
The International Symposium on Hysteresis Modeling and Micromagnetics (HMM) has been designed as an interdisciplinary international forum for discussion of the most recent advancements in domains of science and technology related to hysteresis modeling and micromagnetics.

HMM Symposium offers an opportunity to the scientists with various backgrounds (physicists, mathematicians, engineers, material scientists, etc) to exchange ideas, experiences and to present their most recent results.

The 10th edition of HMM has a three days scientific program structured in different sessions dedicated to topics of interest for the scientists working in hysteresis and micromagnetics.

The jubilee 10th HMM edition is held in Iasi, Romania, the former capital of the Principality of Moldavia between 1564 and 1859.

Iasi is one of the most important education and research centers in Romania, home to the oldest University and to the first engineering school in the country. The city has many cultural landmarks (Palace of Culture, National Theater, University Palace, Central University Library, about 100 historical churches and monasteries, etc.).

**http://hmm2015.uaic.ro/**

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## Publication Information

If your abstract is accepted for presentation at HMM2015, you may contribute a paper for publication in the special HMM issue of Physica B: Condensed Matter. Manuscript submission will be open on April 2015. The deadline for the submission is May 20, 2015.

The review standards will mirror those used for regular articles to be published in Physica B: Condensed Matter. Note that participation in the symposium does not guarantee that a paper will be accepted for publication. Additionally, at least one of the co-authors must present the paper at the symposium in order to get consideration for publication. Presenters may contribute only one paper for publication. Any additional paper will be charged 60 EUR each.

All manuscripts will be submitted via a web submission system. Instructions for submission and accepted formats for the Journal as well as a link to the web submission page will be available in this section.

All papers being published in the special issue of Physica B: Condensed Matter must be submitted this way. No hard paper manuscripts will be accepted.

The length of papers is 6 (six) printed pages for invited papers and 4 (four) printed pages for regular contributed papers.

## Proceedings. Instructions for submission:

The submission website for this journal is located at:

http://ees.elsevier.com/physb/default.asp

To ensure that all manuscripts are correctly identified for inclusion into the special issue you are editing, it is important that authors select "SI: HMM 2015" when they reach the "Article Type" step in the submission process.

The length of papers is 6 (six) printed pages for invited papers and 4 (four) printed pages for regular contributed papers.

## Local Information

*How to get to Iasi by airplane:*

Iasi airport (http://www.aeroport.ro/index.php/en/plecari/articol/destinations.html)

is situated about 6 km from conference site. There are up to five daily flights from/to Bucharest, operated by Romanian TAROM (a SkyTeam member). TAROM also connects Iasi with Roma, Torino, Bergamo, Tel Aviv, London Luton and Dublin, one to three times a week. Austrian Airlines connect Iasi with Vienna four times a week, while low cost Wizzair Company offer flights to Treviso and London Luton. For information regarding the timetables and prices please visit the official airport website.

From the Iasi airport you can take a taxi; currently they charge around 2 RON/km.

The cost up to the Unirea Hotel should be less than 20 RON (5 Euros).

The organizers can arrange the transportation of conference participants to the hotel with an agreed company.

*By train:*

There are five trains a day from Bucharest to Iasi. The journey takes about seven hours and the prices close 100-200 RON (up to 50 EUR). A link to the official site of "Romanian Railways" is http://www.cfrcalatori.ro/ .

*By car:*

The distance between Bucharest and Iasi is about 400 km (by Express way).

The speed limit outside the city is 90 km/h, and 50 km/h inside.

**Local Transportation:**

Bus, tram, trolley bus and Maxi Taxi

The price of a ticket is 2 RON.

Taxi: Current daytime rate is 1.9 RON/km. Some extra charges may apply for night.

**Weather:**

At the conference time the average temperature is 18°C, with an average minimum of 12°C during the night and an average maximum of 24°C during the day. There is a 35% chance that precipitation will be observed at some point during the day. The sun rises at 6:55 a.m. and sets at 7:15 p.m.

**Time Zone:**

Eastern European Time (Summer: UTC+3).

**Currency:**

The local currency is Romanian Lei (RON). The approximate exchange rate is about 1 EUR = 4.5 RON and 1 USD = 4.0 RON

(you can consult the current exchange rates on: http://www.bnr.ro).

For various transactions and money exchange, we recommend you to contact only authorized institutions, such as banks or exchange offices. Opening hours for Banks: Monday to Friday, 9:00 a.m. to 5:30 p.m., closed on Sundays. VISA and Travelers Checks are accepted at most banks. Cash-dispensing ATMs accept Visa, MasterCard and plenty of other plastic. Credit cards are accepted in most of hotels, restaurants and supermarkets.

**Electricity:**

Electricity is supplied at 230 V / 50 Hz. The sockets take the standard continental European dual round-pronged plugs.

**Internet Access:**

During the conference computers with Internet access as well as wireless connection will be available at the Conference Centre.

**Emergency/Medical:**

For emergencies (health or security) call 112.

# Program

## Monday, 18th of May 2015

| | |
|---|---|
| 8:00-9:00 | **Registration** |
| 9:00-9:30 | **Opening ceremony** |
| 9:30-10:20 | Keynote presentation (K1) - **Roy W. Chantrell** |
| 10:20-10:50 | Invited talk (I1) - **Josef Fidler** |
| 10:50-11:10 | Coffee break |
| 11:10-11:40 | Invited talk (I2) - **Thomas Schrefl** |
| 11:40-12:00 | Oral presentation (O1) - **Giovanni Finocchio** |
| 12:00-12:20 | Oral presentation (O2) - **Oscar Iglesias** |
| 12:20-12:40 | Oral presentation (O3) - **Kiwamu Kudo** |
| 12:40-13:00 | Oral presentation (O4) - **Antonio Faba** |
| 13:00-14:30 | Lunch |
| 14:30-15:00 | Invited talk (I3) - **Ermanno Cardelli** |
| 15:00-15:30 | Invited talk (I4) - **Aphrodite Ktena** |
| 15:30-16:00 | Invited talk (I5) - **Leonard Spinu** |
| 16:00-16:20 | Oral presentation (O5) - **Vito Puliafito** |
| 16:20-16:40 | Coffee break |
| 16:40-17:00 | Oral presentation (O6) - **Sebastian Gliga** |
| 17:00-17:20 | Oral presentation (O7) - **Mario Carpentieri** |
| 17:20-17:40 | Oral presentation (O8) - **Marek Frankowski** |
| 17:40-18:00 | Oral presentation (O9) - **Flavio Stellino** |
| 18:00-18:20 | Oral presentation (O10) - **Mykola Dvornik** |
| 18:20-18:40 | Oral presentation (O11) - **Anna Giordano** |
| 18:40-19:00 | Oral presentation (O12) - **Roberto Zivieri** |
| 19:30 | Dinner |

## Tuesday, 19th of May, 2015

| | |
|---|---|
| 9:00-9:50 | Keynote presentation (K2) - **Pavel Kreijci** |
| 9:50-10:20 | Invited talk (I6) - **Martin Brokate** |
| 10:20-10:50 | Invited talk (I7) - **Olaf Klein** |
| 10:50-11:10 | Coffee break |
| 11:10-11:40 | Invited talk (I8) - **Ulrick Nowak** |
| 11:40-12:00 | Oral presentation (O13) - **Julien Tranchida** |
| 12:00-12:20 | Oral presentation (O14) - **Daniele Davino** |
| 12:20-12:40 | Oral presentation (O15) - **Dimitris Kechrakos** |
| 12:40-13:00 | Oral presentation (O16) - **Michele Ruggeri** |
| 13:00-14:30 | Lunch |
| 14:30-15:00 | Invited talk (I9) - **Gergely Zimanyi** |
| 15:00-15:20 | Oral presentation (O17) - **Randy K. Dumas** |
| 15:20-15:40 | Oral presentation (O18) - **Marek W. Gutowski** |
| 15:40-16:00 | Oral presentation (O19) - **Montserrat Rivas** |
| 16:00-16:20 | Oral presentation (O20) - **Lavinia Curecheriu** |
| 16:20-16:40 | Oral presentation (O21) - **Massimiliano D'Aquino** |
| 16:40-17:00 | Oral presentation (O22) - **Claudio Serpico** |
| 17:00-19:00 | **Poster session** & coffee |
| 20:00 | Gala dinner |

Wednesday, 20th of May, 2015

| | |
|---|---|
| 9:00-9:50 | Keynote presentation (K3) - **Seiji Miyashita** |
| 9:50-10:20 | Invited talk (I10) - **Kamel Boukheddaden** |
| 10:20-10:50 | Invited talk (I11) - **Mihai Dimian** |
| 10:50-11:10 | Coffee break |
| 11:10-11:40 | Invited talk (I12) - **Jorge Linares** |
| 11:40-12:00 | Oral presentation (O23) - **Aurelian Rotaru** |
| 12:00-12:20 | Oral presentation (O24) - **Claudio Serpico** |
| 12:20-12:40 | Oral presentation (O25) - **Giovanni Finocchio** |
| 12:40-13:00 | Oral presentation (O26) - **Benjamin Krüger** |
| 13:00-14:30 | Lunch |
| 14:30-15:00 | Invited talk (I13) - **Virgil Provenzano** |
| 15:00-15:30 | Invited talk (I14) - **Gonzalo Vallejo Fernandez** |
| 15:30-15:50 | Oral presentation (O27) - **Sergiu Ruta** |
| 15:50-16:10 | Oral presentation (O28) - **Frank Buijnsters** |
| 16:10-16:30 | Coffee break |
| 16:30-16:50 | Oral presentation (O29) - **Ciro Visone** |
| 16:50-17:10 | Oral presentation (O30) - **Ilia Dubitsky** |
| 17:10-17:30 | Oral presentation (O31) - **Oliver Laslett** |
| 17:30-17:50 | Oral presentation (O32) - **Katsuhiko Yamaguchi** |
| 17:50-18:10 | Oral presentation (O33) - **Elena Gornostaeva** |
| 18:10 | **Closing ceremony** |

## Monday, 18th of May 2015

| | |
|---|---|
| 8:00-9:00 | **Registration** |
| 9:00-9:30 | **Opening ceremony** |

**Morning session**
**Chairs: Massimiliano D'Aquino, Gergely Zimanyi**

| | |
|---|---|
| 9:30-10:20 (K1) | Multiscale Approaches To Magnetic Materials Simulation<br>**Roy W. Chantrell**,<br>*Physics Department, University of York, York, UK* |
| 10:20-10:50 (I1) | Do Micromagnetic Simulations Correctly Predict Hard Magnetic Hysteresis Properties?<br>**Josef Fidler**,<br>*Vienna University of Technology, Vienna, Austria* |
| 10:50-11:10 | Coffee break |
| 11:10-11:40 (I2) | Finite Element Micromagnetics At Non-Zero Temperature,<br>**Thomas Schrefl**,<br>*Center for Integrated Sensor Systems, Danube University Krems, Austria* |
| 11:40-12:00 (O1) | Skyrmion Racetrack Memory Driven By SHE,<br>**R. Tomasello[1], E. Martinez[2], R. Zivieri[3], L. Torres[2], M. Carpentieri[4], and G. Finocchio[5],**<br>*(1) Dept. of Computer Science, Modelling, Electronics and System Science, University of Calabria, Italy.*<br>*(2) Dept. of Fisica Aplicada, Universidad de Salamanca, Salamanca, Spain.*<br>*(3) Dept. of Physics and Earth Sciences and CNISM Unit of Ferrara, University of Ferrara, Italy.*<br>*(4) Dept. of Electrical and Information Engineering, Politecnico of Bari, Italy.*<br>*(5) Dept. of Electronic Engineering, Industrial Chemistry and Engineering, Univ. of Messina, Italy.* |
| 12:00-12:20 (O2) | Modelling Surface And Interfacial Effects In Magnetic Nanoparticles: From Core/Shell To Hollow Structures,<br>**Oscar Iglesias**,<br>Dept. Física Fonamental and Institut de Nanociència and Nanotecnologia, Univ. de Barcelona, Spain. |
| 12:20-12:40 (O3) | Three-Dimensional Magnetic Memory Cell Controlled By A Spin-Torque Oscillator,<br>**K. Kudo, H. Suto, T. Nagasawa, K. Mizushima, and R. Sato**<br>Corporate Research & Development Center, Toshiba Corporation, Kawasaki, Japan |
| 12:40-13:00 (O4) | A Moving Approach For The Vector Hysteresis Model,<br>**E. Cardelli[1], A. Faba[1], A. Laudani[2], S. Quondam[1], F. Riganti Fulginei[2], and A. Salvini[2]**<br>(1) Department of Engineering, University of Perugia, Italy<br>(2) Department of Engineering, Roma Tre University, Rome, Italy |
| 13:00-14:30 | Lunch |

**Afternoon session**
**Chairs: Oscar Iglesias, Thomas Schrefl**

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|---|---|
| 14:30-15:00 (I3) | Phenomenological Modelling Of Magnetic Materials,<br>**Ermanno Cardelli,**<br>Department of Engineering, University of Perugia, Italy |
| 15:00-15:30 (I4) | Vector Hysteresis Models And Magnetization Under Stress,<br>**Aphrodite Ktena,**<br>Department of Electrical Engineering, Technological Educational Institute of Central Greece, Greece |
| 15:30-16:00 (I5) | Micromagnetic Simulations Of Two-Dimensional And Three Dimensional Magnonic Metamaterials,<br>**Leonard Spinu,**<br>Dept. of Physics and AMRI, University of New Orleans, New Orleans, USA |

