficiently long. Note that the total computation time for the FMM is still proportional to $\mathrm{O}\left[(N+M)\ln(N+M)\right]$, however, the proportionality constant becomes very large in this case.

In this paper we present an algorithm based on a technique presented in [5] that reduces the computation time from $O\left[l_{\max}^4\right]$ to $O\left[l_{\max}^3\right]$. This technique is based on splitting the direct translation of the expansion coefficients into a rotation so that the z-axis is parallel to the translation axis, a translation along the z-axis, and another rotation which brings the coefficients in the original system of reference. Since each of these operations requires $O\left[l_{\max}^3\right]$ operations, the total computation time will also require $O\left[l_{\max}^3\right]$ operations, reducing the total computation cost considerably. In the full paper we present an implementation of this FMM algorithm for the computation of magnetic fields and magnetic forces in electromagnetic systems that can be model using finite element methods, such as motors, actuators, etc.

Fig. 1 presents sample results obtained using our technique for the computation of magnetic fields induced by current flowing through a conducting wire around a toroidal system. Our FMM implementation is based on the discretization of the kernel of integral in the Biot-Savart's law and on the efficient summation of the resulting "magnetic charges" by FMM. More simulation results and an in-depth discussion of the numerical algorithm will be presented at the conference.

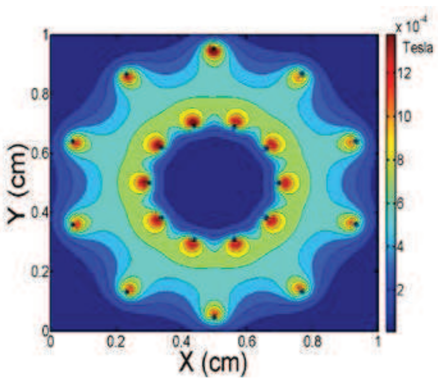

Figure 1: Magnetic field computed by using the FMM.

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Walker's modes in ferromagnetic finite hollow cylinder

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Spin waves interference in non-simply connected domains is of great interest for the possibility to develop logic ports and quantum magnonic devices [1, 2]. The geometry of an hollow cylinder represents a simple but meaningful example of a non-simply connected domain. In this work we focus on the study of magnetostatic modes (then ignoring the effect of ferromagnetic exchange) that are the relevant ones at low wavenumbers. The magnetostatic modes have been studied extensively in ferromagnetic spheroids [3], ferromagnetic thin films [4, 5] and also in ferromagnetic cylinders [6, 7]. In this work we focus on a ferromagnetic finite hollow cylinder. We study the magnetostatic modes in the quasi-static approximation and with an applied magnetic DC-field along the cylinder axis. The hollow cylinder has height L along the $z-$axis and r_1 and r_2 as internal and external radii respectively.

$$\Big[1+\chi\Big]\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \psi_i}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2\psi_i}{\partial \varphi^2}\right]+\frac{\partial^2\psi_i}{\partial z^2}=0 \tag{1}$$

The magnetostatic problem can be solved by writing the *Walker's equation* (1) for the magnetic scalar potential ψ_i, where χ is the susceptibility of the material inside the hollow cylinder and is zero otherwise. The boundary conditions are chosen metallic at the boundaries along the $z-$axis. Additionally we set zero demagnetizing field along z by adding two ideally soft ferromagnetic blocks above and below in order to emulates the case of an infinite cylinder. At the interfaces ($r=\{r_1,r_2\}$) the boundary conditions are set to ensure the continuity of the tangential component of the magnetic field and of the normal component of the magnetic induction. Having in mind to find the normal magnetostatic modes, we write the magnetic potential for the three regions: (-) inside the cylinder hole, (+) outside the cylinder and (m) inside the materials. With our specific boundary conditions we find that each mode can be identified by two indices: the vertical n_z and the azimuthal one n_φ. A particularly interesting case is found with $n_z=0$, i.e. for uniform behaviour along z. In this case the solutions are written in terms of n_φ-powers of the radius. The precession frequencies for the n_φ modes are derived:

$$\omega^2=\omega_0(\omega_0+\omega_M)+\frac{\omega_M^2}{4}\Big\{1-e^{[-4|n_\varphi|\tanh^{-1}(d)]}\Big\} \tag{2}$$

$$d=\frac{r_2-r_1}{r_2+r_1} \tag{3}$$

The mode frequencies resembles in the Damon-Eshbach like-form [4] shown in eq.(2), the ω_0 and ω_M have the customary meaning.

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Stress Self-sensing in Amplified Piezoelectric Actuators through a Fully-Coupled Model of Hysteresis

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The development of Amplified Piezoelectric Actuators (APA) is one of the results of the large effort in the research of last decades about the need for precise micro-positioning devices working with high efficiency and robustness. Indeed, with the aim of developing actuators able to work in widely different fields of application with good accuracy, [1], smart materials, such as piezoelectrics, have been exploited as active core in those devices, leading to non trivial issues concerning their hysteretic behaviour. Such rate independent memory effects require an accurate modelling, [2], and show a strong dependence also on the mechanical state experienced by the active material, [3]. For this reason, the effective stress needs to be measured and taken into account in the closed control loop governing the device, implying the necessity of external and bulky stress sensors. An alternative solution may be represented by self-sensing procedures, as firstly proposed for piezoelectric actuators in [4], where a linear model is exploited. Conversely, the general fully-coupled model of hysteresis developed in [5] could be exploited to build up a robust self-sensing method for APA. The model has been demonstrated to be successfully usable for self-sensing purposes in magnetostrictive actuators in [6] and it is here applied for the the APA 100M by Cedrat Technologies (Figure 1) and expanded to take into account the crossbow-like amplification system and its influences to the behavior of the device.

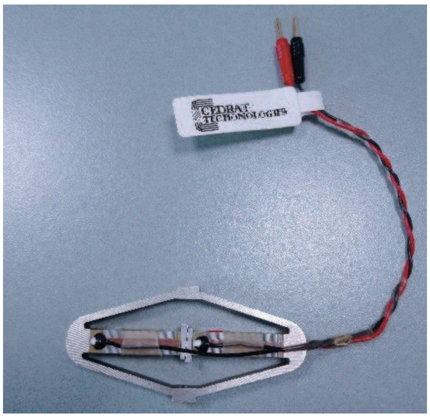

Figure 1: Photo of the piezoelectric actuator.

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Towards a unified approach to hysteresis modeling and micromagnetics: A dynamic extension to the Harrison model

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Hysteresis is a nonlinear phenomenon which attracts a considerable attention of scientific and engineering communities [1]. There exist a number of hysteresis models, differing in their complexity and background. In the paper we focus on the possibility to extend the quasi-static description advanced by Harrison [2] to the dynamic case. This shall be achieved by a proper modification of one of model equations, making it compliant with the one considered previously by Glauber [3] in his extension of the famous Ising model [4].

The Harrison model is based, in its simplest form, on the quantum-physics picture of the atomic moments. It considers irreversible magnetization effects as resulting from a strong positive-feedback process (the Weiss' internal coupling) that occurs at the quantum scale inside the domains. It should be recalled that the concept of effective field introduced over a century ago by Weiss [5] has remained one of the most inspiring ideas in contemporary ferromagnetism [1, 6-9].

The irreversible magnetization processes are expressed in the Harrison description (in dimensionless units) with the relationship $m = \tanh\left(\frac{h+m}{\theta}\right)$, where θ is the reduced temperature. In order to arrive at a dynamic extension, it is sufficient to introduce an additional term with time derivative of m, i.e. $\tau\frac{\mathrm{d}m}{\mathrm{d}t} = -m + \tanh\left(\frac{h+m}{\theta}\right)$, where τ is the relaxation time (cf. e.g. [10, 11] – the latter reference uses a normalization $\tau = 1$). The full paper shall consider the consequences of the proposed extension for the theory used in the Harrison model, like the modified location of bifurcation points, at which the derivative $\mathrm{d}m/\mathrm{d}x$ changes its sign. An experimental verification of the proposed approach shall also be provided.

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Analysis of Thermal Switching and Chaotic Dynamics in ac-driven Nanomagnets

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The understanding of magnetization dynamics in nano-scale magnets subject to time-harmonic (AC) excitations and thermal fluctuations is of crucial importance both from fundamental and application points of view[1]. Magnetization dynamics of uniformly magnetized particles subject to AC fields has been traditionally studied in connection with ferromagnetic resonance[2], where magnetization oscillations are excited around a stable equilibrium corresponding to a system energy minimum. The amplitude of magnetization oscillations as function of frequency follows the classical resonance curve peaked around the Kittel frequency[2]. At somewhat larger AC powers, nonlinearity may lead to the foldover phenomena[3]. At larger AC excitation powers, for submicron particle dimensions, the spin-wave instability phenomena[4] are strongly inhibited by exchange interactions[1]. For this reason, even at considerably large AC powers, nonlinear dynamics in nanomagnets exhibits mostly a spatially uniform mode of oscillations.

In this paper, we consider AC-driven magnetization dynamics for single-domain bistable nanomagnets in the presence of weak thermal noise. The presence of saddle points leads to enormous complexity in AC-excited magnetization dynamics where the chaotic behavior is often dominant. We study these physical phenomena with a special emphasis on the interplay between chaotic dynamics and thermal excitations.

In this respect, it has been recently demonstrated[5] that the aforementioned chaotic dynamics can be the dominant mechanism which controls thermally-activated switching dynamics in ac-driven conditions.

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Skyrmion based Random Bit Generator

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Magnetic skyrmion are topologically protected [1],[2] non-uniform configuration of the magnetization which can behave as particles [3]. They can be easily manipulated (nucleated, shifted and detected) by spin-polarized current, and for this reason they offer a wide range of applicability fields [2]. In this work, we study the skyrmion dynamics driven by the spin-Hall effect in a synthetic antiferromagnet within a micromagnetic framework. We show that, in presence of thermal fluctuations at room temperature, the skyrmion motion is not deterministic [4]. In other words, this motion follows stochastic law of motion (casual sequence of 0 and 1), and therefore it is natural to think skyrmions as building blocks of random bit generators if combined with a device designed for this scope (see figure 1(a)). The parameters used in our study are the same as in [5].
We have shown, via a full micromagnetic simulations, the possibility to move skyrmions randomly in presence of spin-Hall effect and thermal fluctuations in a synthetic antiferromagnets, where the skyrmion hall effect is absent [5]. We have observed that, under the steady action of the current, skyrmions stochastically divided in the two output branches of our device starting from a continuous nucleation in the input branches (see figure 1 (b)). Our results are also robust to the presence of defects in the form of randomly distributed grains of the perpendicular anisotropy. Our achievements open the path for the design of random bit generators based on skyrmions.