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|---|---|
| 16:00-16:20<br>(O5) | Clocking Of Nanomagnetic Logic Driven By Spin-Hall Effect: A Micromagnetic Analysis,<br>**V. Puliafito, A. Giordano, B. Azzerboni, and G. Finocchio,**<br>Dept. of Electronic Eng., Chemistry and Industrial Engineering, University of Messina, Italy. |
| 16:20-16:40 | Coffee break |
| 16:40-17:00<br>(O6) | Tunable Ground State Symmetry Breaking In Artificial Square Spin Ice,<br>**S. Gliga[1,2], A. Kákay[3,4], R. Hertel[5], and O. G. Heinonen[6,7],**<br>(1) Laboratory for Mesoscopic Systems, Department of Materials, ETH Zurich, Switzerland<br>(2) Laboratory for Micro- and Nanotechnology, Paul Scherrer Institute, Villigen, Switzerland<br>(3) Helmholtz-Zentrum Dresden-Rossendorf, Inst. of Ion Beam Physics and Materials Research<br>(4) Peter Grünberg Institute, Forschungszentrum Jülich, Germany<br>(5) IPCMS UMR7504, CNRS and UdS, Strasbourg, France<br>(6) Materials Science Division, Argonne National Laboratory<br>(7) Dept. of Physics and Astronomy, Northwestern University |
| 17:00-17:20<br>(O7) | Topological Skyrmion Dynamics Driven By Spin-Transfer Torque,<br>**M. Carpentieri[1], R. Tomasello[2], G. Finocchio[3] and R. Zivieri[1,4],**<br>(1) Dept. of Electrical and Information Engineering, Politecnico di Bari, Italy.<br>(2) Dept. of Computer Sci. Modelling, Electronics and System Sci., Univ. of Calabria, Rende, Italy.<br>(3) Dept of Electronic Engineering, Industrial Chemistry and Engineering, Univ. of Messina, Italy.<br>(4) Dept. of Physics and Earth Sciences and CNISM Unit of Ferrara, Univ. of Ferrara, Italy. |
| 17:20-17:40<br>(O8) | Micromagnetic Modelling Of Voltage-Induced Spin-Diode Effect In Magnetic Tunnel Junctions,<br>**M. Frankowski, J. Chęciński,**<br>AGH University of Science and Technology, Department of Electronics, Kraków, Poland |
| 17:40-18:00<br>(O9) | Modelling Hysteresis And Creep Through A Nonlinear Circuit,<br>**A. Oliveri, F. Stellino, M. Parodi, M. Storace,**<br>DITEN, University of Genoa, Italy |
| 18:00-18:20<br>(O10) | Micromagnetic Simulations Beyond Landau-Lifshitz-Gilbert Model,<br>**Mykola Dvornik,**<br>Applied Spintronics Group, University of Gothenburg, Sweden |
| 18:20-18:40<br>(O11) | Dynamical Response Of Spin-Hall Nano-Oscillators As Function Of External Bias Field,<br>**A. Giordano[1], R. Zivieri[2], M. Carpentieri[3], A. Laudani[4], G. Gubbiotti[5], B. Azzerboni[1], and G. Finocchio[1],**<br>(1) Dept. of Electronic Eng., Industrial Chemistry and Engineering. University of Messina, Italy.<br>(2) CNISM Ferrara, University of Ferrrara, Italy,<br>(3) Department of Electrical and Information Engineering, Politecnico of Bari, Italy.<br>(4) Department of Engineering, University of Roma Tre, Roma, Italy.<br>(5) Inst. Officina dei Materiali del CNR, Unità di Perugia c/o Dipartimento di Fisica, Perugia, Italy |
| 18:40-19:00<br>(O12) | Skyrmion Motion Under A Spin-Hall Current In Confined Magnetic Nanostructures,<br>**R. Zivieri[1,3], R. Tomasello[2], M. Carpentieri[3], and G. Finocchio[4],**<br>(1) Dept. of Physics and Earth Sciences and CNISM Unit of Ferrara, Univ. of Ferrara, Italy<br>(2) Dept. of Computer Sci., Modelling, Electronics and System Sci., Univ. of Calabria, Rende, Italy<br>(3) Dept. of Electrical and Information Engineering, Politecnico of Bari, Italy<br>(4) Dept. of Electronic Eng., Industrial Chemistry and Engineering, Univ. of Messina, Italy |
| 19:30 | Dinner |

# Tuesday, 19th of May, 2015

**Morning session**
**Chairs: Ermanno Cardelli, Claudio Serpico**

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|---|---|
| 9:00-9:50 (K2) | Mathematical Problems In Modeling Piezoelectricity And Magnetostriction, **Pavel Kreijci,** Institute of Mathematics, Czech Academy of Sciences, Prague, Czech Republic |
| 9:50-10:20 (I6) | Differentiability Properties Of Scalar Hysteresis Models, **Martin Brokate,** Zentrum Mathematik/M6, TU Muenchen, Garching bei Muenchen, Germany |
| 10:20-10:50 (I7) | A Representation Result For Rate-Independent Systems, **Olaf Klein,** Weierstrass Institute for Applied Analysis and Stochastics (WIAS), Berlin, Germany |
| 10:50-11:10 | Coffee break |
| 11:10-11:40 (I8) | Thermally Induced Switching In Synthetic Ferrimagnets, **S. Sievering, S. Wienholdt, D. Hinzke, U. Nowak,** Department of Physics, University of Konstanz, Germany |
| 11:40-12:00 (O13) | Differentiation Formula For The Stochastic Magnetization Dynamics In Ferrimagnets, **J. Tranchida[1,2], P. Thibaudeau[1], and S. Nicolis[2],** (1) CEA\Le Ripault, DAM, BP 16, 37260 Monts, France (2) CNRS-Lab. de Mathématiques et Physique Théorique, Univ. François Rabelais, Tours, France |
| 12:00-12:20 (O14) | 2-Inputs 2-Outputs Relationships Of Smart Materials: An Experimental Evaluation, **C.S. Clemente[1], D. Davino[1], J. Kopfová[2], P. Krejčí[3], and C. Visone[1],** (1) University of Sannio, Italy (2) Silesian University of Opava, Czech Republic (3) Institute of Mathematics, Academy of Sciences of the Czech Republic, Praha, Czech Republic |
| 12:20-12:40 (O15) | Shape-Dependent Exchange Bias Effect In Magnetic Nanoparticles With Core/Shell Morphology, **D.Kechrakos[1], V.A.Dimitriadis[1], O.Chubykalo-Fesenko[2], and V.Tsiantos[3],** (1) School of Pedagogical and Technological Education (ASPETE), Greece (2) Instituto de Ciencia de Materiales de Madrid, CSIC, Spain (3) Dept. of Electrical Engineering, East Macedonia and Thrace Institute of Technology, Greece |
| 12:40-13:00 (O16) | Self-Consistent Computation Of Magnetization Dynamics In The Presence Of Spin-Polarized Currents, **C. Abert[1], G. Hrkac[2], D. Praetorius[3], M. Ruggeri[3], and D. Suess[1],** (1) Christian Doppler Laboratory of Advanced Magnetic Sensing and Materials, Institute of Solid State Physics, Vienna University of Technology, Austria. (2) College of Engineering, Mathematics and Physical Sciences, University of Exeter, UK (3) Institute for Analysis and Scientific Computing, Vienna University of Technology, Austria |
| 13:00-14:30 | Lunch |

**Afternoon session**
**Chairs: Aphrodite Ktena, Leonard Spinu**

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|---|---|
| 14:30-15:00 (I9) | Controlled Limits Of The FORC Theory: Mean Field, Nucleation, **Gergely Zimanyi,** University of California Davis, USA |
| 15:00-15:20 (O17) | Accessing Different Spin-Disordered States Using First-Order Reversal Curves, **R. K. Dumas[1,2], P. K. Greene[1], D. A. Gilbert[1], L. Ye[1], C. Zha[3], J. Åkerman[2,3], and K. Liu[1],** (1) Department of Physics, University of California, Davis, USA (2) Department of Physics, University of Gothenburg, Gothenburg, Sweden (3) Materials Physics, School of ICT, Royal Institute of Technology (KTH), Kista, Sweden |

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| 15:20-15:40 (O18) | Better FORC Diagrams,<br>**Marek W. Gutowski,**<br>Institute of Physics, Polish Academy of Sciences, Warsaw, Poland |
| 15:40-16:00 (O19) | Thermal Decoupling Of Dense-Packed Nanocrystalline Ribbons: Direct Evidence By FORC Technique,<br>**M. Rivas, J. C. Martínez-García, and P. Gorría,**<br>Departamento de Física & IUTA, Universidad de Oviedo, Campus de Viesques, Gijón, Spain |
| 16:00-16:20 (O20) | Using FORC Method For Detection Magnetic Components In $Fe_2O_3$@$BaTiO_3$ Composites With Core-Shell Structure,<br>**L.P. Curecheriu[1], P. Postolache[2], M.T. Buscaglia[3], V. Buscaglia[3], L. Mitoseriu[1], and A. Stancu[2],**<br>(1) Dielectrics, Ferroelectrics & Multiferroics Gr., Dept. of Physics, Al. I. Cuza Univ., Iasi, Romania<br>(2) CARPATH Center, Department of Physics, Al. I. Cuza Univ, Iasi, Romania<br>(3) Institute for Energetics & Interphases - CNR, Genoa, Italy |
| 16:20-16:40 (O21) | Analytical Solution Of Precessional Switching In Nanomagnets Driven By Hard-Axis Field Pulses,<br>**M. D'Aquino[1], S. Perna[2], C. Serpico[2], A. Quercia[2], G. Bertotti[3], and I.D. Mayergoyz[4],**<br>(1) Department of Engineering, University of Naples Parthenope, Naples, Italy<br>(2) DIETI, University of Naples Federico II, Naples, Italy.<br>(3) Istituto Nazionale di Ricerca Metrologica, Turin, Italy<br>(4) ECE Department and UMIACS, University of Maryland, College Park, MD USA. |
| 16:40-17:00 (O22) | Chaotic Assisted Switching Of Magnetic Spin-Valves,<br>**M. D'Aquino[1], A. Quercia[2], C. Serpico[2], G. Bertotti[3], I. Mayergoyz[4], S. Perna[2], and P. Ansalone[3],**<br>(1) Dipartimento di Ingegneria, Università degli Studi di Napoli "Parthenope", Napoli, Italy.<br>(2) DIETI, University of Naples Federico II, Naples, Italy.<br>(3) Istituto Nazionale di Ricerca Metrologica, Turin, Italy.<br>(4) ECE and UMIACS, University of Maryland, College Park, MD, United States. |

**Poster session**
**Chairs: Dorin Cimpoesu, Ionut Dumitru**

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|---|---|
| 17:00-19:00 (P1 – P72) | **Poster session** & coffee |
| 20:00 | Gala dinner |

## Wednesday, 20th of May, 2015

**Morning session**
**Chairs: Mihai Dimian, Giovanni Finocchio**

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| 9:00-9:50<br>(K1) | Various Ordering Processes Of Spin-Crossover Type Systems And Effects Of Elastic Interaction On Them,<br>**S. Miyashita[1], M. Nishino[2], and C. Enachescu[3],**<br>(1) Department of Physics, University of Tokyo, Japan<br>(2) National Institute for Material Science, Tsukuba, Ibaraki, Japan<br>(3) Department of Physics, Al. I. Cuza University, Iasi, Romania |
| 9:50-10:20<br>(I10) | On The Photo-Control Of The Dynamics Of The Spin-Crossover Transition Inside The Thermal Hysteresis Loop,<br>**K. Boukheddaden[1], M. Sy[1], A Slimani[1], F. Varret[1], M Espejo-Paez[1], D. Garrot[1], G. Bouchez[1], and S. Kaizaki[2],**<br>(1) Groupe d'Etude de la Matière Condensée, Université de Versailles, France<br>(2) Department of Chemistry, Graduate School of Science, Osaka University, Toyonaka, Japan |
| 10:20-10:50<br>(I11) | Noise In Hysteretic Systems: The Bad, The Good, And The Ugly,<br>**Mihai Dimian,**<br>Dept. of Electrical Eng. and Computer Science, "Stefan cel Mare" University, Suceava, Romania |
| 10:50-11:10 | Coffee break |
| 11:10-11:40<br>(I12) | Re-Entrance Phase In Spin Crossover Compounds,<br>**Jorge Linares,**<br>"Groupe d'Etude de la Matière Condensée" (GEMaC), CNRS-UMR 8635, UVSQ, 78035 Versailles Cedex, France |
| 11:40-12:00<br>(O23) | Charge transport phenomena in molecular spin crossover materials: DC and AC analysis,<br>**C. Lefter[1,2], I. Rusu[1], S. Tricard[2], H. Peng[2], L. Salmon[2], G. Molnár[2], P. Demont[3], A. Bousseksou[2], and A. Rotaru[1],**<br>(1) Dept. of Electrical Eng. and Computer Science, "Stefan cel Mare" University, Suceava, Romania<br>(2) Laboratoire de Chimie de Coordination and Université de Toulouse UPS, France<br>(3) LPP-CIRIMAT, CNRS & Université de Toulouse (UPS, INP), Toulouse, France |
| 12:00-12:20<br>(O24) | Vortex Nonlinear Dynamics<br>**C. Serpico[1], M. D'Aquino[3], S. Perna[1], A. Quercia[2]**<br>(1) DIETI, University of Naples Federico II, Naples, Italy.<br>(2) Department of Engineering, University of Naples Parthenope, Naples, Italy |
| 12:20-12:40<br>(O25) | Advances In Spin-Torque Diode Sensitivity: Theory And Experiments,<br>**G. Finocchio[1], M. Carpentieri[2], B. Azzerboni[1], B. Fang[3], and Z. Zeng[3],**<br>(1) Dept. of Electronic Eng., Industrial Chemistry and Engineering, University of Messina, Italy<br>(2) Department of Electrical and Information Engineering, Polytechnic of Bari, Italy<br>(3) Key Laboratory of Nanodevices and Applications, Suzhou Institute of Nano-tech and Nano-bionics, Chinese Academy of Sciences, Suzhou, P. R. China |
| 12:40-13:00<br>(O26) | Spin Dynamics Of Skyrmionic Magnetic Bubbles,<br>**B. Krüger[1], F. Büttner[1,2], C. Moutafis[3], M. Schneider[2], C. M. Günther[2], J. Geilhufe[4], C. von Korff Schmising[2], J. Mohanty[2], I. Makhfudz[5], O. Tchernyshyov[5], B. Pfau[2], S. Schaffert[2], A. Bisig[1], M. Foerster[1], T. Schulz[1], C. A. F. Vaz[1,6], J. H. Franken[7], H. J. M. Swagten[7], S. Eisebitt[2,4], and M. Kläui[1],**<br>(1) Institut für Physik, Johannes Gutenberg-Universität Mainz, Mainz, Germany,<br>(2) Institut für Optik und Atomare Physik, Technische Universität Berlin, Berlin, Germany,<br>(3) Swiss Light Source, Paul Scherrer Institut, Switzerland,<br>(4) Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Berlin, Germany,<br>(5) Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD, USA,<br>(6) SwissFEL, Paul Scherrer Institut, Villigen, Switzerland,<br>(7) Dept. of Appl. Physics, Center for NanoMaterials, Eindhoven Univ. of Technology, Netherlands |
| 13:00-14:30 | Lunch |

**Afternoon session**
**Chairs: Josef Fidler, Vito Puliafito**

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| 14:30-15:00 (I13) | Materials Displaying Large MCE Peaks Resulting From Field-Induced Metamagnetic Transitions Without Any Appreciable Hysteresis,<br>**V. Provenzano, E. Della Torre, and L. H. Bennett,**<br>The Institute of Magnetic Research, George Washington University, Washington D.C., USA |
| 15:00-15:30 (I14) | Anisotropy Distribution Effects On Hysteresis Losses For Magnetic Hyperthermia Applications,<br>**Gonzalo Vallejo Fernandez,**<br>Physics Department, University of York, York, UK |
| 15:30-15:50 (O27) | Hysteresis Loop-Based Identification Of Thermal Switching Field Distributions In Magnetic Granular Systems,<br>**S. Ruta[1], O. Hovorka[2], K. Wang[3], G. Ju[3], and R. Chantrell[1],**<br>(1) Physics Department, University of York, York, UK<br>(2) Faculty of Engineering and the Environment, Univ. of Southampton, Southampton, UK<br>(3) Seagate Technology, Fremont, CA, USA |
| 15:50-16:10 (O28) | Motion Of Domain Walls In The Magnetic Peierls Potential,<br>**F. J. Buijnsters, A. Fasolino, and M. I. Katsnelson,**<br>Institute for Molecules and Materials, Radboud University Nijmegen, Nijmegen, Netherlands |
| 16:10-16:30 | Coffee break |
| 16:30-16:50 (O29) | Comparison Of Prandtl-Ishlinskii And Preisach Modeling In Micro-Positioning Control Systems Applications,<br>**M. Al Janaideh[1], D. Davino[2], P. Krejci[3], and C. Visone[2],**<br>(1) Department of Mechatronics Engineering, The University of Jordan, Amman, Jordan.<br>(2) Dipartimento di Ingegneria, Università degli Studi del Sannio, Benevento, Italy<br>(3) Mathematical Institute, Academy of Sciences of the Czech Republic, Praha, Czech Republic |
| 16:50-17:10 (O30) | Inverse Opal-Like Structure – 3D Antidot Array Exhibiting Spin Ice Behavior: Micromagnetic Study,<br>**I. S. Dubitskiy[1,2], A. V. Syromyatnikov[1,2], N. A. Grigoryeva[1], A. A. Mistonov[1,2], I. S. Shishkin[1,2], and S. V. Grigoriev[1,2],**<br>(1) Faculty of Physics, Saint-Petersburg State University, Saint Petersburg, Russia<br>(2) Petersburg Nuclear Physics Institute, Gatchina, Saint Petersburg, Russia |
| 17:10-17:30 (O31) | Quantifying History Dependence Of Thermal Relaxation In Clusters Of Magnetic Nanoparticles,<br>**O. Laslett[1], S. Ruta[2], J. Barker[3], G. Friedman[4], R. Chantrell[2], and O. Hovorka[1],**<br>(1) Engineering and the Environment, University of Southampton, Southampton, UK<br>(2) Department of Physics, University of York, York, UK<br>(3) Institute for Materials Research, Tohoku University, Sendai, Japan<br>(4) Electrical and Computer Engineering Department, Drexel University, Philadelphia, USA |
| 17:30-17:50 (O32) | Monte Carlo Simulation For Thermal Assisted Reversal Process Of Micro-Magnetic Torus Ring With Bistable Closure Domain Structure,<br>**K. Terashima, K. Suzuki, and K. Yamaguchi,**<br>Fukushima University, Fukushima, Japan |
| 17:50-18:10 (O33) | One-Phase Flow In Porous Media With Hysteresis,<br>**N. Botkin, E. El Behi-Gornostaeva,**<br>Technical University of Munich, Zentrum Mathematik, Garching, Germany |
| 18:10 | **Closing ceremony** |

# Multiscale Approaches To Magnetic Materials Simulation

**R. Chantrell**
*Physics Department, University of York, York, UK*

Dynamic models of the properties of magnetic materials are generally based on the formalism of micromagnetics, which is a continuum formalism derived for the investigation of relatively large structures. It is formulated around macrospins with typical size a few nm, within which the magnetisation is assumed constant. This allows the efficient calculation of magnetostatic fields, but forces a long-wavelength approximation to the exchange energy. As a consequence, although thermal activation can be included in the formalism, micromagnetics is restricted to low temperatures where the assumption of long-wavelength thermal fluctuations is reasonable.

Recent developments in ultrafast magnetisation dynamics and practical applications such as Heat Assisted Magnetic Recording (HAMR) are not amenable to treatment by the standard micromagnetic approach. In addition, the properties of interfaces are often difficult to investigate using micromagnetics.

Here we describe an atomistic model approach where the system is discretised at the atomic level. We will outline the atomistic formalism, including a brief description of the VAMPIRE atomistic code. We will also describe the essential multiscale aspects of the approach, which includes the introduction of the magnetostatic field and also ab-initio information relating to the intrinsic properties of the atomic spins (principally magnetic moment values, exchange and anisotropy contributions. As a particular example we will present recent calculations on the determination of the site-resolved spin Hamiltonian for a FePt/Fe bilayer, where it is shown that the interface exchange and anisotropy values are considerably modified, leading to a discontinuous domain structure at the interface. We will also describe the development of a multiscale model of the properties of NdFeB and apply it to the temperature dependence of magnetic properties. Atomistic models are giving an increasingly important contribution to the understanding of the static and dynamic properties of magnetic materials and form an important link in the chain of multiscale modelling from ab-initio models to large scale micromagnetic simulations: a factor which will become increasingly important following the trend to smaller lengthscales and complex nanostructures. We will conclude by summarising the current status of multiscale models and consider some possible future trends.

K2 – Tuesday, 19th of May, 2015 – 9:00-9:50

# Mathematical Problems In Modeling Piezoelectricity And Magnetostriction

**P. Krejcí**

*Institute of Mathematics, Czech Academy of Sciences, Prague, Czech Republic*

Piezoelectric and magnetostrictive materials exhibit strong hysteresis effects with respect to coupled mechanical and electromagnetic dynamics. Experiments confirm that all electro-magneto-mechanical hysteresis effects can be modeled by a single Preisach hysteresis operator and its associated energy potential, both acting on one self-similar variable. Well-posedness of the full PDE system of balance equations is a challenging problem which requires new mathematical tools such as inversion of Preisach operators with time dependent measures.

Joint work will D. Davino, B. Kaltenbacher, and C. Visone will be referred to.

# Various Ordering Processes Of Spin-Crossover Type Systems And Effects Of Elastic Interaction On Them

**S. Miyashita[1], M. Nishino[2], C. Enachescu[3]**

*(1) Department of Physics, University of Tokyo, Tokyo, Japan*
*(2) National Institute for Material Science, Tsukuba, Ibaraki, Japan*
*(3) Department of Physics, Al. I. Cuza University, Iasi, Romania*

The spin-crossover type systems have bistable local states, e.g. (HS, LS), and the system is modeled by an Ising variable. However, because of the differences of the energy (or entalpy H) and the degeneracy (or entropy S) of the bistable states, even within the case of simple ferromagnetic local interaction, the system exhibits various types of successive phase transitions and metastable processes. These variety is understand from a general view point in which hidden phases have been discovered. More over depending on the local interaction among the spin state, the systems show various step-wise phase successive phase transitions. For example, antiferromagnetic interaction in a bipartite system brings an intermediate phase where a staggered structure appears which causes a step in the ordering process of the high spin fraction. The competition among the interaction (frustration) causes a large unit cell of the order parameter, and the system exhibits interesting successive phase transitions. As typical cases, we study the antiferromagnetic Ising model on the triangular lattice with next-nearest neighbour ferromagnetic interaction (Mekata model) and the ANNNI model.

Moreover, in the spin-crossover type systems, the change of state causes distortion of the lattice, and it brings new characteristics in cooperative behaviour of the system. We will study the effects in static and also dynamic properties of the ordering process.

I1 – Monday, 18th of May 2015 – 10:20-10:50

# Do Micromagnetic Simulations Correctly Predict Hard Magnetic Hysteresis Properties?

**J. Fidler**
*Vienna University of Technology, Vienna, Austria*

The search for candidates of suitable magnetic materials, structures and their expected behavior as reduction of the heavy rare earth content or the replacement for rare earth containing permanent magnets is of great economical and scientific interest. We have performed electronic structure calculations together with finite element micromagnetic simulations based on the Landau-Lifshitz-Gilbert equation for magnetization reversal in order to study the influence of the real microstructure on the hysteresis properties of large grained sintered and small grained melt spun rare earth magnets. The results of modelling are compared with high resolution, nanoanalytical TEM investigations of various RE-Fe-B sintered magnets with different RE content and coercive field, respectively. We also have performed numerical finite element micromagnetic simulations in order to study the possibility of shape anisotropy effects of packed Fe and Co based nanorod structures as candidates for rare earth free permanent magnetic applications. Recent developments in nanoscience enabled the production of the nanostructured systems with dimensions approaching the order of few nanometres.

I2 – Monday, 18th of May 2015 – 11:10-11:40

# Finite Element Micromagnetics At Non-Zero Temperature

**T. Schrefl**

*Center for Integrated Sensor Systems, Danube University Krems, Austria*

The coercive of magnets is a function of temperature and measurement time. At zero temperature magnetization reversal occurs when the energy barriers as function of applied field vanishes. At non-zero temperature the system may jump over a finite energy within the measurement time. By computing the energy barrier as function of applied field we can estimate the coercive field at non-zero temperature.

We will review different numerical methods for computing the saddle point in particular the nudged elastic band method and the string method in the framework of finite element micromagnetics. Applications will be given for vortex nucleation in thin film magnetic elements and magnetic recording media, and permanent magnets. The proper evaluation of the temperature dependent coercivity is of utmost important for permanent magnet applications in motors of hybrid vehicles where the operation temperature is around 450 K.

I3 – Monday, 18th of May 2015 – 14:30-15:00

# Phenomenological Modelling Of Magnetic Materials

**E. Cardelli**

*Department of Engineering, University of Perugia, Perugia, Italy*

A general modelling of vector magnetization processes in 2-d and 3-d for many engineering applications, such as electrical machines, is not completely available at the moment. Physical approaches at nano-magnetic scale have been proposed, but they are not usable in practice, due to the large amount of computer time and memory required to compute the behaviour of real devices. Phenomenological approaches on the other hand, have been proposed on a macro-magnetic scale for the numerical modelling of magnetic materials with hysteresis. They have been used successfully at first to a 1-d analysis of magnetic materials, and, more recently, their extension to vector hysteresis problems has been discussed. The capability to represent with accuracy usual soft magnetic materials, like electrical steels, has not been definitely proved, and this point deserves probably further study.

A detailed discussion about some open questions and challenging formulations will be presented.

I4 – Monday, 18th of May 2015 – 15:00-15:30

# Vector Hysteresis Models And Magnetization Under Stress

**A. Ktena**

*Department of Electrical Engineering, Technological Educational Institute of Central Greece, Greece*

Phenomenological models are typically being used to calculate the dependence of a material's magnetization on magnetic fields when efficient core models in simulations or inverse problems are needed. Several approaches have been proposed over the years and tested in a variety of problems with two issues being often the source of debate, namely whether vector formulations are really necessary and whether these models can be used to reproduce the magnetization dependence on the underlying microstructure of a material as in the case of residual stresses in plastically deformed materials.

This talk will offer an overview of the current state of the art in vector hysteresis models and their applications with respect to scalar ones, will discuss the challenges of modeling the stress-dependent magnetization processes and will argue the necessity for vector modeling. A case of using a 2D hysteresis model to model the effect of residual stress on the magnetization process will be presented.

I5 – Monday, 18th of May 2015 – 15:30-16:00

# Micromagnetic Simulations Of Two-Dimensional And Three Dimensional Magnonic Metamaterials

**L. Spinu**
*Dept. of Physics and AMRI, University of New Orleans, New Orleans, USA*

Magnonic metamaterials or magnonic crystals (MC) are artificial assembly of "man-made" building blocks with tailored properties via their geometrical shaping and compositional modulation. This fact makes possible the confinement of solid state excitations and formation of a discrete spectrum of the allowed modes. Magnonic crystals open huge possibilities for device application as the frequency and strength of resonances related to the propagation of the magnons can be controlled by the geometry and magnetization configuration of meta-atoms.