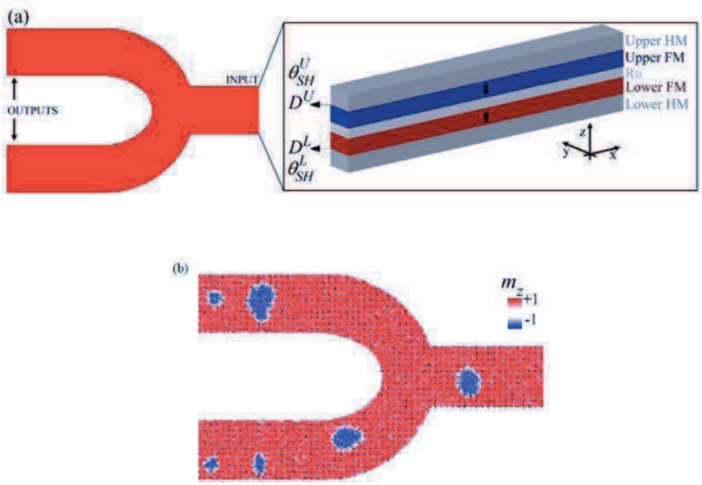

Figure 1: (a) 2D view of the synthetic antiferromagnet under investigation where the input and output branches are indicated. The magnification in the right panel is a 3D sketch of the device where the ferromagnets (FM), separated by a Ru layer, are sandwiched between different heavy metals (HM). (b) Example of spatial distribution of the magnetization for the lower ferromagnetic layer after 30 ns. Two skyrmions went to the upper output branch, three skyrmions went to the lower output branch, while another skyrmion is coming from the input branch.

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Second order anisotropy contribution on magnetization dynamics in fully perpendicular spin transfer torque nano-oscillators

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The discovery of interfacial perpendicular magnetic anisotropy made possible the fabrication of fully perpendicular MgO-based magnetic tunnel junctions (pMTJs) having lower dimensions, lower switching current, and higher thermal stability than planar MTJs [1]. These perpendicular nano-structures were generally studied for the optimization of magnetic random access memories performances, but other applications can be also addressed, such as, magnetic field sensors or spin transfer torque oscillators (STNOs). In this context, we numerically analyzed the magnetization dynamics of the free layer (FL) of STNOs based on fully perpendicular MTJs optimized for memory functions. In order to induce self-sustained magnetization oscillations by spin transfer torque effect the out of plane symmetry of the pMTJ need to be broken. This condition is fulfilled by applying a magnetic field with a strong planar component. The simulations were performed by solving the Landau-Lifshitz-Gilbert equation [2] in the macrospin approach. The effects created by the spin polarized current in MTJs were described by adding to the LLG equation two new terms, the damping-like spin transfer torque term and the field-like spin transfer torque term. Moreover, recent studies [3, 4] revealed that a second order easy-axis magnetic anisotropy contribution, K_2, has to be considered in order to describe the crystallographic mismatch effects at the MgO-magnetic layer interface. In this case, the ground state of the FL can evolve from the easy-axis state, parallel to the out of plane direction, to the easy-cone state, where the magnetization is tilted away from out of plane direction by a certain polar angle θ (the system energy remain invariant around a cone with the opening angle θ). Using this formalism, we simulate the magnetic behavior of FL magnetization of STNOs function of several physical and geometrical parameters, such as, the first and second order anisotropy term amplitude, the out of plane angle of the applied magnetic field, the amplitude of damping-like and field-like torques, the sample temperature [5], or the FL thickness and surface. For $K_2=0$ the voltage-field diagrams of states present one out of plane stable state (OPS), one in-plane stable state (IPS) and two dynamic areas with in-plane precession states (IPP). The IPP oscillations frequency increases in current or field and ranges between 1 and 7 GHz. When K_2 is taken into account, the voltage-field diagrams of states change and a new dynamic state appears, the out of plane precession state (OPP). Frequencies of the OPP mode variate from 1 GHz to 14 GHz and increase with increasing voltage. We showed that, combining the second order easy-axis magnetic anisotropy contribution with an external magnetic field applied slightly out of plane, a large self-sustained magnetization oscillations area can be generate, of interest for RF applications. We also mention that some of our results were compared and validated by experimental measurements.

Acknowledgement: Funding from the European Union's Horizon 2020 research and innovation programmeunder grant agreement No 687973, acronym GREAT, is highly acknowledged.

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Micromagnetic simulation of spiral domain structures in microwires under influence of circular magnetic field

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Magnetic spiral domain structure has been observed recently in glass-covered cylindrical amorphous microwires [1]. Using an external axial magnetic field, we demonstrated experimentally the surface nucleation and migration of spiral domain structure of length limited only by the sample size.

Here we present the results of the micromagnetic simulations of the influence of the circular magnetic field created by the electric current passing through the microwire on the modification of a spiral domain structure during the magnetization reversal process.

We carried out micromagnetic simulations of a cylindrical-shaped microwire with a diameter of 1 μm and a length of 15 μm, which during the discretization was divided into cuboid volumes of $10 \cdot 10 \cdot 5$ nm^3. The simulations were performed using the $mumax^3$ program for microwire with a small positive magnetostriction constant ($\lambda = 2 \cdot 10^{-7}$), taking into account the distribution of internal stresses in a glass-covered microwire.

In Figure 1 we present distribution of the magnetization at the remanence state for selected values of circular magnetic fields. At zero circular field, the spiral domain structure consists of two parts with: left- or right-handed helicity (see Fig. 1b). Under applied circular magnetic field, the helicity of the spiral structure becomes uniform in the whole wire, with the direction dependent on the direction of the current (see Figs 1a and 1c). Furthermore these selected magnetic structures collected in Figs. 1c-1f allow to conclude that an increase of the circular magnetic field leads to a decrease of the density of the spiral domain structure.

We demonstrated that the growing circular magnetic field drives the magnetization towards the circular direction, perpendicular to the axis of the microwire. This process is accompanied by the gradual migration of the spiral domain structure from the surface to the core of the microwire. It is also worth mentioning that the inclination of the domain walls of the spiral structure decreases with an increase of the amplitude of the circular magnetic field.

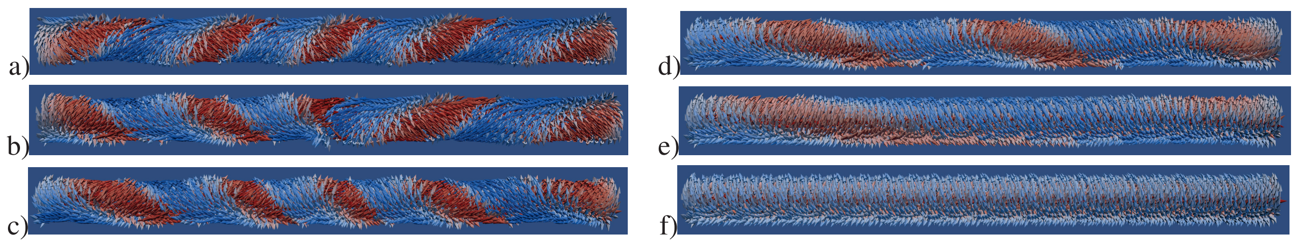

Figure 1: Images of simulated magnetic structures at the remanence state for different amplitudes of the circular magnetic field created by the electric current (I) passing through the microwire: a) $I = -1$ mA, b) $I = 0$ mA, c) $I = 1$ mA, d) $I = 5$ mA, e) $I = 7$ mA, f) $I = 10$ mA. The colors correspond to an axial (along the wire) component of the magnetization with $+M_Z$ (red) and $-M_Z$ (blue) orientations.

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Calculating coercivity at finite temperatures by micromagnetic simulations: a comparative study

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Since all the applications based on magnetic materials are generally at finite temperatures, predicting the magnetic properties with the consideration of finite-temperature effects is indispensable. Even though micromagnetic simulation has become a standard tool for the design of various magnetic structures ranging from permanent magnets, magnetic recording devices, and spintronic devices to magnetic logic elements [1], its application to the calculation of finite-temperature properties still requires careful examinations.

In this contribution, we present a comparative study on the calculation of coercivity of magnetic materials at finite temperatures by micromagnetic simulations. In detail, we show three ways to calculate the coercivity by performing micromagnetic simulations. The first two ways are based on solving the stochastic Landau-Lifshitz-Gilbert (sLLG) equation which takes the temperature effects as thermal fluctuations. In the first approach, we apply a stepwise external field to calculate the hysteresis at finite temperatures and then determine the coercivity. Whereas in the second approach we apply a series of constant fields for a sufficient long time to induce the magnetization switching and then calculate the relaxation time. In this way, we can either derive the energy barrier [2,3] as a function of switching field (from which the coercivity can be determined by the critical energy barrier $25k_BT$), or the switching field as a function of time (from which the coercivity at the characteristic measurement time can be obtained by fitting the Sharrock's equation [4,5]). In the third way, we utilize the elastic band method and compute the energy barrier as a function of the external field by micromagnetic simulations without the consideration of thermal fluctuations [6]. Benchmark simulations are performed on the Stoner–Wohlfarth (SW) model to check the consistence of these three methods. More simulations are carried out to calculate the finite-temperature coercivity of single and multi grains. The results of these three methods are compared and discussed.

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Using FORC to understand the Microstructure-Micromagnetism Relationship in Supermagnets

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First-order-reversal-curve (FORC) diagrams yield a great variety of magnetic information such as coercive and interaction field distributions. We have recently shown that FORC diagrams can provide detailed information, as being just a magnetic fingerprint [1,2,3]. Groß *et al.* demonstrated on microstructured model systems that FORC can be used to quantify the micromagnetic interaction between two magnetic phases [4]. Following these studies we investigated the temperature dependent interaction of soft and hard magnetic components in a real system, namely a commercial, sintered neodymium magnet and deduce two microstructure-micromagnetism relationships using FORC measured at temperatures between 50 K and 350 K with a Quantum Design MPMS 3 VSM SQUID magnetometer.

The temperature dependent FORC densities show three distinct features, where two correspond to a soft and hard magnetic component, respectively, and the third one appears due to micromagnetic interaction between those components. Projecting the FORC density onto the actual first-order-reversal curves shows that the magnetization reversal of the two components dependents on each other, and the reversal of the soft component can pull along some of the hard component. The temperature dependent FORC diagrams have the same overall structure but the intensity of the interaction peak decreases with decreasing temperature. Taking the peak volume of the interaction peak as a measure for the effective interaction strength between soft and hard magnetic components we see that below 250 K there is almost no interaction whereas above it increases dramatically. With the temperature where the interaction peak volume starts to increase and the corresponding coercive field of the sample at this temperature the interaction strength can be quantitatively approximated.

Furthermore, we systematically manipulated the microstructure of the samples by consecutive annealing (at different temperatures and intervals), and correlated their grain size distributions with FORC diagrams. All magnetic measurements as well as the annealing cycles were performed using a Quantum Design MPMS 3 VSM SQUID magnetometer. Microstructural information were obtained by SEM and Kerr microscope images. Our analysis of the grain size distributions showed that the grain sizes shift to higher diameters and the distribution broadens for longer annealing times, as expected due to Ostwald ripening of the grains. The room temperature FORC diagrams revealed that the coercive field distribution moves to slightly lower coercive fields for longer annealing durations and the width of this field distribution increases. Correlating the widths of grain size- and coercive field distributions reveals a linear dependence, which enables us to draw conclusions about grain sizes directly from FORC measurements. The results agree with micromagnetic theory which states a dependence of the coercive field on the grain size, more precisely a decreasing of coercivity with increasing diameters [5].

Our results demonstrate the versatility of FORC investigations providing rich additional information, beyond magnetic fingerprints, enabling detailed understanding of micromagnetic interactions between to magnetic phases.

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The effects of disorder on hysteresis loops in chiral magnets

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In this talk we investigate the effect of the distribution of pinning sites on the magnetization behavior in systems with Dzyaloshinskii–Moriya interaction (DMI). We consider the following standard classical spin Hamiltonian [1]:

$$\mathcal{H} = -\frac{1}{2}J\sum_{ij}\vec{s}_i\cdot\vec{s}_j - \frac{1}{2}D\sum_{ij}\vec{d}_{ij}\cdot(\vec{s}_i\times\vec{s}_j) - \sum_i K_i(\vec{s}_i\cdot\hat{z})^2 - \sum_i \vec{h}\cdot\vec{s}_i$$

where the first term corresponds to Heisenberg exchange, the second term is the DMI energy, the third term represents uniaxial anisotropy energy K_i acting on a given spin site i and the last term is the Zeeman energy. To model the effect of disorder we consider spatial Gaussian distribution of the anisotropy constants K_i having mean K and standard deviation σ. First we discuss the reduction of the model to a lattice resolved mean-field theory, and develop energy minimisation algorithm for solving it. This approach allows to compute systematically and efficiently the magnetisation versus field dependence $M(H)$ for variable distributions of K_i and temperature, and can be used for computing qualitative thermodynamic phase diagrams to explore material behaviour and to guide computationally costly Monte-Carlo simulations.

We show that as the standard deviation σ of the anisotropy distribution increases, relative to the strength of exchange interaction and DMI, the nature of the reversal modes observed along a typical $M(H)$ hysteresis loop changes in a certain temperature window. Namely, in 'clean' systems with small σ, the reversal proceeds through the appearance of skyrmion lattices at low external fields, while in 'dirty' systems with large σ the reversal is through the nucleation of individual or small groups of skyrmions. We systematically quantify this effect and discuss its broader implications for applications.

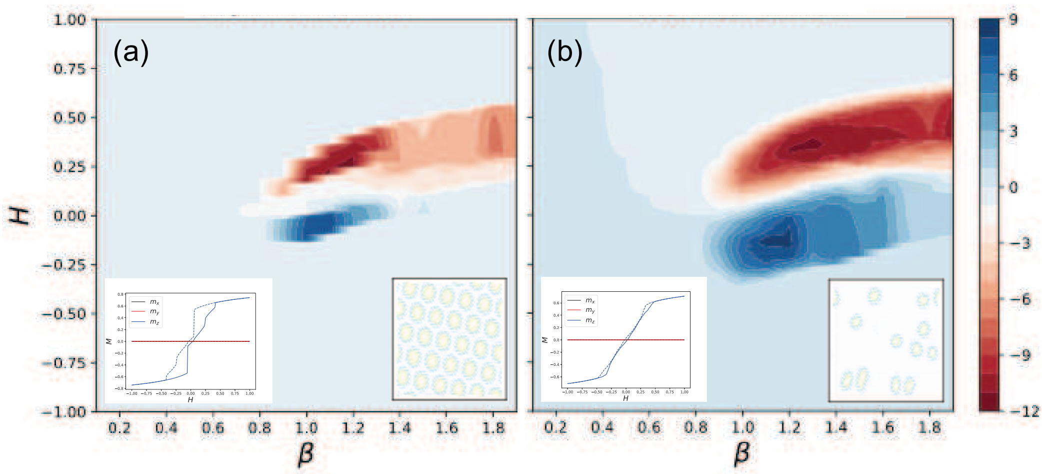

Figure 1: A color-coded plot of a skyrmion number computed from a lattice resolved mean-field model for different values of normalized fields H and inverse temperatures $\beta = T^{-1}$ for the uniaxial anisotropy distribution with standard deviation (a) $\sigma = 0$ when the magnetisation reversal along the hysteresis loop obtained at $\beta = 1$. (left inset) proceeds through the emergence of a skyrmion lattice (right inset), and (b) $\sigma = 0.2$ the magnetisation reversal proceeds through single or small groups of skyrmions.

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Micromagnetic simulation analysis of two-magnon relaxation processes in nanocrystalline thin films

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In this study we investigated the influence of the magnetization ripple structure on two-magnon relaxation processes in nanocrystalline thin magnetic films (TMFs). The numerical calculation of high-frequency magnetic susceptibility based on a micromagnetic model of TMF showed that the magnetization ripple substantially affects the relaxation in nanocrystalline films. Particularly, it was found that the ferromagnetic resonance (FMR) linewidth $\Delta H^{(2m)}$ had a sharp peak at a specific frequency f_1 that depended on thickness and magnetic characteristics of the film (Fig.1). A significant shift of the FMR resonance field $H^{(2m)}$ was was also observed, and the value of this shift changed its sign at the frequency $\sim f_1$.

To explain the nature of magnetic relaxation in nanocrystalline thin films we considered a theoretical model of spin waves scattering on magnetic nonuniformities caused by a nonuniform stochastic structure of magnetization ripple. A good correspondence between the main findings of the developed theoretical model and results of micromagnetic modelling confirms that the magnetization ripple plays a key role in the magnetic relaxation processes in nanocrystalline thin films.

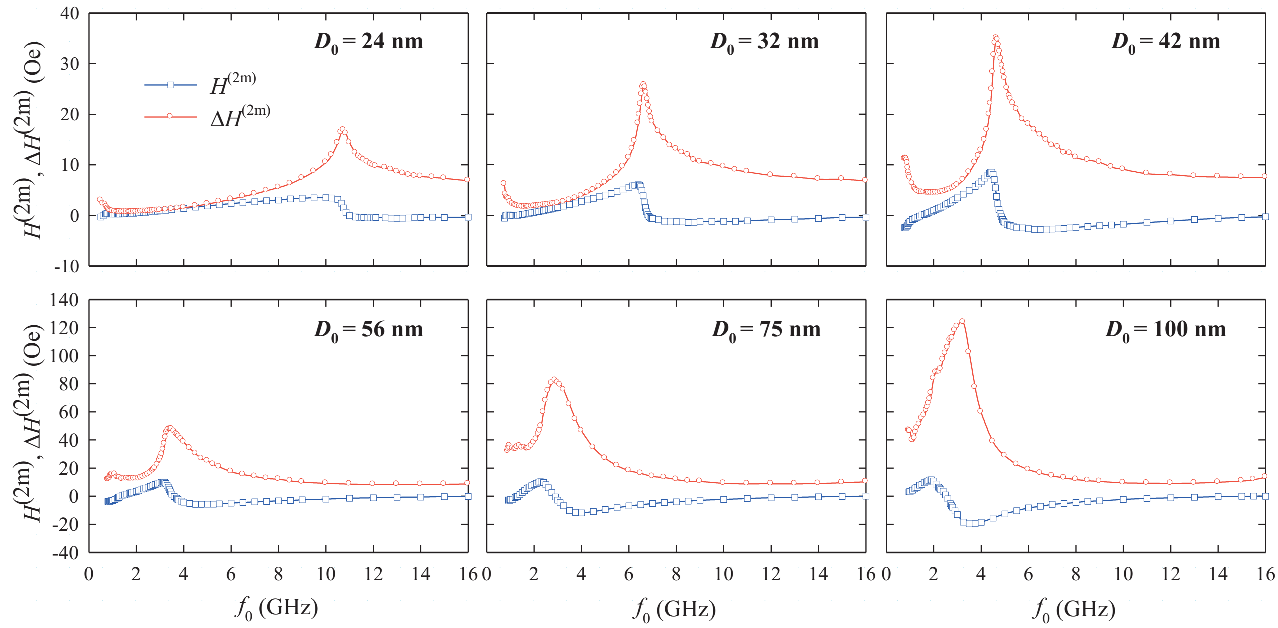

Figure 1: Dependences of the FMR resonance field shift $H^{(2m)}$ and FMR linewidth $\Delta H^{(2m)}$ on frequency obtained by the numerical micromagnetic modelling of high-frequency magnetic susceptibility of nanocrystalline thin films with the crystallite sizes D_0 = 24, 32, 42, 56, 75, and 100 nm.

This work was supported by the Ministry of Education and Science of the Russian Federation, №RFMEFI60417X0179.

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Modeling hysteresis loops of SMC cores with the Jiles-Atherton-Sablik description

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The Jiles-Atherton-Sablik model still remains one of the most commonly used formalisms to describe magneto-mechanical coupling [1-7]. The effect of stress may be accounted in the description by introducing an additional term to the so-called effective field. Most of the papers devoted to Sablik's model extension were devoted to classical core materials, i.e. electrical steels. At the same time it should be recalled that the Jiles-Atherton model and its subsequent refinements were successfully applied to other soft magnetic materials used in practical applications, to mention Soft Magnetic Composites (SMCs) [8-11]. In the afore-mentioned papers the effects of stress were accounted in modeling by appropriate updates of some values of model parameters. The novelty of the present paper relies in the direct application of the Jiles-Atherton model with Sablik's extension to describe the modifications in the shapes of modeled hysteresis loops of self-developed SMC cores subject to different compaction pressures.

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Effects of the Double Gaussian Random Field Distribution on the Hysteresis Characteristics of the Magnetic Binary Alloy

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Today, irregular magnetic binary alloy systems exhibit a wide range of theoretical and experimental literature in terms of their applicability to many physical systems with their multicritical behavior. The random field Ising model (RFIM) consists of a randomly distributed magnetic field on lattice sites according to a given distribution. This model was presented by Larkin [1] for superconductors and then generalized to spin systems by Imry and Ma [2]. Spin-1/2 Ising model under random field distribution has been studied with many approximations such as the renormalization group (RG) technique, Monte Carlo simulation (MC) [4] and effective field theory [5]. The random field spin-1 Ising model was studied by methods such as mean field approach (MFA) [6], RG technique [7] and EFT [8]. In addition, complex systems such as mixed spin systems [9] have also been studied.

In this study, the effect of the double gaussian random magnetic fields on binary magnetic alloys which consists of spin-1/2 and spin-1 magnetic atoms was investigated by means of effective field approach. In order to generalize our binary Ising model [10] and bimodal random field distributed binary alloy study [11], double gaussian random field distribution was investigated. The evolution of phase diagrams is presented with the relevant parameters in different planes. Order and disorder phase boundary was determined and multicritical behavior of the system was obtained. The results were consistent with the literature. By examining the behavior of the order parameter, striking results were obtained about first and second order transitions under concentration and randomness. It has been observed that double gaussian random magnetic field distributed binary alloy system could exhibit double hysteresis behavior. Besides, the dependence of hysteresis loop areas, coercive field and remanent magnetization on the concentration has been investigated.