Micromagnetic simulations are essential in understanding and predicting the properties of magnonic crystals and guiding magnetization dynamics experiments. Complicated shapes of magnetic elements forming three-dimensional (3D) MCs determine a rather complex structure of a spin wave spectrum of these individual nanosized elements. Thus, full scale micromagnetic simulations that go beyond the macrospin approximation are needed to accurately evaluate the structure of spin wave modes in these elements.

In this work we present systematic micromagnetic simulations of the frequency response of a series of two-dimensional (2D) and three-dimensional periodic magnetic arrays. A special attention is paid to the influence of the MC's ground state on the properties of the collective resonance modes of the MC. Thus, the possibility to dynamically reconfigure a ground state of 3D MCs is systematically analyzed. In each case the resonance frequencies is investigated by spectral analysis. The frequency response of a finite 3D MC cluster is extracted from the spatially and temporarily resolved data produced by micromagnetic simulations.

# Differentiability Properties Of Scalar Hysteresis Models

**M. Brokate**
*Zentrum Mathematik/M6, TU Muenchen, D-85747 Garching bei Muenchen, Germany*

We consider scalar hysteresis models (like the Preisach model) in the form w = W[u], where u = u(t) is a given time-dependent input function and w = w(t) is the corresponding output function. It is well-known that, when considered as an operator between suitable function spaces, W is Lipschitz continuous but not differentiable in the classical sense. However, the following turns out to be true. If h is a variation of u and if d_s(t) = (W[u+sh](t) - W[u](t))/s) denotes the difference quotient, then the function d_s = d_s(t) converges to a limit function d = d(t), again in a suitable function space. Such results are useful, for example, when one wants to optimize a dynamical system which involves a hysteresis nonlinearity, either by a direct optimization method which involves derivatives, or by exploiting optimality conditions expressed in terms of derivatives.

The results of this talk have been jointly obtained with Pavel Krejci.

I7 – Tuesday, 19th of May, 2015 – 10:20-10:50

# A Representation Result For Rate-Independent Systems

**O. Klein**
*Weierstrass Institute for Applied Analysis and Stochastics (WIAS), Berlin, Germany*

The representation formula for hysteresis operators acting on scalar-valued continuous input functions being piecewise monotone that was derived by Brokate and Sprekels, see [1], has been extended to hysteresis operators dealing with inputs in a general topological vector space $V$, see [2-5]. In the current paper this result is extended to rate-independent systems, as considered for example in [6]. The input functions are requested to be piecewise strictly *monotaffine*, i.e. to be piecewise the composition of a **strictly monotone** increasing function with an **affine** function, the strictly monotone function being applied first.

For real numbers $T_0, T_1$ with $T_0 < T_1$ let $C_{\text{pw.s.ma.}}[T_0, T_1; V]$ denote the set of all continuous, piecewise strictly monotaffine functions from $[T_0, T_1]$ to $V$. Let $S_{F,*}(V)$ be the set of all $(v_{0,} \dots v_n) \in V^{n+1}$ with $n$ being a natural number such that for all $i = 1, \dots, n-1$ it holds that $v_{i-1} = v_i \neq v_{i+1}$ or that $v_{i-1} \neq v_i = v_{i+1}$ or that $v_i$ can not be written as convex combination of $v_{i-1}$ and $v_{i+1}$. Let $Y$ be some given set. Let $\mathfrak{M}$ be the set of all functions on $S_{F,*}(V)$ such that $(v_0, \dots, v_n) \in S_{F,*}(V)$ is mapped to a subset of $\{(f_1, \dots, f_n) | \; f_1, \dots, f_n : ]0,1] \to Y, \; f_i \text{ is constant if } v_{i-1} = v_i\}$.

The new representation result in [7] reads as:

- Every function $G \in \mathfrak{M}$ generates an input-output system $\mathcal{H}_G$ that maps for all real numbers $T_0, T_1$ with $T_0 < T_1$ the input data $y_0 \in Y$ and $u \in C_{\text{pw.s.ma.}}[T_0, T_1; V]$ to $\mathcal{H}_G([T_0, T_1].y_0, u) := \{y_{y_0,(f_1, \dots, f_n)} \mid (f_1, \dots, f_n) \in G(u(t_0), \dots, u(t_n))\}$ with
    - o $y_{y_0,(f_1, \dots, f_n)} : [T_0, T_1] \to Y$ being defined by $y_{y_0,(f_1, \dots, f_n)}(0) := y_0$ and $y_{y_0,(f_1, \dots, f_n)}(t) := f_i(\alpha_{t,i})$ with $\alpha_{t,i} \in ]0,1]$ such that $u(t) = (1 - \alpha_{t,i})u(t_{i-1}) + \alpha_{t,i} u(t_i)$ for all $t \in ]t_{i-1}, t_i]$ and all $i = 1, \dots, n$,
    - o $T_0 = t_0 < t_1 \cdots < t_n = T_1$ being the standard strict monotaffinicity decomposition of $[T_0, T_1]$ for $u$, i.e. the uniquely defined decomposition of $[T_0, T_1]$ such that for all $i = 1, \dots, n$ it holds that $t_{i-1}$ is the maximal $t \in ]t_{i-1}, T_1]$ such that $u$ is strictly monotaffine on $[t_{i-1}, t]$.

  Then it follows that $\mathcal{H}_G$ is a rate-independent system as defined in [6, Def. 1.1].
- For every rate-independent system $\mathcal{B}$ there exists a unique function $G \in \mathfrak{M}$ such that $\mathcal{B}$ is the input-output system $\mathcal{H}_G$ generated by $G$.

It will be discussed which conditions $G \in \mathfrak{M}$ must satisfy to ensure that $\mathcal{H}_G$ is also a multivalued evolutionary system as considered in [6].

***Refrences***

*[1] M. Brokate, J. Sprekels, Hysteresis and Phase Transitions, Springer-Verlag (1996)*
*[2] O. Klein, Physica B, 407 (2012), 1399-1400*
*[3] O. Klein, Adv. Math. Sci. Appl., 22 (2012), 471-500*
*[4] O. Klein, Physica B, 435 (2014), 113-115*
*[5] O. Klein, Habilitationsschrift, Humboldt-Universität zu Berlin, 2014*
*[6] A. Mielke, Ch. 6 in Handbook of Differential Equations, Evolutionary Equations 2, Elsevier B.V. (2005)*
*[7] O. Klein, in preparation*

# Thermally Induced Switching In Synthetic Ferrimagnets

**S. Sievering, S. Wienholdt, D. Hinzke, U. Nowak**
*Department of Physics, University of Konstanz, 78464 Konstanz, Germany*

It has been demonstrated recently that linearly polarized laser pulses in the fs regime can trigger a thermally driven switching in ferrimagnetic GdFeCo compounds via a so called "ferromagnetic-like state", where the rare-earth and transition metal sublattice magnetizations are aligned parallel on a ps time scale.

Based on atomistic spin models, we investigate this mechanism and the material properties that are needed for this kind of switching. Furthermore, we investigate the possibility of thermally induced switching in synthetic ferrimagnets comprised of bi- or multilayers of coupled ferromagnets.

I9 – Tuesday, 19th of May, 2015 – 14:30-15:00

# Controlled Limits Of The FORC Theory: Mean Field, Nucleation

**G. Zimanyi**

*University of California Davis, USA*

In the first part of the talk, a well-controlled mean field limit of the FORC theory is developed. Then, a framework of adding local fluctuation corrections is presented. The analytic theory is verified numerically and experimentally. The experimental test is performed on a tunable array of Co nano-ellipses. In all of these cases two ridges are observed, approximately aligned with the coercivity and bias axes.

The second part of the talk concentrates on the FORC theory of nucleation. The theoretical results are compared to experimental studies of permanent magnets. In these nucleation-dominated samples a two ridge structure dominates again, but rotated by 45 degrees relative to the coercivity and bias axes. Connections of the above ideas with the parallel work of the Stancu group will be analyzed.

# On The Photo-Control Of The Dynamics Of The Spin-Crossover Transition Inside The Thermal Hysteresis Loop.

**K. Boukheddaden[1], M. Sy[1], A Slimani[1] , F. Varret[1], M Espejo-Paez[1], D. Garrot[1], G. Bouchez[1] and S. Kaizaki[2]**

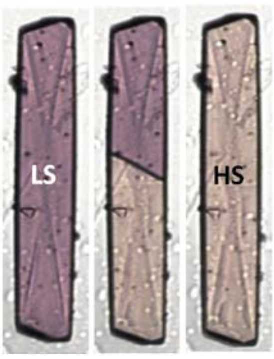
*(1) Groupe d'Etude de la Matière Condensée, Université de Versailles, CNRS UMR 8635, Versailles, France*

*(2) Department of Chemistry, Graduate School of Science, Osaka University, Toyonaka, Osaka, Japan*

We investigated single crystals of the dinuclear iron(II) compound [{Fe(NCSe)(py)2}2(m-bpypz)], which exhibit a thermal spin transition with hysteresis near 100 K. The robust character of the crystals made possible the investigation of both on-cooling and on-heating processes. We observed well-defined transformation fronts [1] between macroscopic high spin (HS) and low-spin (LS) phases during the thermally-induced phase transition. The obtained HS/LS interfaces are almost straight in shape (see figure on the right), and propagate through the entire crystal at constant velocity. The interface orientation was invariant during the process and the measured propagation speed was typically between ~ 1 and 10 µm/s for the cooling and heating processes, respectively. The videos of the spin transition processes will be shown in real (or accelerated) time.

The second part of the talk will be devoted to the photo-control of the HS/LS interface dynamics using the light as an external stimulus.

Using microscopic models [2, 3, 4] combining the elastic (volume change) and the electronic (spin state change) degrees of freedom involved in the spin transition phenomenon, we succeeded to simulate the interface orientation and to explain its physical origin.




***References***

*[1] A. Slimani, F. Varret, D. Garrot, H. Oubouchou, S. Kaizaki and K. Boukheddaden, Phys. Rev. Lett. 110 (2013) 087208.*

*[2] A. Slimani, k; Boukheddaden, F. Varret, H. Oubouchou, M. Nishino, S. Miyashita , Phys. Rev. B. 87, 014111 (2013).*

*[3] Miguel Paez-Espejo, Mouhamadou Sy, François Varret and Kamel Boukheddaden, « Macroscopic treatment of the spatiotemporal properties of spin crossover solids, based on Reaction Diffusion Equation», Phys. Rev. B. 89, 024306 (2014).*

*[4] M. Sy, F. Varret, K. Boukheddaden, J. Marrot, G. Bouchez, S. Kaizaki, Angew. Chem. Int. Edt., 139, 194706 (2014).*

I11 – Wednesday, 20th of May, 2015 –10:20-10:50

# Noise In Hysteretic Systems: The Bad, The Good, And The Ugly

**M. Dimian**

*Department of Electrical Engineering and Computer Science, "Stefan cel Mare" University, Suceava, Romania*

Noise and hysteresis are ubiquitous phenomena in science and engineering and yet are far from being well understood both in terms of their fundamental origins and their effects on nowadays technologies. As a result, phenomenological models have flourished in both areas and play increasingly important roles in research and technological developments. However, the stochastic modeling of noise effects in hysteretic systems has been rather limited and specific to each area of applications.

The purpose of this talk is to present a unitary framework for the analysis of various stochastic aspects of hysteresis, its implementation in an open-access academic software and its applications in multiple areas. Based on these analytical and numerical tools, both disruptive and constructive effects of white and arbitrary colored noises are discussed in several differential, integral, and algebraic models of hysteresis, including thermal assisted relaxations, memory losses, noise induced amplifications and stochastic resonances.

I12 – Wednesday, 20th of May, 2015 – 11:10-11:40

# Re-Entrance Phase In Spin Crossover Compounds

**J. Linares**

*"Groupe d'Etude de la Matière Condensée" (GEMaC), CNRS-UMR 8635, UVSQ, 78035 Versailles Cedex, France*

In spin-conversion compounds (SCO) containing molecules organized arount an iron (II) ion the fundamental velvel of the ion i slow-spin (LS), S=0, and its first excited one is high spin (HS), S=2. This energy diagram is due to the ligands field interaction on 3d electrons and to the spin pairing energy. Heating the compound increases the magnetic susceptibility which corresponds to a change of population of both levels and consequently a change of spin value of the molecules. This mechanism, called spin conversion (SC), can be accompanied by thermal hysteresis. In that case one considers that the (SC) takes place through a first-order phase transition due to intermolecular interactions.

In this contribution we explain, in the framework of the "atom-phonon coupling", the evolution of the hysteresis width as function of Delta, the energy gap between LS and HS states. We show the unusual case of re-entrance phase: the disappearance and reappearance of the hysteresis loop. We study the role of the ratio of the degeneracy between HS and LS $r= g_{HS}/g_{LS}$ as well of the variation of the re-entrance case with N, the number of molecules.