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Magnetic skyrmion formation on cylindrical surfaces with chiral interactions

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Magnetic skyrmions are localized spin textures with a whirling configuration arising in systems with competing symmetric exchange (Heisenberg) and chiral (Dzyaloshinskii-Moriya) interactions. They have been theoretically studied and experimentally observed in planar magnetic nanostrips of ferromagnetic – heavy metal bilayers. On the other hand, the study of magnetic structure of curved surfaces and nanostructures has attracted research interest that stems from the possibility of tailoring the magnetic behavior of (non-chiral) ferromagnetic systems through the curvilinear characteristics of the surface, such as curvature and torsion [1]. The combined effect of curvature-induced chiral and intrinsic chiral interactions is anticipated to lead to a rich phase diagram of skyrmion stability and related properties in curved nanostructures. In the present work we study the conditions for magnetic skyrmion formation on the cylindrical surface of a magnetic nanoshell. A 2-D nanoshell serves as a simple structural model of either a thin cylindrical shell of a non-centrosymmetric (B20) material or the thin external layer of a nanowire with heavy metal core and ferromagnetic shell. To model the magnetic structure, we assume 3-D classical spins interacting via 1NN symmetric exchange interactions (Heisenberg) and chiral (Dzyaloshinskii-Moriyia) interactions. The local anisotropy axes are taken normal to the surface of the shell. The ground state configuration of the system is obtained by a simulated annealing process using the Metropolis Monte Carlo algorithm with single-spin updates and adaptive spin-step. We present simulation results for the evolution of the total topological charge with surface curvature during a continuous transformation from a planar nanostrip to a cylindrical nanotube. The geometrical characteristics (size and shape) of a skyrmion are studied as a function of the surface curvature. Finally, we demonstrate stability of skyrmions on curved surfaces without application of an external magnetic field. This result paves the way to electric control of magnetic skyrmions on nanotubes which is expected to benefit from the lack of the undesired edge annihilation effect met in planar nanostrips [2].

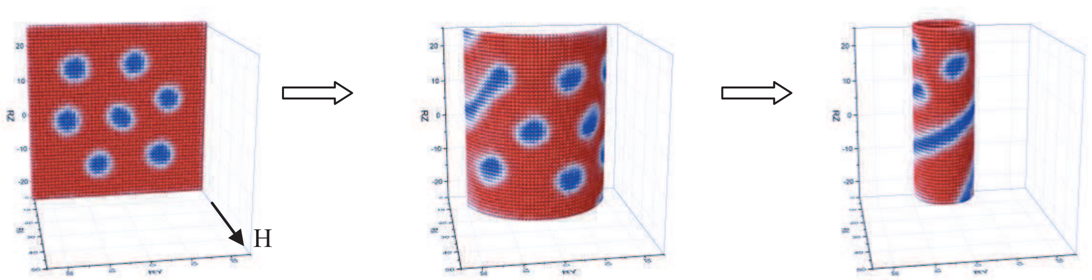

Figure 1: Transition from skyrmions to stripe-domains as the curvature of the system increases

DK acknowledges support by the Special Account for Research of ASPETE through program *NANOSKY* (Project No 80146). AP acknowledges support from the State Scholarships Foundation through a Doctorate Scholarship (No 2018-050-0502-14077).

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Antiskyrmion-mediated phase transition in ideal and defective hexagonal skyrmion lattices

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Skyrmions are unique magnetic whirling structures in magnetic recording materials that can be generated through the competition between short-range and long-range interactions. By virtue of their robust stability and potential for scalability, these quasi-particles spin textures are becoming promising candidates for next generation information storage devices, while their topological stability also significantly enhances the tolerance to materials defects. One of the effective fundamental systems for studying such topological textures are high-density hexagonal skyrmion lattices (SkL), whose existence have been both described theoretically and demonstrated experimentally [1-2]. The magnetic interactions and topological constraints are key factors on the formation of SkL configurations, but the underlying physical mechanisms and creation and annihilation of topological charge still remain unsolved. At the same time, defects, generally and inevitably, exist in real nanofabricated devices, and it is therefore essential to determine their role during lattice transitions.

In our work [3], using GPU-accelerated Mumax^3 [4], we numerically demonstrate a field-induced SkL phase transition which generally exists in both isotropic (bulk) and anisotropic (interfacial) Dzyaloshinkii-Moriya interaction (DMi) systems: topological charge effectively delocalises and redistributes, inducing the formation of a 2π-domain-wall network, and then the ideal hexagonal lattice undergoes the first-order radical phase transition in critical magnetic field. We show that during the transition process, a transient collective antiskyrmion excitation mediates lattice inversion process which, in return, results in the reformation of new SkL with opposite polarity.

However, even in the presence of one single magnetic defect, the stability of SkL can be radically affected. We observe a gradual melting of global topological charge in the defective lattice from a very low field, and the phase transition changes from first-order to second-order.

Our findings reveal the possibility for a collective antiskyrmion-mediated phase transition mode in skyrmion lattice textures. We also shed light on the importance of managing imperfections/defects in materials in order to enable enhanced functionalities like future skyrmion-based storage or nanocomputing devices.

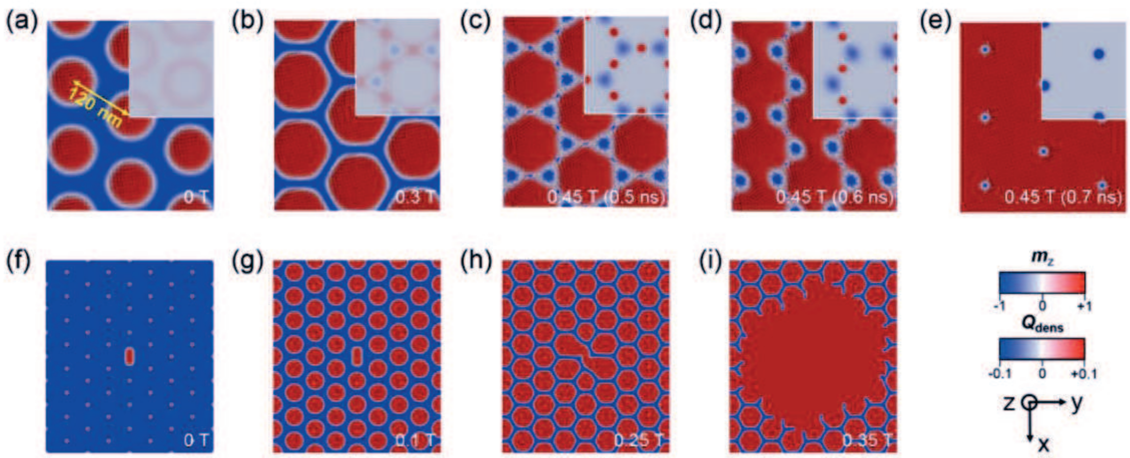

Figure 1: (a-e) Field-induced first-order phase transition with lattice inversion in ideal SkL, and transient antiskyrmions phase is mediated during the process. **Topological charge density** is illustrated in the top-right corner. (f-i) Field-induced second-order phase transition with lattice gradually melting.

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A Neural Networks method based on Preisach model for hysteresis inverse problem

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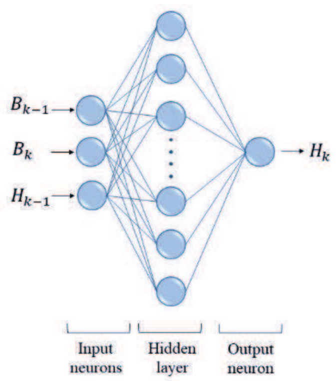
The issue of developing hysteresis models able to identify magnetic materials from experimental data has stressed the need of appropriate tools able to make the model embeddable in simulation algorithms. This latest aspect shows the necessity of avoiding computationally demanding solutions. The problem is often addressed to in a twofold manner: the model has to be suitable to provide both a direct form of the problem, i.e. to compute the flux density field, B, given H, and the opposite, that is the inverse problem. Above all, the latter kind of model is important when finite element formulation is used, starting from a magnetic vector potential description of the problem. Unfortunately, most of hysteresis model are formulated in direct form.
A Neural Networks (NNs) based approach allows addressing an inverse modelling of hysteresis with low computational costs. In this work, a feed forward NN, trained by using the Levenberg Marquardt Backpropagation algorithm, is set up to address the magnetic modelling problem. All the steps (generation of the training set, choice of the hidden layer characteristic, etc) for the developing a neural system are described. The final NN architecture is composed by three inputs neurons, representing the flux density field, ***B***, at steps *(k-1)* and *k*, and the value of the magnetic field, ***H,*** at step *(k-1)*. The hidden layer consists of 15 neurons. The output neuron returns the *k*-th value of ***H***, as shown in fig. 1. The training set is made up by using asymmetric loops, generated by using the Preisach model in Matlab environment. The loops are split into two groups, ascending and descending: the first one includes loops that share a portion of the descending branch of the major-saturated-loop, and a unique ascending path of the non-symmetric loops. The second comprises loops that share a portion of the ascending branch of the major-saturated-loop, and a unique descending path of the non-symmetric loop. The three co-ordinates [B(k-1), B(k), H(k-1)] of each *k*-th sampled point constitutes the input of the NN, while the corresponding output is the H(k) value. Thus, by the knowledge of flux density and of *(k-1)*-th value of the magnetic field, it is possible to estimate the *k*-th value of H, this constitutes the *inverse problem*.
Validation sets are derived from the Preisach static model that provides the experimental loops. The trained NN is used to predict the hysteretic path by applying an oscillating waveform of the flux density field as input; the results in Fig. 1 highlight the capabilities of the NN in fitting experimental data. In addition, the computational cost during execution of this kind of model is very low, being less than a third of the computational cost of a traditional direct approach.



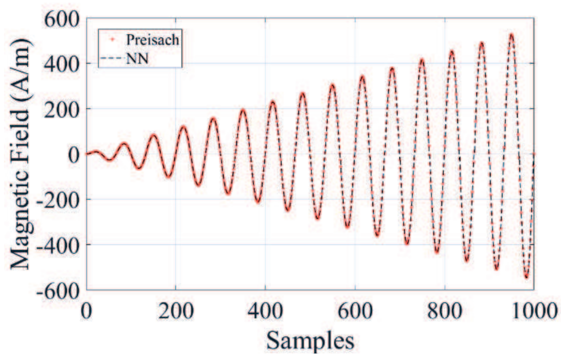


Figure 1. From left to right: the implemented NN architecture predicting the magnetic field H and the static waveform of the magnetic field predicted by NN vs Preisach model.

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Parallel Neural Networks system for dynamic magnetic hysteresis modelling

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A Neural Network (NN) based approach exploiting the properties of *Singular Value Decomposition* (SVD) technique for modelling dynamic hysteresis is presented. The development of static and dynamic hysteresis model is one of the most challenging topics in the field of computational magnetism for two reasons. On one side, it is important to develop a model able to represent the behaviour of different materials and able to be identified by means of a set of measurements, regardless of the amount of computations required in the implementation. On the other hand, the model must be embeddable in simulation codes and, hence, its computational costs should be reduced as much as possible. In such cases, the implementation of a NN represents a reasonable alternative to the use of classic models such as the Preisach or Jiles-Atherton one [1]. The aim of this paper is to present a Neural Network based System able to provide the dynamic constitutive laws, preserving the low computational cost for neural networks training. This task is achieved by exploiting the Singular Value Decomposition, a technique that can be used to decompose a complex MISO (Multiple Input Single Output) problem in several simpler SISO (Single Input Single Output) problems. As far as the problem of hysteresis modelling is concerned, a 3D array coming from the sampling of the differential magnetic permeability μ for different values of the flux density, B, the magnetic field H and frequency f is considered. Such values are collected into an array to which we refer as $\mu \in R^{m\times n\times r}$, where m is the length of B vector, n of H vector and r is the number of frequency samples, $f(x_{1,i}, x_{2,j}, x_{3,h}) = \mu(H_i, B_j, f_h)$. By applying recursively SVD, presented in [2], the magnetic permeability assumes the following reduced form:

$$\mu(B_i, H_j, f_h) = \sum_{s=1}^{\hat{p}} \sigma_s(f_s) \left[\sum_{t=1}^{p_s^{\psi}} \sigma_{s,t}^{\psi}\, \varphi_{s,t}^{\psi}(B_i) \lambda_{s,t}^{\psi}(f_h)\right] \left[\sum_{t=1}^{p_s^{\eta}} \sigma_{s,t}^{\eta}\, \varphi_{s,t}^{\eta}(H_j) \lambda_{s,t}^{\eta}(f_h)\right] \quad (1)$$

Where each of the unknown univariate functions can be approximated through a feed-forward SISO NN, as shown in Fig 1. The main advantage of this method consists in the possibility of speeding up the NN learning process, preserving the accuracy of the solution.

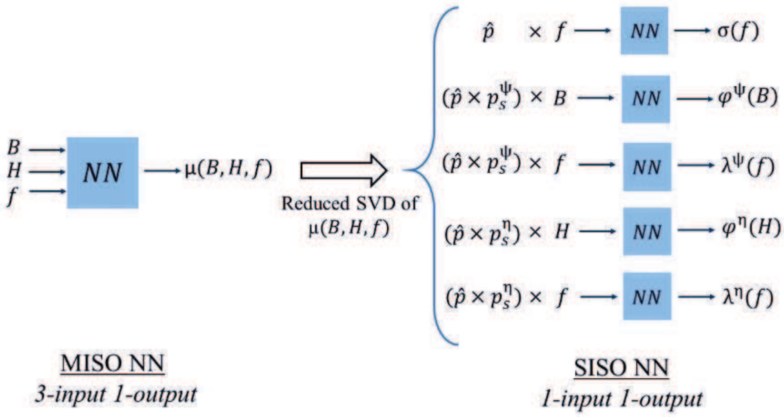

Figure 1. Transformation of a MISO NN into SISO NNs. In the specific case of 3-input 1-output NN, the total number of SISO NNs is $[2(\hat{p} \times p_s^{\psi}) + 2(\hat{p} \times p_s^{\eta}) + \hat{p}]$.

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First principles study of structural and magnetic properties in $Fe_{100-x}Ge_x$ alloys

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Fe-based alloys are interesting due to their unusual mechanical, magnetic and electrical properties which significantly depend on the chemical and structural ordering [1, 2]. Binary phase diagram of Fe-Ge alloys is not so investigated such as phase diagrams for Fe-(Ga, Si, Al) alloys, especially in the low-temperature range.

This work presents the results of structural and magnetic properties of $Fe_{100-x}Ge_x$ (x= 9.375 - 25 at.%) with the different structures A2, B2, $D0_3$, $L1_2$, and $D0_{19}$ from first principles. The geometric optimization of crystal structures was done by VASP package [3] within the generalized gradient approximation in the Perdew, Burke, and Ernzerhof form [4]. With an account of supercell approach the A2 ($Im\bar{3}m$), B2 ($Pm\bar{3}m$), $D0_3$ ($Fm\bar{3}m$), $L1_2$ ($Pm\bar{3}m$), and $D0_{19}$ ($P6_3/mmc$) were modeling. Using the SPR-KKR package [5] the magnetic exchange coupling constants and Curie temperatures were obtained for $Fe_{100-x}Ge_x$ with the different structures. Curie temperature was calculated by mean field approximation (MFA) [6]. Figure 1(a) shows the calculated energy difference of A2, $D0_3$, B2, $L1_2$, and $D0_{19}$ structures with respect to the minimal energy (E_{min}) of a favorable phase ($D0_3$ phase in our case) as a function of Ge concentration for $Fe_{100-x}Ge_x$ alloys. The obtained phase diagram is a qualitative agreement with experimental one [1, 2, 7]. Figure 2 1(b) presents the calculated Curie temperature as a function of Ge concentration for $Fe_{100-x}Ge_x$ alloys with A2, $D0_3$, B2, $L1_2$, and $D0_{19}$ structures. In general, values estimated with MFA are larger than experimental Curie temperatures for considered structures, i.e. for $D0_3$ $T_C^{MFA} = 1100$ K and the $T_C^{exp} = 994$ K [1].

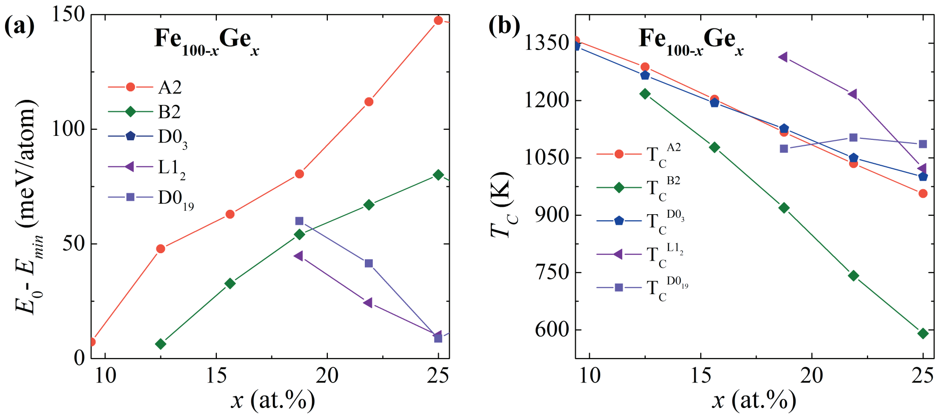

Figure 1: (a) The calculated energy difference between the ground state energy (E_0) and the minimal energy (E_{min}) of a favorable phase ($D0_3$) and (b) the calculated Curie temperature as a function of Ge concentration for $Fe_{100-x}Ge_x$ alloys with A2, $D0_3$, B2, $L1_2$, and $D0_{19}$ structures.

This work is supported by Russian Science Foundation Grant No. 18-12-00283.

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Verification of self-similar model of hysteresis loop

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Hysteresis loops provide crucial information about magnetization processes, characteristic parameters and energy dissipation in soft magnetic materials. Therefore, the modelling of hysteresis loop is an essential issue for scientists and designers of magnetic circuits. There are many physical or mathematical models of hysteresis loops, including those proposed by Preisach, Stoner-Wohlfarth, Jiles-Atherton, Harrison or Takács. A novel approach to the hysteresis loop description was proposed by Kobayashi *et al.* [1-3], who used scaling laws to analyze minor hysteresis loops. Recently, Sokalski proposed a self-similar model of hysteresis loop [4-5], which could express the hysteresis self-similarity using the generalized homogenous function.

The self-similar model of hysteresis loop is based on an extended hyperbolic tangent function tanH(·), in which the natural logarithm *e* is substituted by four independent, positive coefficients *a*, *b*, *c* and *d*:

$$\mathrm{tanH}(a,b,c,d|x) = \frac{a^{x}-b^{-x}}{c^{x}+d^{-x}}\,. \tag{1}$$

This approach allows one to describe the major hysteresis loop, including the initial magnetization curve as well as upper and lower branches of hysteresis loop, as follows:

$$M_{\mathrm{int}}\left(\frac{H}{h},\epsilon\right) = M_{\mathrm{S}}\cdot\frac{a^{\left(\frac{H}{h}-\epsilon\right)}-b^{-\left(\frac{H}{h}-\epsilon\right)}}{c^{\left(\frac{H}{h}-\epsilon\right)}+d^{-\left(\frac{H}{h}-\epsilon\right)}}\,, \tag{2}$$

$$M_{\mathrm{upp}}\left(\frac{H}{h},\theta\right) = M_{\mathrm{S}}\cdot\frac{a^{\left(\frac{H}{h}+\theta\right)}-b^{-\left(\frac{H}{h}+\theta\right)}}{c^{\left(\frac{H}{h}+\theta\right)}+d^{-\left(\frac{H}{h}+\theta\right)}}\,, \tag{3}$$

$$M_{\mathrm{low}}\left(\frac{H}{h},\epsilon\right) = M_{\mathrm{S}}\cdot\frac{a^{\left(\frac{H}{h}-\theta\right)}-b^{-\left(\frac{H}{h}-\theta\right)}}{c^{\left(\frac{H}{h}-\theta\right)}+d^{-\left(\frac{H}{h}-\theta\right)}}\,, \tag{4}$$

where: M_{S} is saturation magnetization, H is magnetic field strength, h is a field normalization coefficient, ϵ is a model parameter of the order $\theta/2$ and θ is a parameter depending on $(H/h)_{\mathrm{max}}$. The equations (2)-(4) can describe minor hysteresis loops after their conversion using a so-called gauge transformation.

The self-similar hysteresis model was tested only in numerical simulations for *a priori* chosen values of above-mentioned coefficients. Therefore, its usefulness in the modelling of hysteresis loop of real soft magnetic materials has not been confirmed. In the full paper, the self-similar model will be verified using measured hysteresis loops of commercial magnetic materials, such as electrical laminations or amorphous and nanocrystalline alloys.

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Asymmetric power-law model for compensating rate-dependent hysteresis in piezoresistive strain sensors

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Strain sensors are increasingly employed in emerging areas such as wearable electronics and soft robotics, for their simple transduction mechanism and low cost. Piezoresistive sensor technology [1] is a common method for creating textile-based strain sensors. Usually, piezoresistive strain sensors exploit the electrical resistance change due to an applied mechanical stretching, but they present remarkable electro-mechanical hysteresis and relaxation dynamics. This is known as a major drawback of resistance-type sensors, which can limit severely the applicability of these materials as sensors. Several methods have been proposed to reduce the impacts of these factors [2], but compensation through mathematical modeling is unavoidable to improve the stretch sensing accuracy. In [3] a novel model, referred to as asymmetric power-law (APL) model, has been proposed for the compensation of the main distortions intrinsic to these soft sensors. The model capabilities have been tested on experimental data measured on Electrolycra [4]. The APL model is able to compensate for the typical nonlinear behaviors of Electrolycra: (1) the relationship between strain and resistance is hysteretic, and the hysteresis loop is traveled clockwise; (2) the hysteresis loop rotates counterclockwise around its lower-left corner as the strain rate increases; (3) in the presence of a constant strain, the resistance slowly drifts (relaxing dynamics); (4) the relaxation is negligible for up-down strain steps. These behaviors are shown in Fig. 1, where ξ denotes the normalized strain, whereas ψ is the normalized resistance. The APL model is a variant of the power-law (PL) model [5], which is suitable for compensating hysteresis and creep in piezoelectric actuators (PEAs), i.e., devices which undergo a deformation in response to an applied voltage. The main PEA characteristics, correctly reproduced by the PL model, are: (a) the relationship between deformation and voltage is hysteretic, and the hysteresis loop is traveled counterclockwise;(b) the hysteresis loop rotates counterclockwise around its center as the voltage rate increases; (c) in the presence of a constant voltage, the deformation slowly drifts (creep); (d) the relaxation is not negligible for up-down voltage steps. In this work, all the modifications applied to the PL model in order to make it suitable to reproduce the Electrolycra features (1), (2), (4) (which are qualitatively different from the corresponding PEA features (a), (b), (d)) are detailed and discussed.