I13 – Wednesday, 20th of May, 2015 – 14:30-15:00

# Materials Displaying Large MCE Peaks Resulting From Field-Induced Metamagnetic Transitions Without Any Appreciable Hysteresis

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A first-order magnetostructural transition refers to the thermally-driven process during which a magnetic material is transformed from one phase structure to a different phase structure with the attendant change in its magnetic state. For example, during the thermally-driven magnetostructural transition, the Gd5Ge2Si2 alloy is converted from the ferromagnetic orthorhombic structure to the paramagnetic monoclinic structure. The MnFeP0.5As0.5 and La (Fe, Si)13 alloys along with the Ni2GaMn Heusler alloy and related alloys are examples of other materials that are known to undergo thermally-driven first-order phase transitions close to room temperature. However, in this class of materials and within relatively narrow temperature ranges, each of the thermally-driven phase transitions can be field-induced in the reversed order by the application of a strong enough external field. The temperature range where the field-induced reversed phase transition occurs has been defined as the "metamagnetic transition region". The majority of materials that undergo reverse field-induced magnetostructural transitions typically display high but narrow magnetocaloric effect (MCE) peaks, accompanied by presence of large hysteresis. In contrast to the above first-order materials, we report on a small number of metallic materials that typically display broad and high MCE peaks also resulting from field-induced transitions in their respective metamagnetic regions but with negligible hysteresis. The Fe-doped HoTiGe and $Gd_{22}Ge_8Si_{34}Fe_{36}$ alloys and the ordered $Cr_7Te_8$ compound belong to this small group of materials. The critical difference between these materials and the previously mentioned first- order materials is due to the nature of their respective field-induced transitions. In first-order materials, the field-induced transitions involve both magnetic and structural changes, whereas in the small group of materials the field-induced transitions are purely magnetic and thus they do not involve any structural changes, except for changes in the crystal lattice parameters that have the effect of changing the sign of the exchange energy, but the crystal structures remain the same. When the exchange energy changes sign, it produces a change in the slope of the magnetization versus field curve that has the effect of changing the magnetic state of the material. For example, at 5 K and for field values below 320 kA/m (0.4 T), the $Gd_{22}Ge_8Si_{34}Fe_{36}$ alloy is paramagnetic, while above this values, the alloy becomes superparamagnetic. The combination of broad MCE peaks with negligible hysteresis makes these materials attractive refrigerants for magnetic refrigeration applications. In this lecture we will review the very interesting and unique magnetic properties of this group of materials and propose possible mechanisms to account for their field- induced magnetic transitions with no changes in their crystal structures that give rise to enhanced MCE peaks without any appreciable hysteresis.

# Anisotropy Distribution Effects On Hysteresis Losses For Magnetic Hyperthermia Applications

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*Physics Department, University of York, York, UK*

Traditional methods for cancer treatment are based on the unspecific death of cancerous cells using drugs or highly energetic radiation which cause drastic side effects. Magnetic hyperthermia has been shown to have no known side effects and will allow for reduced doses and even replacement of those more conventional treatments. Currently, only magnetite ($Fe_3O_4$) / maghemite ($\gamma$-$Fe_2O_3$) nanoparticles have been approved for use in humans. In most studies of magnetic hyperthermia the value of the anisotropy constant is assumed to be uniform although a distribution will occur. This is due to the fact that the anisotropy of magnetite/maghemite nanoparticles is dominated by shape anisotropy where an increase in the aspect ratio from 1.1 to 1.5 varies the shape anisotropy constant by 300%. This is critical as in most experimental studies particles have elongation ratios in that range. Hence, any theoretical model of magnetic hyperthermia needs to take into account the distribution of aspect ratios, i.e. shape anisotropy constants, for its conclusions to be valid. Calculations based on our previous work which showed that hyperthermia is dominated by hysteresis heating will be presented where a distribution of anisotropy constants has now been taken into account.

O1 – Monday, 18th of May 2015 – 11:40-12:00

# Skyrmion Racetrack Memory Driven By SHE

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*(2) Dept. of Fisica Aplicada, Universidad de Salamanca, Spain.*
*(3) Dept. of Physics and Earth Sciences and CNISM Unit of Ferrara, University of Ferrara, Italy.*
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*(5) Dept. of Electronic Engineering, Industrial Chemistry and Engineering, University of Messina, Italy.*

Magnetic skyrmions are attracting a growing interest from both a fundamental and a technological point of view. A promising application concerns the racetrack memory, where skyrmions (moved by spin-transfer torque (STT) or spin-Hall effect (SHE)) can be used to carry the information bit, replacing domain walls [1,2,3]. Skyrmions are nucleated in out-of-plane materials, where the Dzyaloshinskii–Moriya interaction (DMI) arises: Bloch skyrmions are stabilized in the case of bulk DMI, whereas Néel skyrmions are obtained in the case interfacial DMI.

Here, we show that a skyrmion racetrack memory can be obtained in four scenarios, by combining the skyrmion type and the motion source [4]. In particular, the Néel skyrmion motion driven by the SHE (fig. 1a), exhibits a large velocity-current tunability, as well as a good robustness towards surface roughness and thermal fluctuations at room temperature. Moreover, we micromagnetically prove that motion of the Néel skyrmion is mainly along the direction perpendicular to the electrical current flow (y-axis if the current is along the x-axis). This outcome is confirmed by analytical results (fig. 1b) obtained from an analytical formulation based on the Thiele's equation:

$$v_x = \frac{\alpha_G \mathcal{D} B}{1+\alpha_G^2 \mathcal{D}^2} j_{HM}, \quad v_y = \frac{B}{1+\alpha_G^2 \mathcal{D}^2} j_{HM} \tag{1}$$

where vx and vy are the skyrmion velocity components in the x- and y-direction respectively. $\alpha_G$ is the Gilbert damping, $\mathcal{D}$ is the dissipative tensor, $B$ is a coefficient linked to the SHE and jHM is the electrical current flowing through the heavy metal. Both velocity components are proportional to jHM. However, being vx also proportional to the $\alpha_G$<<1, it follows that $v_x << v_y$.

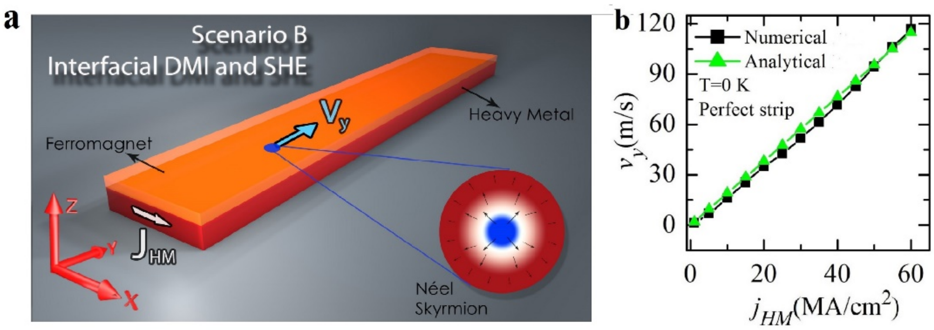


*Fig 1: **a**. Sketch of the Néel skyrmion racetrack memory driven by SHE. **b**. comparison between the numerical and analytical velocity-current relations.*

### *References*

*[1] A. Fert et al. Nat. Nanotech. 8, 152 (2013).*
*[2] J. Iwasaki et al. Nat. Nanotech. 8, 742 (2013).*
*[3] J. Sampaio et al. Nat. Nanotech. 8, 839 (2013).*
*[4] R. Tomasello et al. Sci. Rep. 4, 6784 (2014).*

O2 – Monday, 18th of May 2015 – 12:00-12:40

# Modelling Surface And Interfacial Effects In Magnetic Nanoparticles: From Core/Shell To Hollow Structures

**Ò. Iglesias**

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The properties of magnetic particles show interesting peculiar behavior when going to the nanometric and low temperature regimes. Nanoparticles (NP) with non-homogeneous compositions or peculiar morphologies, which can be tuned by proper control of the conditions of the synthesis method, have been shown to be useful for technological and biomedical applications. Over the last decades, it has been shown that finite-size and surface effects, together with collective effects, are crucial to understand the magnetic phenomenology of NP assemblies. In this contribution, we will show examples of results of our recent work on atomistic modeling of NP systems by means of Monte Carlo simulations that take into account the specific compositions and morphologies of the real samples [1]. Among them, we will present results of studies of: 1) $Fe_2O_3$ hollow NP synthesized by the Kirkendall effect showing peculiar magnetic properties [2] due to enhanced surface effects (Fig.2). 2) Co based NPs that, when passing from core/shell to fully oxidized and hollow compositions, show appearance of hysteresis above 300 K and shifts of field-cooled hysteresis loops proportional to the CoO shell thickness [3]. 3) Hybrid Au - $Fe_3O_4$ composites with nanoflower and dumbbell geometries (Fig.1) [4]. Through the exposition, we will argue on the different contributions that surface and interfacial effects may have into these diverse experimental phenomenology.

This work is supported by Spanish MINECO (MAT2012-33037), Catalan DURSI (2014SGR220) and European Union FEDER funds (Una manera de hacer Europa).

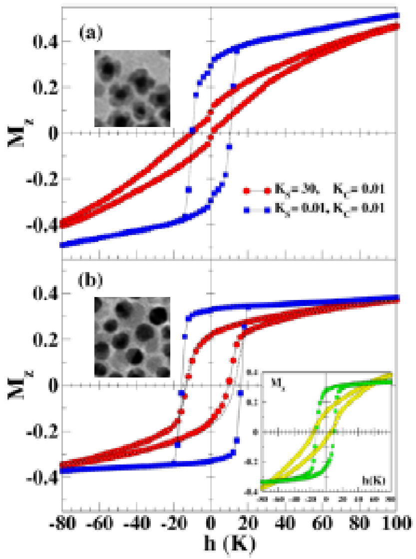


*Fig. 1: Simulated low T hysteresis loops after field cooling individual NPs with cluster (a) and dimer (b) geometries for different surface anisotropies $K_s$*

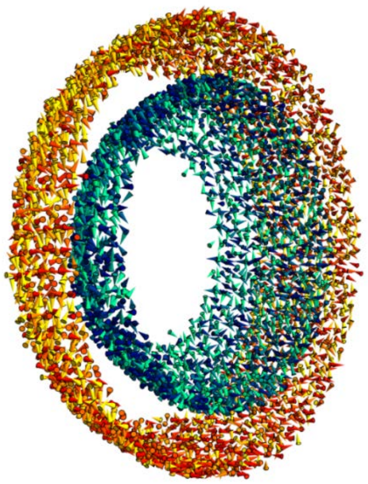

*Fig. 2: Snapshot of the remanent state of the inner and outer surface spins of a hollow NP.*

***References***

*[1] O. Iglesias, A. Labarta and X. Batlle, J. Nanoscience and Nanotecnology 8, 2761-2780 (2008).*
*[2] A. Cabot, et al., Phys. Rev. B 79, 094419 (2009); H. Khurshid, P. Lampen-Kelley, Ò. Iglesias, M.-H. Phan, M.L Saboungie, C. Sun, and H. Srikanth, submitted to Scientific Reports (2015)*
*[3] K. Simeonidis, et al., Phys. Rev. B, 84 144430 (2011). [4] S. Chandra, N.A. Frey Huls, M. H. Phan, S. Srinath, M. A. Garcia, Y. Lee, C. Wang, S. Sun, Ò. Iglesias, and H. Srikanth, Nanotechnology 25, 055702 (2014).*

O3 – Monday, 18th of May 2015 – 12:20-12:40

# Three-Dimensional Magnetic Memory Cell Controlled By A Spin-Torque Oscillator

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Developing three-dimensional (3D) magnetic storage technology is a solution to increasing storage capacity [1, 2]. In this work, we propose a multi-bit magnetic memory cell that consists of a spin-torque oscillator (STO) [3] and vertically stacked multiple storage layers (SLs) [Fig. 1(a)]. This memory cell has a specific writing scheme, in which magnetization switching of an SL is executed only by exciting a designated oscillation of an STO. In the switching process, the SL magnetization initially exhibits cooperative dynamics with the STO through dipolar interaction, in which its precession amplitude resonantly increases in synchronization with the STO, and then the magnetization relaxes into a final switched state. This *resonant magnetization switching* occurs only under a certain frequency range of the STO and depends on intrinsic ferromagnetic resonance (FMR) frequency of the SL. Considering the resonant switching characteristics, SLs are designed to have different FMR frequencies for ensuring the one-to-one correspondence between a given STO oscillation and an SL switching. A micromagnetic simulation of the selective magnetization switching of an SL on a possible cell design is shown in Fig. 1(b): Under a specific current, the AF coupled magnetizations of the second SL (SL2) successfully switch via transient synchronization with the STO [see a time zone labeled "SYNC"]. The resonant magnetization switching using an STO provides one-step writing scheme and enables simple storage cell structures.

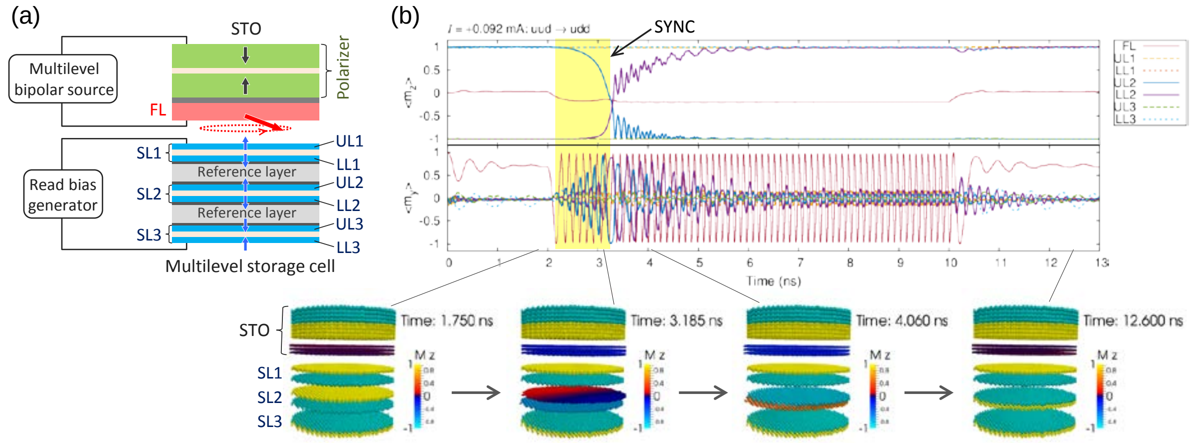


*Fig. 1: (a) Schematic of 3D magnetic memory cell. The read operation is based on sensing series magnetoresistance of the storage cell. The write operation is based on the resonant magnetization switching. (b) Selective resonant switching of SL2 by the free layer (FL) precession under 8-ns-duration current pulse. Each SL comprises an upper layer (UL) and a lower layer (LL) interacting through the antiferromagnetic (AF) coupling so that stray fields among SLs are reduced.*

This work was supported by Strategic Promotion of Innovative Research and Development from Japan Science and Technology Agency, JST.