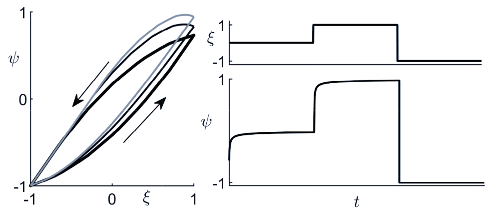

Figure 1: Left: hysteresis loops ψ vs ξ (darker colors mean higher input rate). Right: model input (top) and output (bottom).

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Magnetic states and dynamics of bistable square Fe nanoislands

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Square iron nanoislands have been recently proposed as macrospin-like elements out of which systems following the dipolar four-state Potts model can be built [1]. These can be used as a tunable magnetic metamaterials, extending the typically used in spin-ices, two-state macrospins [2]. This behavior has been obtained for 300nm elements at low enough thicknesses for which the “single domain” (“leaf”-like) spin configurations are the lowest energy ones [1]. Micromagnetic simulations using the mumax3 package show that for thicknesses above 2.5nm vortex configurations become the lowest energy states. For the thickness range 1.5-2.5nm “leaf”, vortex and “C” state configurations have comparable energies and can be all stabilized as the energy barriers between them are larger than the energy differences. Therefore in ordered arrays of such elements different states could be simultaneously present depending on the local interactions, the previous history and the “basin of attraction” of each configuration. In view of their use as tunable magnonic metamaterials the high frequency response of each configuration is micromagnetically simulated. The resonance frequencies for each state in single elements as well as for arrays, and the modes that correspond to each resonance, are extracted following the methods, excitation signal and Fourier analysis considerations described in reference [3].

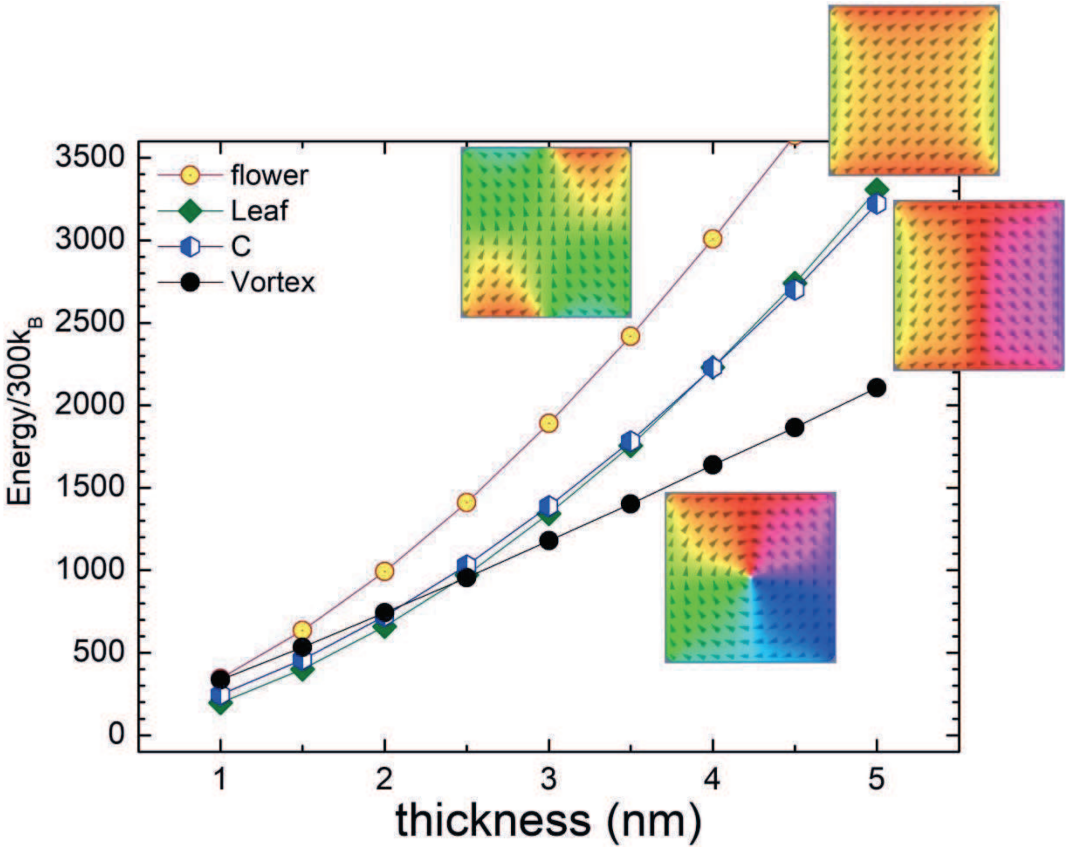

Figure 1: Energy of different magnetic states of 300nm square Fe islands as a function of island thickness.

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Structural, magnetic and electronic properties of $FeRh_{1-x}Pd_x$ compounds: ab initio study

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Fe-Rh-based alloys have attracted a lot of attention because of their possible application in magnetic cooling, thermally assisted magnetic recording and spintronic devices [1-3]. Fe-Rh alloys exhibit a metamagnetic phase transition (AFM-FM). The metamagnetic phase transition in Fe-Rh succeeds also the large change in magnetization, which is responsible for a giant magnetocaloric effect upon variation of a magnetic field.

It well known, that the magnetic order in FeRh compounds depends strongly on the concentration. In this work, we present theoretical investigations of the structural and magnetic properties $FeRh_{1-x}Pd_x$ (x = 0.5, 0.625, 0.75, 0,875, 1) alloys.

The structural and magnetic properties of Pd-doped Fe-Rh alloys are investigated by using the density functional theory calculations as implemented in the VASP package. The ab initio calculations have been carried out by using the 16-atom supercell approach with different initial spin configurations. The energy calculations were performed for the supercell ($FeRh_{1-x}Pd_x$). Calculations were carried out for ferromagnetic, paramagnetic and three kinds of antiferromagnetic states as functions of the lattice parameter. The equilibrium lattice parameters a = 3.012 for $FeRh_{1-x}Pd_x$ (x = 0.5) up to 3.05 for $FeRh_{1-x}Pd_x$ (x = 1). It can be concluded that the addition of Pd atoms leads to an increase in the lattice equilibrium parameter due to the larger atomic radius of Pd compared to the lower Rh value.

The calculation of the total energy for the tetragonal distortion of the cubic structure along the z axis is performed also. To accomplish this, we fixed the volume of a supercell as $V_0 = a_0^3 \approx a^2c$. In this case, the zero value of ΔE corresponds to the austenitic phase for each compound. Our calculations have shown that the substitution of Pd for Rh results in an appearance of stable body-centered tetragonal state. We also calculated the lattice constants, volume cell, partial and total magnetic moments.

This work was supported by RSF-Russian Science Foundation No. 17-72-20022.

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Computational studies of the nonlinear dynamics of magnetic skyrmions

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We present our open-source Python module *Commics* (COmputational MicroMagnetICS) [1] for the study of the magnetization dynamics in ferromagnetic materials via micromagnetic simulations. It implements state-of-the-art unconditionally convergent finite element methods for the numerical integration of the Landau–Lifshitz–Gilbert equation. The implementation is based on the multiphysics finite element software *Netgen/NGSolve* [2]. The simulation scripts are written in Python, which leads to very readable code and allows for extensive postprocessing. The code is freely available on GitLab [3] together with documentation and example scripts.

In order to illustrate the usage of the software, in this work we numerically investigate the stability and field-induced dynamics of magnetic skyrmions in helimagnetic nanostructures [4]; see Figures 1–2. The motivation of this study is to understand how large the non-equilibrium dynamics is and to lay the foundation to use a combination of electrical measurements and time-resolved scanning Kerr microscopy (TRSKM) to map and directly observe the dynamics of magnetic skyrmions.

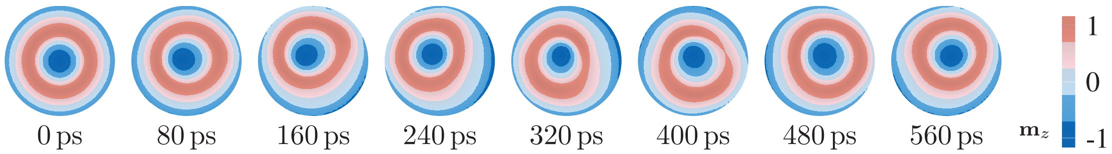

Figure 1: Snapshots of the skyrmion dynamics from a recent experiment in [1]: Magnetization in the xy-plane viewed from the top of a helimagnetic nanodisk at different times. Starting from the relaxed configuration at $t = 0\,\mathrm{ps}$, the skyrmion is deflected from the center of the disk by a current pulse. Then, the skyrmion oscillates around the center of the disk with an observed period of approximately $400\,\mathrm{ps}$. Due to damping, over the relaxation period of $20\,\mathrm{ns}$ the amplitude of the oscillations decreases to almost zero, and the initial equilibrium configuration is restored.

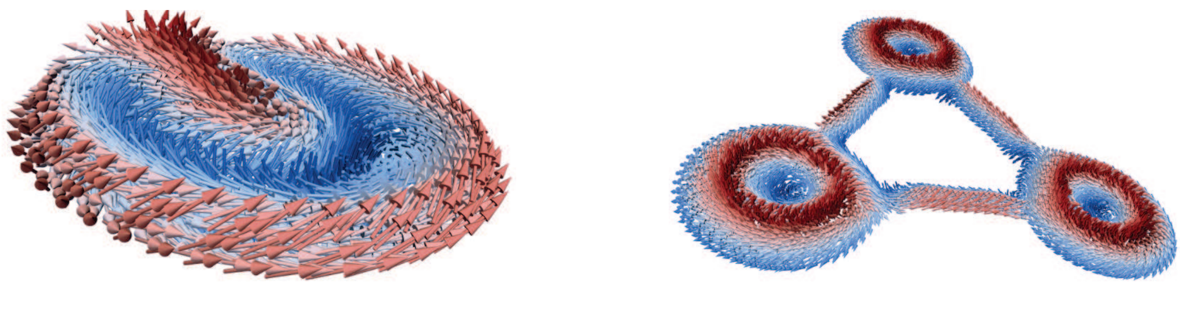

Figure 2: Left: So-called *horseshoe* state in nanodisk; Right: Triangle setting of nanodisks.

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Magnetic properties of Fe/Au barcode nanowire arrays and NdFeCoB nanoparticles studied by the FORC diagram method and micromagnetic simulations

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Barcode nanowires (BNWs) were first synthesized in 2001 [1] and already have been proven as the point of interest in nanomaterials science due to unique combination of 1D and 3D structural and magnetic properties and their promising potential applications [2-4]. The NdFeCoB nanoparticles (NPs) are novel object with improved functionality compared with widely used NdFeB systems.

BNWs were embedded into porous anodized aluminum oxide (AAO) membranes by pulsed electrodeposition [5] in the single bath by alternating the current densities. The length of the different segments was controlled by duration of the pulse. The BNWs were 200 nm in diameter and 110 nm long Fe and Au segments were alternately deposited. The microstructures and compositions of barcode nanowires were studied by XRD, SEM, and TEM. The Au and Fe segments had face-centered-cubic (*fcc*) and body-centered-cubic (*bcc*) polycrystalline structures, respectively. The NdFeCoB NPs with different amounts of cobalt were synthesized by sol-gel/reduction-diffusion process.

Magnetic properties of BNWs and NdFeCoB NPs were investigated by vibrating sample magnetometer (LakeShore VSM 7410). To determine the non-trivial magnetic behavior of magnetic nanowires arrays First Order Reversal Curves (FORC) method have been used. The FORC method represents measurements of several minor hysteresis loops, beginning at various starting fields H_r and going to positive saturation. FORC-distribution is made of hysterons with individual values of H_r and H and can be calculated with a second order mixed derivative of magnetization M in respect to applied field H: $\rho(H,H_r)=-1/2\ \partial 2M/(\partial H\ \partial H_r)$.

This method does not show the information about reversible processes that makes it perfect for studying the irreversible mechanisms of magnetization, such as individual Barkhausen jumps. Resulting datasets were processed with FORCinel software to provide the complete image of FORC-distribution as shown in Fig. 1.

To investigate further into the meaning of FORC diagrams, micromagnetic simulation was performed, using MuMax3 and OOMMF packages. As a result, evolution of magnetic properties based on structural properties was described, values of interaction fields and coercive force has been determined, mechanisms of magnetization had been studied using simulation.

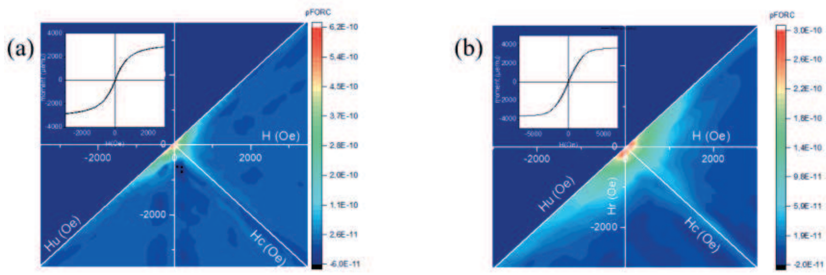

Figure 1: FORC diagrams for a) $Fe_{100}\ Au_{100}$ b) $Fe_{200}\ Au_{100}$ nanowire arrays, field applied perpendicular to the main axis of nanowires.

This work has been supported by the Russian Science Foundation (project № 19-72-20071). Korean partners thank the National Research Foundation of Korea (2014M3A7B4052193).

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Preisach and Steinmetz analyses of asymmetric hysteresis curves measured by lock-in amplifier

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This paper presents minor hysteresis loops on Ni-Zn ferrite toroid measured by using a lock-in amplifier and its analysis based on the Preisach model and the Steinmetz law.

The measurement of linear (χ_0) and nonlinear ($\chi_n : n > 0$) susceptibilities have been recognized an effective method of studying magnetic response at temperatures near the Curie point T_C [1]. The most common method of measuring χ_n makes use of a mutual inductance bridge. A magnetic sample is placed in a core of a transformer whose secondary coil is a first-order gradiometer. The χ_0 and χ_n are measured by detecting $n\omega$ components of an induced voltage using a lock-in amplifier (LIA). Many experimental results of χ_n at temperatures near T_C have shown that magnetic loss and nonlinearity of magnetization significantly increase in the critical region below T_C [2]. These imply a magnetization curve has a complicated hysteretic behavior even in very low field. However, the measurement of a BH curve in such a very low field is difficult to be performed by a usual technique.In previous paper, we proposed a new method to measure magnetic hysteresis curves by using an LIA with a harmonic-detection function [3]. The drawback of this method has been not to be able to measure asymmetric hysteresis curve. In this work, we report a measuring method of asymmetric hysteresis curves.

Symmetric curves are measured based on the spectral decomposition of a magnetization and measurement of different harmonics by using an LIA. In a demagnetizing state, when an ac field $h = h_0 \cos \omega t$ is applied, the ac response of induction B can be expressed as $B = h_0[\mu_0 \cos \omega t + \sum(\chi'_{n-1} \cos n\omega t - \chi''_{n-1} \sin n\omega t)]$ where μ_0 is permeability of free space. Differentiating B with respect to t gives an induced voltage in a secondary coil as $V = \sum(V'_{n-1} \cos n\omega t + V''_{n-1} \sin n\omega t)$ where V'_{n-1} and V''_{n-1} are in-phase and out-of-phase components of harmonics of V and satisfy following relations: $\mu_0 + \chi'_0 \propto V''_0$, $\chi'_{n-1} \propto V''_{n-1} (n > 2)$, and $\chi''_{n-1} \propto V'_{n-1} (n > 1)$ The V'_{n-1} and V''_{n-1} are sequentially measured by using a harmonic-detection function of an LIA. To measure asymmetric curves, two DC coils are added to the measurement system shown in figure 1. Figure 2 shows the first-order transition curves of NiZn Ferrite toroid measured at room temperature by this system. The detailed experimental method, results, and analyses will be shown in the full paper.

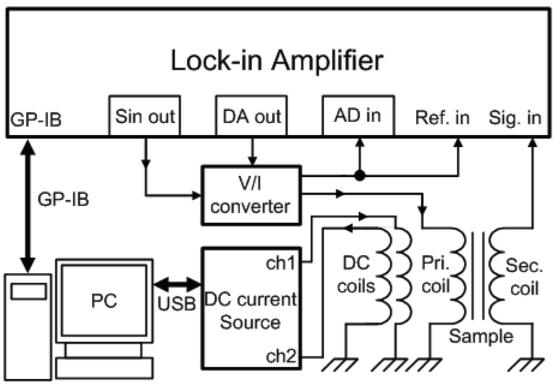

Figure 1: Schematic of hysteresis measurement system

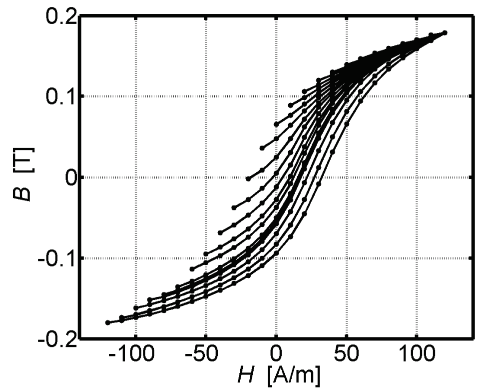

Figure 2: First-order transition curves measured by LIA

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Regression approach for steel characterization based on magnetic hysteresis

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The hysteresis curves of magnetic materials are rich in information with regard to the material microstructure, a fact that yields an indirect access to their mechanical and metallurgical properties. This indirect link is of particular practical importance for non-destructive characterization of industrial materials like steels, since it allows to assess the material state and to retrieve information about its structure or history by means of macroscopic magnetic measurements.

Nevertheless, ab-initio models establishing this indirect link between hysteresis data and material properties are available for a limited number of special cases. To address particle cases, a pragmatic approach relies on the fact that families of materials used in specific applications are nuances of nominal/reference structures, with parameters varying in relatively narrow intervals. Recognizing this reality, one can resort to data-driven approaches for training generic machine-learning models using labeled hysteresis data of specimens as a representative set. The hysteresis curves, which span the input space of the learning algorithms, are obtained by applying parametric models like the Jiles-Atherton model [1], the Mel'gui model [2] or the Preisach model with parametric distribution [3]. Hence, the relation between hysteresis parameters and sought material properties can be learnt from a dataset called training set.

In a previous work, a meta-modelling approach has been proposed for the fast calculation of hysteresis curves, which allows us to establish this relation in a computationally efficient way [4]. In the present contribution, the sparse grid metamodel proposed in [4] is replaced by a kernel method (e.g., kernel ridge regressor, support vector regressor, etc.), and is combined with a dedicated sampling strategy of the solution space manifold (i.e., the B(H) curves space). The use of kernel-based regressor and the thereto-related sampling strategy can virtually provide a sparser training set compared to [4], which turns into a lower amount of physical model evaluation. The developed approach is then used to carry out sensitivity studies of material properties and hysteresis parameters via efficient calculations of Sobol indices [6]. With the sensitivity study at hand, the introduced meta-model can then be used to build regression models in order to estimate material properties of interest from hysteresis measurements.

Results obtained from hysteresis measurements made by the system described in [7] on sets of cold rolled low carbon steel samples isothermally annealed at laboratory at different temperatures with variations in the annealing time [8, 9] will be presented.

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Typical hysterons and interactions in a multiphase flow of a ferrofluid in biological tissues

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The flow of fluids in porous media is accompanied by hysteretic processes due to capillarity which is due to the intermolecular forces at the liquid/solid interface. As the process is observed in many physical systems, the proper description of the hysteretic processes involved in various practical situations is of considerable interest and could percolate interesting ideas between these areas of knowledge. We mention for example here the interest in applications related to the water content of the soil with paramount importance in modern agriculture in the time of climate change or the processes related to hydraulic fracturing and techniques to recover gas or oil from unconventional reservoirs. We also wish to use our experience in the study of hysteretic processes observed in magnetic and ferroelectric materials to develop practical new characterization tools for the hysteretic flow in porous materials.

Our focus in this work is the process of fluid flow in biologic tissues especially when an external fluid is injected with the aim of treatment. We are especially interested in therapies based on injection of magnetic fluids in malignant tissues like in magnetic hyperthermia [1]. In previous studies, ([2] and reference within), we have developed a model able to describe the ferrofluid injection process. In this study we go a step further in the physical analysis of the effect of the porosity of the biological tissue and the hysteretic processes related to that property. As it is of paramount importance to accurately estimate the region in which the therapeutical fluid infiltrate in a biological tissue in order to correctly evaluate the effects, the hysteretic effects seems to be significant for a proper modeling of the entire process.

In this work we start with analyzing the fundamental hysteretic processes in typical porous structures (see the results of a COMSOL modeling for such a structure in the Figure 1). The goal of this study is to have a clearer image of the fundamental hysteretic elements (we can call them hysterons) and to relate them to the geometrical and physical properties of the tissue (see also [3]). In the full presentation we shall show a number of such fundamental structures and their hysterons and how the connection elements (capillary tubes) can be related to the concept of inter-element interactions. This study could provide a very general tool of characterization of the biological tissues from the point of view of porosity and their hysteretic behavior. The accurate identification of the hysteresis loops of the component hysterons could provide a technique to find the distribution of the geometrical characteristics of the pores in the tissues. This technique (similar to the first-order reversal curve technique in magnetism [4]) could become a quantitative tool as it was proven possible in the hysteresis of arrays of magnetic wires [5-7].