***References***

*[1] W.-C. Jeong, B.-I. Lee, and S.-K. Joo, J. Appl. Phys.* ***85****, 4782 (1999).*
*[2] H. Suto, T. Nagasawa, K. Kudo, K. Mizushima, R. Sato, Nanotechnology* ***25****, 245501 (2014).*
*[3] Z. Zhongming, G. Finocchio, and H. Jiang, Nanoscale* ***5****, 2219 (2013).*

# A Moving Approach For The Vector Hysteresis Model

**E. Cardelli[1], A. Faba[1], A. Laudani[2], S. Quondam[1], F. Riganti Fulginei[2] and A. Salvini[2]**
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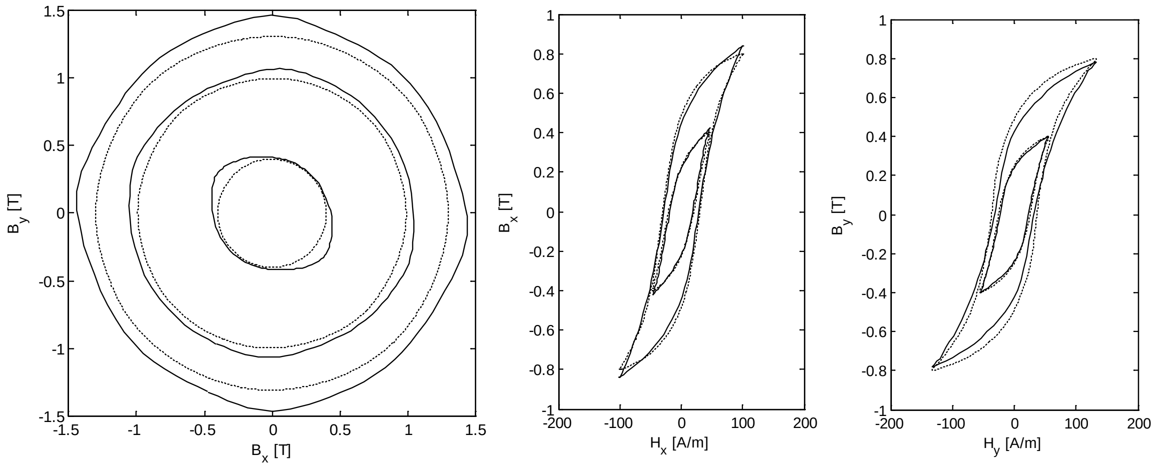
*(2) Department of Engineering, Roma Tre University, Via V. Volterra 62, 00146, Rome, Italy*

A moving approach for the VHM (Vector Hysteresis Model [1-2]) is here described, to reconstruct both scalar and rotational magnetizations of electrical steels with weak anisotropy, like non-grain oriented Silicon steel. The hysterons distribution is postulated to be function of the magnetization state of the material, in order to overcome the practical limitation of the congruency property of the standard VHM approach [3]. By using this formulation we have seen that the model is also very accurate in reproducing the experimental behavior approaching to the saturation region and this is a real improvement respect to the standard approach. The hysterons distribution is postulated to be a Lorentzian function with a standard deviation that moves from a minimum value, when the magnetization is directed along the easy axis, to a maximum value when the magnetization is directed along the hard axis. The difference between the values of the deviation assumed for different magnetization directions suitably decreases when the magnetization modulus approaches the saturation region and tends to zero. The parameters of the distribution functions and the moving functions have be computed using dedicated optimization procedures and a suitable set of experimental data [4-5]. In particular, the parameters can be found by using a family of measured magnetization cycles. The parameters of the distribution function we get in this way have been used to reconstruct other magnetization paths, for example scalar alternating magnetization along different directions respect to the easy axis. In the figures below some comparison between computed and measured data are shown.




(a) (b) (c)

*Fig. 1: Comparison between measured (dot lines) and computed (strength lines) data for rotational magnetizations (a) and for scalar magnetizations along the easy axis (b) and hard axis (c).*

***References***

*[1] E. Cardelli, "A general hysteresis operator for the modeling of vector fields," IEEE Trans. Magn., vol. 47, no. 8, pp. 2056–2067, 2011.*
*[2] E. Cardelli, E. Della Torre, A. Faba, "A General Vector Hysteresis Operator: Extension to the 3-D Case", IEEE Transaction on Magnetics, Vol. 46, NO. 12, Pages: 3990-4000, December 2010.*
*[3] E. Cardelli, E. Della Torre, A. Faba, "Properties of a class of vector hysteron models", Journal of Applied Physics 103, Article number 07D927, 2008.*
*[4] F. Riganti Fulginei, A. Salvini and G. Pulcini, "Metric-Topological-Evolutionary Optimization", Inverse Problems in Science & Engineering (IPSE), vol. 20, p. 41-58, 2012.*
*[5] A. Laudani, F. Riganti Fulginei, A. Salvini, M. Schmid, S. Conforto, "CFSO3: a new supervised swarm-based optimization algorithm", Mathematical Problems in Engineering, Vol. 2013, 2013.*

O5 – Monday, 18th of May 2015 – 16:00-16:20

# Clocking Of Nanomagnetic Logic Driven By Spin-Hall Effect: A Micromagnetic Analysis

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Nanomagnetic logic is based on the transmission of information along a path of single domain nanomagnets, whose magnetization can change by means of the effect of the dipolar coupling due to the neighbor magnet. Magnets are usually elliptically patterned in order to take advantage of their shape anisotropy. The two configurations along the easy axis will represent the bits 1 and 0. Before transmitting a bit, anyway, it is necessary to reset the path and make the magnetizations of the magnets aligned to the hard axes. This process, known as clocking, prepares magnets to receive information from the neighbor and it is usually achieved by means of an external magnetic field [1]. The usage of an external clocking field, however, implies a high energy consumption that has limited so far the practical implementations of nanomagnetic logic.

Recently [2], the possibility to clock the magnets by means of a current only has been studied in a bilayered structure (heavy metal - ferromagnet) exploiting spin Hall effect [3].

With this regard, we have performed micromagnetic simulations on a similar bilayer (Fig. 1a) to study spin-Hall-effect-driven magnetization dynamics in a CoFeB magnet placed on a Ta layer. Our simulations started from a perpendicular configuration of the magnetization, considering that in the experiments CoFeB is covered by MgO that makes the magnet with perpendicular anisotropy. By increasing the current, we got three different states: (i) magnetization remains perpendicular (b) net magnetization goes in-plane (z-component is on average null), (iii) magnetization reverses. The second configuration can represent the clocked state obtained without an external field. In particular, in this case, we could observe the creation of magnetization strips moving in the magnet (Fig. 1b).

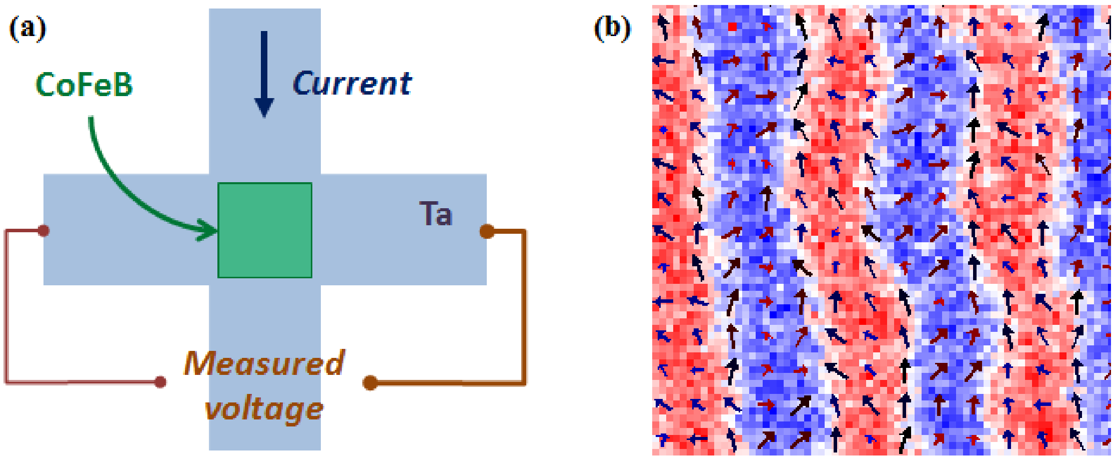


*Fig. 1: (a) Schematics of the bilayered structure under investigation; (b) Example of configuration of the magnetization in the CoFeB layer (zoomed-in area) under the influence of spin-Hall effect.*

***References***

*[1] A. Imre, et al., Science 311, 205-208 (2006).*
*[2] D. Bhowmik, et al., Nature Nanotech. 9, 59-63 (2014).*
*[3] I.M. Miron, et al., Nature 476, 189-193 (2011).*

# Tunable Ground State Symmetry Breaking In Artificial Square Spin Ice

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*(3) Helmholtz-Zentrum Dresden-Rossendorf, Institute of Ion Beam Physics and Materials Research*
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*(6) Materials Science Division, Argonne National Laboratory*
*(7) Dept. of Physics and Astronomy, Northwestern University*

In artificial square spin ice, magnetic nanoelements are geometrically arranged in arrays to mimic the frustration found in rare earth titanate pyrochlore crystals[1]. So far, such arrays have implicitly been considered to be a more or less exact analogue of their atomic counterpart with each nanoisland having two possible orientations of the magnetization owing to shape anisotropy. In this picture, artificial square ice is characterized by a two-fold degenerate ground state, which has been observed in recent measurements[2]. It has been shown, however, that in addition to the overall direction of the magnetization, artificial square ice possesses a large number of internal degrees of freedom owing to the structure of the magnetization and that these degrees of freedom give rise to distinct features in the resonant dynamics spectrum of the system[3]. Some of the degrees of freedom are connected to the bending of the magnetization at the edge of the nanostructures resulting from magnetostatic coupling to its nearest neighbors[4] and leading to the formation of C or S states in the elements[5]. Using micromagnetic simulations, we demonstrate that the C and S states are degenerate and that their presence gives rise to a large ground state degeneracy with an extensive entropy. The increased degeneracy is visible in the resonant spectrum obtained in the presence of a symmetry-breaking field pulse along the diagonal of the array. The spectrum reveals distinct signatures for the C and S states and the resonances are about 800 MHz apart, making them experimentally observable. Moreover, this degeneracy can be tailored by tuning the magnetostatic coupling within the array through the saturation magnetization ($M_S$) or thickness $t$ of the islands. For large coupling (or $M_St$), islands have C- or S-end-domains, while for small $M_St$, the magnetization in each element is in a symmetric onion state and the two-fold degenerate ground state is recovered. Our work demonstrates how subtle changes in nanoelement geometry and in magnetic properties can lead to fundamentally novel collective behavior in artificial spin ice. This opens additional possibilities of tailoring the properties of artificial spin ice for potential magnonic applications[6].

***References***

*[1] R. F. Wang, C. Nisoli, R. S. Freitas, J. Li, W. McConville, B. J. Cooley, M. S. Lund, N. Samarth, C. Leighton, V. H. Crespi and P. Schiffer, Nature 439, 303 (2006)*
*[2] A. Farhan, P. M. Derlet, A. Kleibert, A. Balan, R. V. Chopdekar, M. Wyss, J. Perron, A. Scholl, F. Nolting, and L. J. Heyderman, Phys. Rev. Lett. **111**, 057204 (2013)*
*[3] S. Gliga, A. Kakay, R. Hertel, and O. G. Heinonen, Phys. Rev. Lett. 110, 117205 (2013)*
*[4] N. Rougemaille, F. Montaigne, B. Canals, M. Hehn, H. Riahi, D. Lacour, and J.-C. Toussaint, New J. Phys. **15** 035026 (2013)*
*[5] S. Hankemeier, R. Frömter, N. Mikuszeit, D. Stickler, H. Stillrich, S. Pütter, E. Vedmedenko, and H. Oepen, Phys. Rev. Lett. **103**, 147204 (2009)*
*[6] M. Krawczyk and D. Grundler, J. Phys.: Condensed Matter **26**, 123202 (2014)*

O7 – Monday, 18th of May 2015 – 17:00-17:20

# Topological Skyrmion Dynamics Driven By Spin-Transfer Torque

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Very recently, an important class of magnetic solitons called magnetic skyrmions has been widely studied [1,2]. The stability of these topological defects has been analyzed in the presence of intrinsic dissipation both as a function of Dzyaloshinskii–Moriya interaction (DMI) and of a spin-polarized current (SPC). Here, we show that in a spin-valve consisting of Pt(5 nm)/Co(0.6 nm)/Cu (4 nm)/CoPt(4 nm) a perpendicular spin current, in the presence of DMI [3] and strong perpendicular anisotropy, induces the rotation of the spins from the hedgehog-like to the vortex-like texture in the topological droplet state and excites low-frequency topological modes. The SPC is injected locally in the Co giving rise to the local excitation of the magnetization. The FL has a square cross section of 400 x 400 nm$^2$, while the point contact has a diameter of 70 nm. Both FL and polarizer have out-of-plane magnetic state at zero bias field. The "topological droplet" state (integer skyrmion number) arises and its dynamical response, namely a "topological mode" (TM), can be excited and sustained by a SPC. The low-frequency TM is linked to a continual conversion from hedgehog-like (Néel skyrmion) to vortex-like (Bloch skyrmion) state, preserving the topology represented by the skyrmion number S = -1. The topological character of these spin-wave excitations results from the synchronized dynamics between the 360$^{\circ}$ rotation of the spin of the outer droplet domain and the expansion/shrinking of the droplet core. A quantitative description of topological droplet modes is given according to an analytical model based on the linearization of the equations of motion including intrinsic positive Gilbert damping and negative damping related to the spin-transfer torque. The predictions on the TM dynamics of the analytical model are quantitatively enforced by the ones obtained according to numerical simulations. The micromagnetic parameters are typical of Co: saturation magnetization $M_s$=900 kA/m, perpendicular anisotropy constant $k_u$=1.10 MJ/m$^3$, exchange constant A=20 pJ/m, DMI parameter 0<D<3.0 mJ/m$^2$ and magnetic damping $\alpha_G$=0.1. Fig.1 shows the topological mode frequencies as a function of the current density above its threshold value for two different values of D. The frequencies show red-shift behavior as a function of the current and the analytical calculations are in good accordance with micromagnetic predictions. The theoretical results could open the route for experiments based on the giant magnetoresistance effect able to detect the topological modes and for the design of a further generation of nanoscale microwave oscillators.