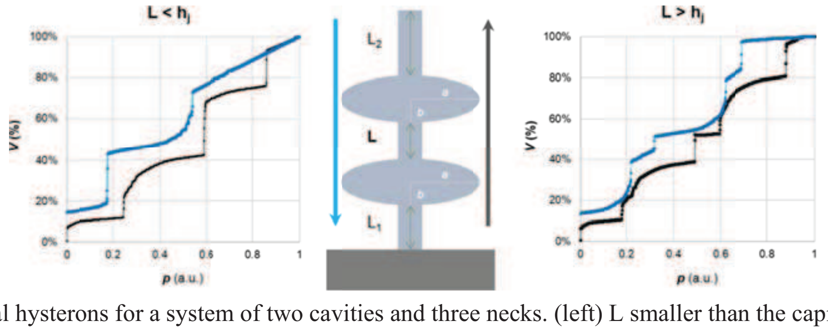

Figure 1: Typical hysterons for a system of two cavities and three necks. (left) L smaller than the capillary rise height (h_j); (right) L>h_j where h_j is the capillary rise of the fluid in the tube

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The use of quasi-static loops of magnetic hysteresis in prediction losses in non-oriented electrotechnical sheets

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The paper presents the possibilities of using a parametric equation to describe a quasi-static loops of magnetic hysteresis. Then, using the Poynting theorem, it is possible to obtain a theoretical expression for hysteresis losses. Knowledge of the share of these losses in total losses is significant when applying the Jordan model and the Bertotti model to their prediction. The currently used hysteresis loss prediction method is based on extrapolating the dependence of total losses on the zero-going frequency. The method of determining hysteresis losses proposed in the presented work and its inclusion in the total loss prediction based on the above models allows to reduce the error of their prediction for non-oriented electrotechnical sheets.

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Micromagnetic modelling of reversal nucleation generated by magnetic nanoparticles on spintronic sensors

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Chip based manipulation and detection systems using spintronic structures and magnetic nanoparticles (MNPs) demonstrated versatility and high sensitivity. We present, in this contribution, a micromagnetic analysis of the magnetization processes in exchange biased microstructures which interact with MNPs placed in the vicinity of their surface. The structures are of the type Permalloy/NM(x)/AFM where AFM denotes antiferromagnetic layer whereas NM denotes nonmagnetic layer. Basically, two magnetic fields are used in our study: (i) a magnetic field perpendicular to the sensor surface, H_{bias}, that magnetizes the MNPs and (ii) a magnetic field, applied in the film plane, H_{appl} that controls the sensor's behaviour. Because these structures are less sensitive to perpendicular fields no higher than hundreds of Oe, the in plane components of the field generated by the MNPs will induce the main changes of the magnetisation state in the sensing layer (Permalloy). Two field scanning methods will be studied when MNPs are placed over the sensor's surface: (i) H_{bias} will be swept between ±500 Oe for constant values of H_{appl} and (ii) H_{appl} varies between ±150 Oe for constant values of the biasing field. A Planar Hall Effect (PHE) setup is used for detection of MNPs. In this study special attention is given for structures where the Permalloy layer is weak coupled with the AFM layer. For such structures the magnetization reversal is mainly dominated by domain walls movement which can be controlled by a field applied in the film plane [1]. We observed that particular magnetization states, e.g., close to coercive field, can provide convenient method to detect very small variations of an external field applied perpendicular to the film plane. This is reflected by the simulated and measured field dependence of the sensor signal, Figure 1. Such behaviour can be used, for example, to build a static switch with two stable outputs or for detection of magnetic nanoparticles placed over the sensor surface [2].

The micromagnetic simulations presented in this study will be compared with experimental data and provides useful information for the future development of novel spintronic sensors.

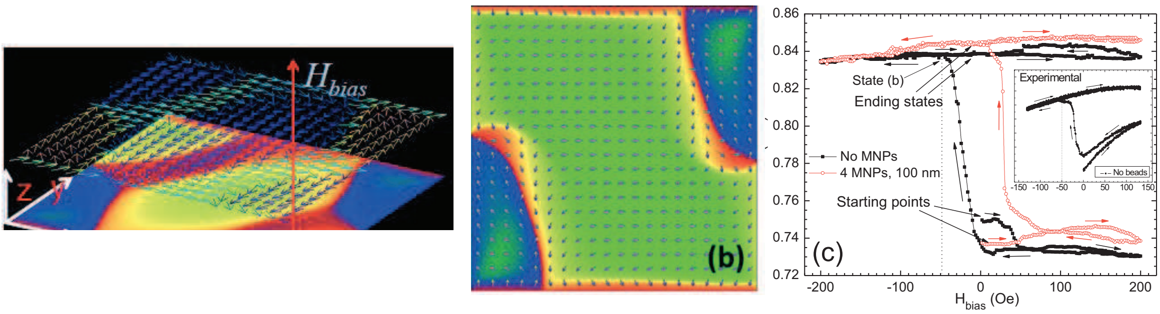

Figure 1: Micromagnetic simulations showing: (a) the spin configuration when H_{bias}=0 and (b) H_{bias}=-50 Oe; this state is marked in Fig. 1(c). The calculated and measured response of the PHE structure is presented in (c). H_{bias} is perpendicular to the film plane; initially the structure was polarized near the coercive field. The inset shows the signal measured on a Permalloy based PHE sensor used to detect magnetic nanoparticles, as described in [2]. The presented sensor signal was measured without magnetic nanoparticles. The simulated structure is a Permalloy square 2 µm wide and 10 nm thick; the cell size is 5x5x5 nm^3. An exchange biasing field of 20 Oe was considered. The presence of 4 MNPs, assimilated like cubes with 100 nm each side produces a shift of the switching curve (red) shown in (c).

Acknowledgements: *This work was supported by a grant of the Romanian Ministry of Research and Innovation, CCDI-UEFISCDI project number 3PCCDI/2018, within PNCDI III.*

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Phenomenological modeling of thermal hysteresis in $Ni_{2.18}Mn_{0.82}Ga$ Heusler alloys in magnetic field

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The ferromagnetic shape memory alloys (FSMA) exhibit a number of important mechanical and magnetic properties. These properties are related with coupled magnetostructural phase transition from the high temperature phase to the low-temperature phase in FM state under cooling [1]. Evidently, due to the nature of the first-order transition, the coupled magnetostructural transformation is accompanied by a thermal hysteresis. Besides, the hysteresis width depends on the intrinsic contributions (linked to the electronic structure, magnetism, chemical order, etc.) and extrinsic influence (related to microstructure) [1]. In the present study, we focus on the magnetic field effects on the structural phase transformation and hysteresis width in $Ni_{2.18}Mn_{0.82}Ga$ alloy (one of the best representatives of the FSMA alloy) with the magnetostructural transition in the framework of Landau theory of phase transitions. We used the expression for the Landau functional of cubic ferromagnet in the case of the absence of the crystal lattice modulation from works [2]:

$$F = \frac{1}{2}ae^2 + \frac{1}{3}be^3 + \frac{1}{4}ce^4 + \frac{1}{2}\alpha m^2 + \frac{1}{4}\delta m^4 + \frac{1}{2}B_0 e^2 m^2 + \frac{1}{2}Eem^2 - M_0 H m, \qquad (1)$$

where $e = (2e_{zz} - e_{yy} - e_{xx})/\sqrt{6}$ is the tetragonal deformations, $m = M/M_0$ is the normalized magnetization, a, b, and c are 2^{nd}-, 3^{rd}-, and 4^{th}-order elastic moduli, α, δ are the exchange parameters, E, B_0 are the anisotropic and volume magnetoelastic constants; H is the external magnetic field, and M_0 is the saturation magnetization. The parameters a, and α depends linearly on temperature and concentration as follows: $a = a_0 (T - T_m(x))$, $\alpha = \alpha_0 (T - T_C(x))$ [1, 2].

The phase diagram in coordinates $(T - H)$ obtained with numerical calculations is shown in Fig. 1(a). It is shown on this phase diagram, that the first-order phase transition from FM cubic phase to FM tetragonal phase has a finite point (T_{cr}, H_{cr}), corresponding to the critical point. The second-order-like behavior of austenite-martensite transformation without thermal hysteresis can be realized above this point. The temperature dependences of strains at the constant magnetic fields of 5, 10, 20, 25, and 30 T are presented in Fig. 1(b). It is seen that the hysteresis of the structural phase transition vanishes in an external magnetic field with the magnitude of ≈ 25 T.

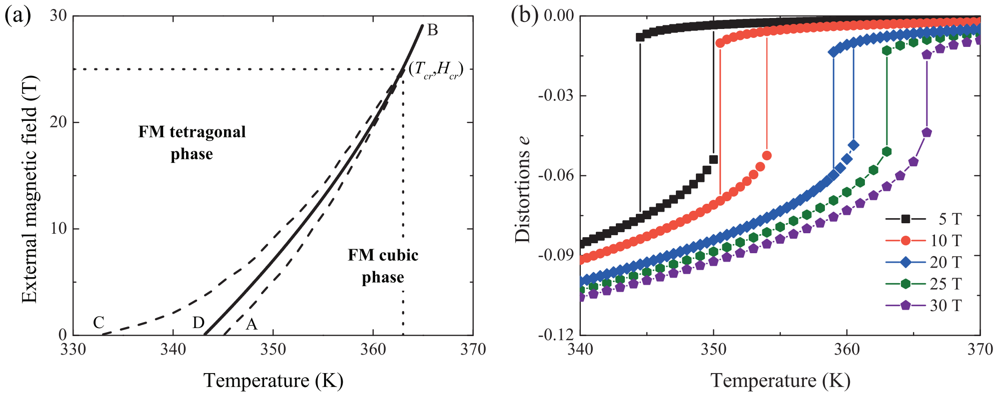

Figure 1: (a) The $(T - H)$ phase diagram for $Ni_{2.18}Mn_{0.82}Ga$, (b) tetragonal distortions e as functions of temperature T at constant external magnetic field of 5, 10, 20, 25, and 30 T.

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Magnetization processes of irregular dendrite structures - a Monte Carlo study

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Magnetic materials are very important in nowadays technologies. New and continuously increasing requirements can be fulfilled by modern nanostructured magnetic composites containing phases characterized by different magnetic properties. Recently, we reported ultra-high coercivity (> 7 T) in Fe-Nb-B-Tb type of bulk nanocrystalline alloys [1]. It was shown that in such materials the interactions between soft and hard magnetic phases with specific irregular branches are especially important and can lead to an appearing of new and unique properties. A better understanding the interactions in such systems is interesting form scientific and application point of view.

In the present work we performed some simulated annealing plus Monte Carlo studies (for method description see [2]) concerning an irregular dendritic branches of soft and hard magnetic phases embedded into none-magnetic or magnetic matrix. Magnetization process of such system depends on exchange interactions of soft and hard magnetic phases and an interface shape between them. The dendritic structure was generated base on so-called diffusion limited aggregation (DLA) algorithm and it is strongly similar to the branches observed in real materials with ultra-high coercivity. Especially interesting is the comparison of interactions in systems with different, regular and irregular geometry as well as different kind of anisotropy and degree of branches extension.

The studies show a significant dependence of magnetization processes (determined by the simulations of magnetic hysteresis loops) on the dendrite development state. The results allows better understanding magnetic properties of materials fabricated by fast cooling in which crystallization of magnetic phase is blocked on the stage of dendritic-like grains.

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