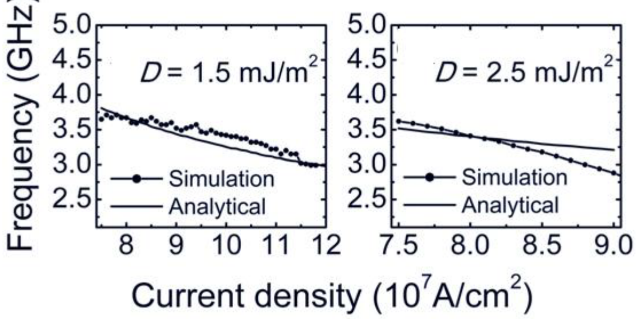


*Fig. 1: Oscillation frequency of the TM as a function of the current density for different DMI.*

***References***

*[1] Fert, V. Cros, and J. Sampaio, Nat. Nanotech. 8, 152, (2013).*
*[2] J. Iwasaki, M. Mochizuki, and N. Nagaosa, Nat. Comm. 4, 1463, (2013).*
*[3] T. Moriya, Phys. Rev. Lett. 4, 228, (1960). I. Dzyaloshinskii, J. Phys. Chem. Solids 4, 241, (1958).*

# Micromagnetic Modelling Of Voltage-Induced Spin-Diode Effect In Magnetic Tunnel Junctions

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Recently, the possibility of inducing ferromagnetic resonance (FMR) in magnetic tunnel junctions (MTJs) by electric field has been shown experimentally and described with macrospin model [1]. By applying an alternating voltage to a high-resistance MTJ, one can observe perpendicular magnetic anisotropy (PMA) changes which may result in magnetization precession while the effects of small current flow on magnetization remain negligible. The signal can be detected by measurements of the static voltage arising from the mixing of alternating current and resistance changes during magnetization precession. It is a particularly interesting effect because of low power consumption in comparison to magnetic field and electric current excitation methods.

In this work we use Object Oriented Micromagnetic Framework [2] to analyse the dynamics in CoFeB/MgO/CoFeB PMA junction induced by high-frequency anisotropy changes. We calculate the mixing voltage [3] during the sweep of the excitation frequency in order to investigate line shape. We extract the phase shift between voltage-induced anisotropy changes and the resistance response and use it to quantitatively separate between current-voltage and anisotropy-resistance phase shift contributions to symmetric and antisymmetric component of the detected signal. Example results are depicted in Fig.1.

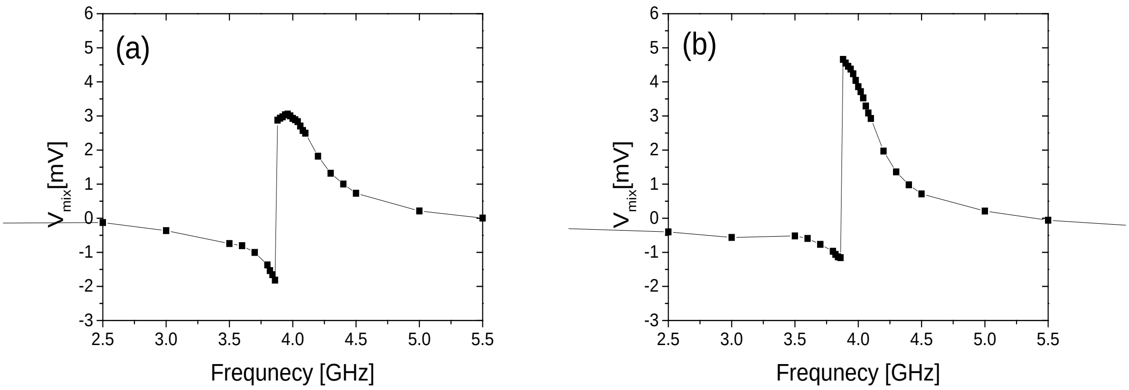


*Fig 1. Example of line shape obtained for the same system with different current-voltage shifts of 0 (a) and π/6 (b).*

Project was co-financed by the Polish Ministry of Science and Higher Education - Diamond Grant DI2011001541 and Polish National Science Center grant Harmonia DEC-2012/04/M/ST7/00799.

***References***

*[1] T. Nozaki, Y. Shiota, S. Miwa, S. Murakami, F. Bonell, S. Ishibashi, H. Kubota, K. Yakushiji, T. Saruya, A. Fukushima, S. Yuasa, T. Shinjo, Y. Suzuki, Nature Physics 8, 491–496 (2012).*
*[2] M.J. Donahue, D.G. Porter, OOMMF User's Guide, Version 1.0, NIST report (1999).*
*[3] M. Frankowski, M. Czapkiewicz, W. Skowroński, T. Stobiecki, Physica B: Condensed Matter 435, 105 (2014).*

O9 – Monday, 18th of May 2015 – 17:40-18:00

# Modelling Hysteresis And Creep Through A Nonlinear Circuit

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Hysteresis and creep are nonlinear phenomena affecting the behaviour of piezoelectric actuators (PEAs). Since PEAs are widely employed in micro-positioning applications because of their high stiffness and resolution [1,2,3], the hysteretic and creep nonlinearities are highly undesirable, as they result in loss of positioning precision and repeatability. In order to reduce these undesired effects, feed-forward compensation approaches are a very attractive choice, because of their sensorless nature; however, these techniques require accurate modelling of the PEA dynamical behaviour, including its hysteresis and creep. While there is an extensive literature on mathematical models and memory characteristics of rate-independent hysteresis, this is not so for creep, which is usually modelled through a logarithmic dependence on time.

Several phenomenological models of varying complexities have been proposed [4,5,6] to represent both phenomena, but usually they combine distinct models of hysteresis and creep.

In this paper, we refer to a recently proposed circuit model [7], shown in Fig. 1, in which hysteresis and creep are modelled together. This is possible since the main nonlinear elements in the model are resistors that exhibit the power law characteristic shown in Fig. 2.

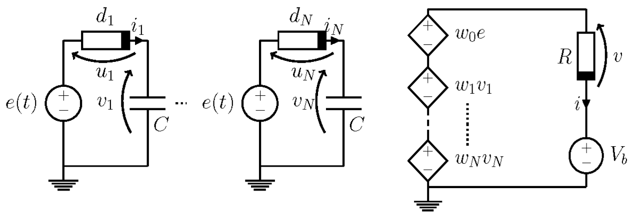


*Fig. 1*

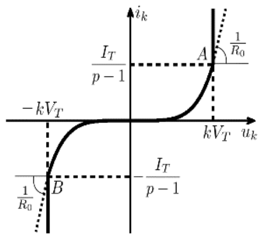


*Fig. 2*

With respect to [7], here we provide a more detailed analysis of the model and better compare it to the Kuhnen's one [5]. Moreover, we propose some possible alternatives for specific model elements and for the numerical procedure to identify the model parameters from experimental measurements.

***References***

[1] *S. Devasia et al, IEEE Trans. Ctrl. Sys. Tech., **15**, (2007), 802-823.*
[2] *X. Wang et al, Contr. Eng. Pract., **33**, (2014), 48-62.*
[3] *S. Moriyama et al, Opt. Eng., **27**, (1988), 1008-1012.*
[4] *H. Jung, D. Gweon, Rev. Scient. Instr., **71**, (2000), 1898-1900.*
[5] *K. Kuhnen, Contr. Intell. Syst., **33**, (2005), 134-147.*
[6] *K. Kuhnen, P. Krejci, IEEE Trans. Autom. Contr., **54**, (2009), 537-549.*
[7] *M. Biggio et al., IEEE Trans. Circ. Syst. II, in the press, doi: 10.1109/TCSII.2014.2385412*

# Micromagnetic Simulations Beyond Landau-Lifshitz-Gilbert Model

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Micromagnetic simulations play a vital role in modern nanomagnetism having both explanatory and predictive powers. They typically rely on the phenomenological theory proposed by Landau, Lifshitz and Gilbert, i.e. the so-called LLG model. It neglects longitudinal magnetization dynamics, symmetry properties of the damping constant and relaxations of the exchange nature. As the experiments on the magnetization dynamics approach the length- and time- scales of the exchange interaction, the aforementioned effects cannot be neglected anymore. Since more advanced theories are still in their infancy, there is a need for novel micromagnetic tools that could account for emerging magnetic phenomena, maintaining the flexibility of the state-of-the-art LLG-based solvers, e.g. mumax3, OOMMF, nmag. Here we present hotspin[1] - an open-source GPU-accelerated finite-difference micromagnetic solver that incorporates Landau-Lifshitz-Baryakhtar (LLBar) phenomenological equation[2] that allows for the separation of the spin-electron and spin-phonon relaxation terms and their self-consistent coupling to the two-temperature model. The theory generalizes LLG approach to include all the aforementioned effects. We demonstrate how our package could be used to (a) simulate paramagnetic-to-ferromagnetic phase transition, (b) fit electron-phonon coupling and intrinsic damping constants and (c) demonstrate how the anizotropy of the damping constant could be extracted from the FMR measurements.

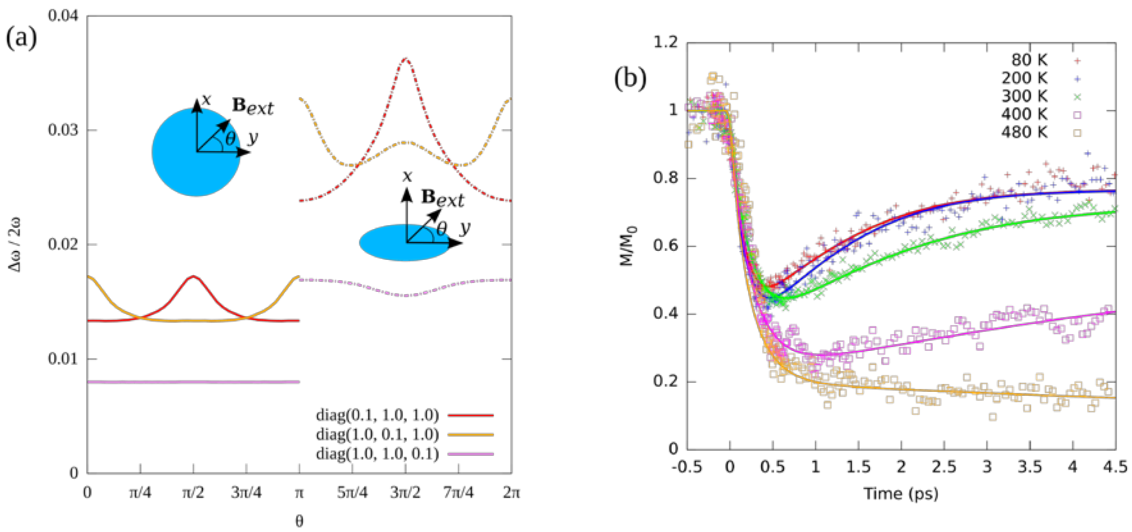


*Fig. 1. (a) The macroscopic damping constant calculated using LLBar model for different sample geometries and symmetries of the damping constant [3]. (b) Fitting of the LLBar-2TM model (solid lines) to the experimental data on the ultrafast demagnetization of Nickel (points) for various ambient temperatures [4].*

***References***

[1] M. Dvornik, computer code HOTSPIN (Ghent University, Belgium, 2014).
[2] I. V. Baryakhtar and V. G. Baryakhtar, Ukr. J. Phys. 43, 1433 (1998).
[3] M. Dvornik, A. Vansteenkiste, and B. Van Waeyenberge, PRB 88, 054427 (2013).
[4] M. Dvornik, A. Vansteenkiste, and B. Van Waeyenberge, APL 105, 162411 (2014).

O11 – Monday, 18th of May 2015 – 18:20-18:40

# Dynamical Response Of Spin-Hall Nano-Oscillators As Function Of External Bias Field

**A. Giordano[1], R. Zivieri[2], M. Carpentieri[3], A. Laudani[4], G. Gubbiotti[5], B. Azzerboni[1], G. Finocchio[1]**

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In these last years, the study on nano-oscillators gave rise to the starting point of new applications in spintronics. Here we studied systematically the excitation mode in spintronic oscillators based on the Spin-Hall effect. We studied a new structure with two layers, heavy-metal coupled with a ferromagnet. The structure used in this study has dimensions 1.5μm x 3.0 μm with rectangular shape. The two contacts (fig.a-inset 1 ) are positioned above a bi-layer of (CoFeB(1nm)/ Pt(8nm)) (fig.a- inset 2) at a distance of d=100nm. The current is injected (along the x-direction) via the two Gold contacts (Au (150nm)). We have performed a systematic study based on micromagnetic simulations to understand the origin of the exited modes and the dynamical behavior as a function of field amplitude and current. In the figure a) is represented the behavior of the current density threshold for different values of field. Our main results is the identification of a new mode with a spiral structure, we namely spiral mode (see figure b) for a snapshot).

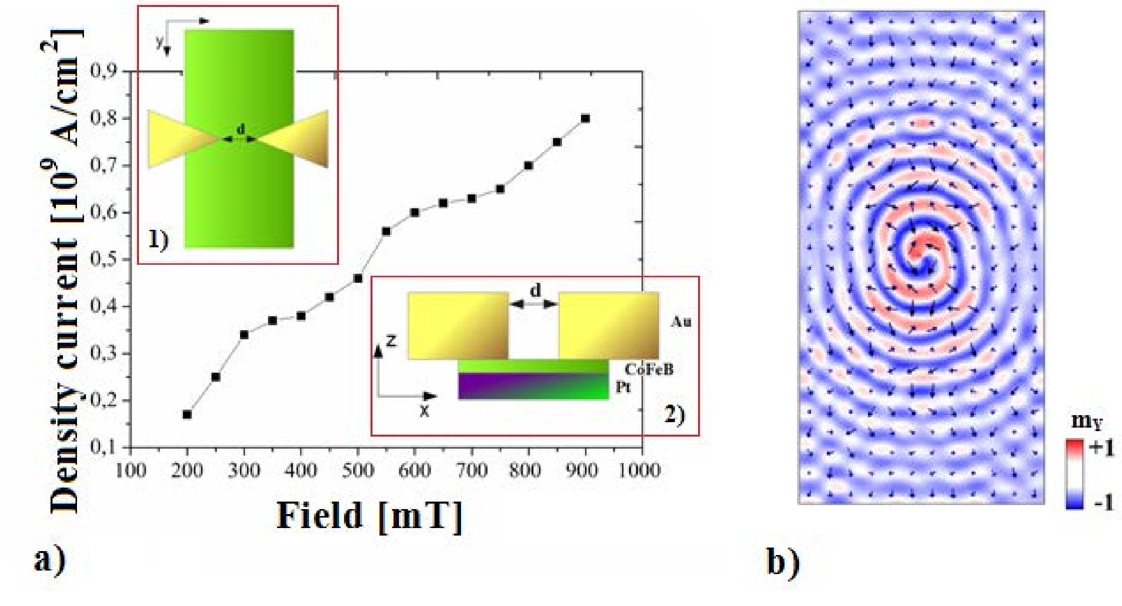


*Fig: a) It is perform the trend of the threshold density of current for different values of fields (inset 1 indicates the device in piano x-y; inset 2 shows front view of the device, it is constitutes by three layers); b) shows the progress of the frequency respect at the density current also is shows the configuration of magnetization.*

# Skyrmion Motion Under A Spin-Hall Current In Confined Magnetic Nanostructures

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We solve both analytically and numerically Thiele's equation describing the motion of a magnetic skyrmion in the presence of a spin-Hall current with no external field and by taking into account confinement effects in magnetic nanostructures [1]. In particular, the solution of Thiele's equation is found for describing the skyrmion motion in a thin magnetic nanostripe. The spin-Hall current injected in the heavy metal combined with the interfacial Dzyaloshinskii–Moriya interaction favors the Néel (hedgehog-like) skyrmion nucleation in the magnetic nanostripe. Confinement effects are modeled by introducing a potential at the boundaries of the magnetic stripe. This potential can be thought of as a repulsive barrier associated to the static magnetization rotation at the stripe borders. The Nèel skyrmion is interpreted as a quasi-particle which interacts repulsively with this barrier. The effect of this interaction is to cause a deviation of the magnetic skyrmion trajectory. When confinement is neglected the Néel magnetic skyrmion moves along an in-plane direction perpendicular to that of the spin-Hall current inside the ferromagnetic nanostripe [2]. Instead, in the presence of confinement effects the trajectory followed by the Nèel skyrmion is perpendicular to that of the spin-Hall current in the central portion of the stripe where the effects of the force arising from the boundary potential are opposites, while it deviates considerably from this direction when the Néel skyrmion approaches the upper (or the lower) border of the stripe placed perpendicularly to the skyrmion velocity. This behavior is interpreted in terms of the scattering of a quasi-particle with the potential barrier created by the rotation of the magnetization on the border. The dependence of this deviation on the stripe magnetic parameters is discussed both analytically and micromagnetically.

This work was supported by MIUR-PRIN 2010-11 Project2010ECA8P3 "DyNanoMag".

***References***

*[1] J. Iwasaki, M. Mochizuki, and N. Nagaosa, "Current induced skyrmion dynamics in constricted geometries", Nat. Nanotech. 8, 742 (2013).*
*[2] R. Tomasello, E. Martinez, R. Zivieri, L. Torres, M. Carpentieri, and G. Finocchio, Sci. Rep. 4, 6784 (2014).*

O13 – Tuesday, 19th of May, 2015 – 11:40-12:00

# Differentiation Formula For The Stochastic Magnetization Dynamics In Ferrimagnets

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For many applications where magnetic properties play a crucial role, temperature effects can become a limiting factor (aging issues, magnetic resonance broadening …). In this context, predictive models taking these effects into account and providing an overview of the temperature dependence on the functional properties can be of fundamental importance.

A temperature dependent equation for the magnetization dynamics can be obtained by introducing a random torque in the Landau-Lifshitz-Gilbert equation [1]. A fluctuation-dissipation theorem is established, relating the temperature of an external thermal bath to the amplitude of the noise fluctuations. Moreover, the transverse form of the damping term in this stochastic equation ensures the conservation of the magnetization norm, which is essential for atomistic spins.

Atomistic simulations of interacting spins at finite temperature show that the magnetization, averaged over the noise, does not conserve its norm. D.A. Garanin [2] and P.-W. Ma [3] have considered several approximation schemes to mimic this collective effect by introducing an effective, temperature--dependent, longitudinal damping term.

Following these ideas and inspired by the theory of liquids, a hierarchy of coupled equations of motion is derived for the correlation functions of both noise and spins in the case of colored noise. Valid for every correlation order, a consistent closure relation is imposed to solve the dynamics of the magnetization, averaged over the noise.

We finally compare the predictions for the dynamics of this solution to results of our atomistic spin dynamic code [4] in the case of ferrimagnetic exchange interactions.

***References***

*[1] I.D. Mayergoyz, G. Bertotti, and C. Serpico. Nonlinear magnetization dynamics in nanosystems. Elsevier, 2009.*

*[2] D.A. Garanin. Fokker-Planck and Landau-Lifshitz-Bloch equations for classical ferromagnets. Physical Review B, 55(5):3050, 1997.*

*[3] P-W. Ma and S.L. Dudarev. Langevin spin dynamics. Phys. Rev. B, 83(13):134418, 2011.*

*[4] D. Beaujouan, P. Thibaudeau, and C. Barreteau. Thermal behavior of superparamagnetic cobalt nanodots explored by anisotropic magnetic molecular dynamics simulations. J. Appl. Phys., 111(7):07D126, 2012.*

# 2-Inputs 2-Outputs Relationships Of Smart Materials: An Experimental Evaluation

**C.S. Clemente[1], D. Davino[1], J. Kopfová[2], P. Krejčí[3], C. Visone[1]**

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*(3) Institute of Mathematics, Academy of Sciences of the Czech Republic, Praha, Czech Republic.*

Smart materials applications are growing year after year. Piezoelectrics are the most known. This advantage is due to the fact that the piezoelectric effect is driven by voltage and charge and it's easier to exploit in electronic oriented applications. Magnetostrictives like Terfenol-D are employed in actuation applications, both in quasi-static and resonant-like behavior while Galfenol can be employed for energy harvesting [1]. But, their smartness has not been exploited all yet because of the hysteretic and complex character of the coupling between mechanical and electro-magnetic variables. Usually, simple 1-input 1-output hysteresis operators are proposed [2], while the fully coupling must be exploited through 2-inputs 2-outputs models that take into account thermodynamic compatibility [3]. For magnetostrictives:

$$\varepsilon = \frac{\sigma}{E_0} - f'(\sigma) P\left[h/f(\sigma)\right], \qquad b = \mu h + U\left[h/f(\sigma)\right]. \tag{1}$$

where $\varepsilon$ is the strain, $\sigma$ the stress, $h$ and $b$ are the magnetic field and induction, respectively. $P$ is a hysteresis operator and $U$ its potential, while $f$ is a suitable function. On the other hand, when models have to be employed in ODE or PDE numerical codes, it is useful to have formulations where ε and h are inputs [4]:

$$\sigma = E_0\varepsilon + \lambda h + P_1\left[h,\varepsilon\right], \qquad \mathrm{b} = \lambda\varepsilon + \mu\,\mathrm{h} + \mathrm{P}_2\left[h,\varepsilon\right]. \tag{2}$$

Aim of this paper is to present a complete characterization of smart materials as Terfenol-D, Galfenol, and piezos, where experiments are performed with different controlled inputs, in order to have suitable hints for different modeling, as (1) and (2). For example, Fig.1 shows the classical butterfly-like ($\varepsilon$ vs $h$) behaviour at different $\sigma$ of Terfenol-D. Fig.2 shows experimental mechanical behavior $\left(\lambda h + P_1\left[h,\varepsilon\right]\right)$ at different h-fields.

*Fig. 1 Butterfly-like curves of Terfenol-D at different σ.*

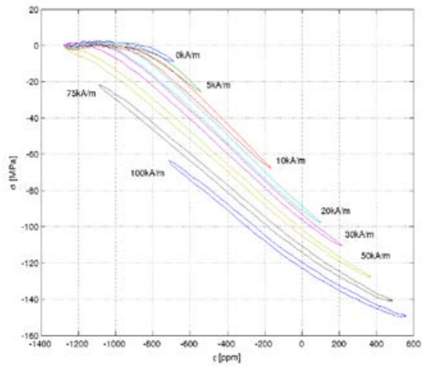


*Fig. 2 Mechanical plots ( σ vs ε) of Terfenol-D at different fields h.*

### *References*

*[1] D.Davino et al, IEEE Trans on Mag, 48(11), pp.3096-3099, 2012.*
*[2] K. Kuhnen, P. Krejci, IEE Trans on Automatic Control, 54(3), pp. 537-550, 2009.*
*[3] D.Davino, P. Krejci, C. Visone, 22(9), 095009, 2013.*
*[4] B.Kaltenbacher, P.Krejci, arXiv:1412.4527 [math.AP], submitted for publication.*

O15 – Tuesday, 19th of May, 2015 – 12:20-12:40

# Shape-Dependent Exchange Bias Effect In Magnetic Nanoparticles With Core/Shell Morphology

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*(3) Department of Electrical Engineering, East Macedonia and Thrace Institute of Technology, GR-65404*

We study the isothermal magnetic hysteresis of cubical and spherical nanoparticles with FM core/AF shell morphology, in order to elucidate the sensitivity of the exchange bias effect on the shape of the particles and the structural imperfections at the core-shell interface. We use a classical Heisenberg Hamiltonian with local anisotropy for modelling the magnetic structure and the Metropolis Monte Carlo algorithm to study the field-cooled process and the isothermal hysteresis loop. The coercive and exchange bias fields for spherical and cubical nanoparticles with similar nominal sizes are compared.

Our simulations at low temperature show that : (i)Cubical particles exhibit higher coercivity than spherical ones, however this situation can be reversed for strongly disorderd interfaces. (ii) Cubical particles exhibit lower exchange bias field than spherical ones, owing to the lower number of uncompensated spins, a fact that stems from the geometrical shape of the FM-AF interface. (ii) The presence of interface disorder supresses the exchange bias field in the case of uncompensated interfaces (spherical or cubical particles), while the opposite trend is observed for compensated interfaces (cubical particles, only). (iii) With increasing degree of interface disorder the differences between spherical and cubical particles are gradually smeared out, rendering the shape effects of minor importance. (iv) The atomic scale details of the interface disorder (alloying or roughness) are of secondary importance in the dependence of the exchange bias and coercive fields on the degree of disorder. Our results shed new light in the interpretation of recent experimental findings on the shape-dependent exchange-bias effect in nanoparticles.

**Acknowledgment:** research co-financed by the European Social Fund and Greek national funds through the Research Funding Program *ARCHIMEDES-III*.

# Self-Consistent Computation Of Magnetization Dynamics In The Presence Of Spin-Polarized Currents

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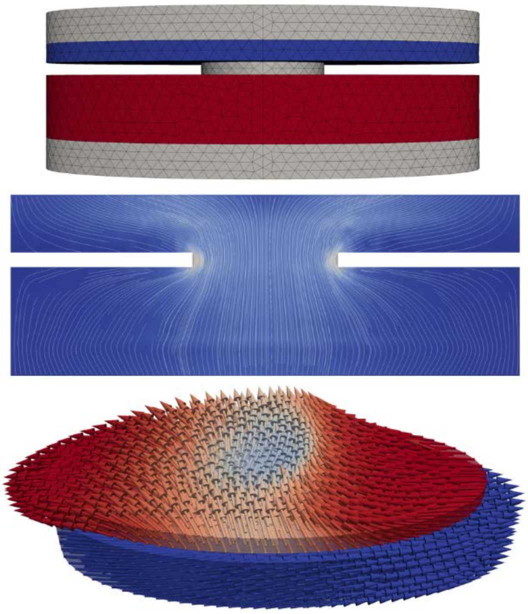
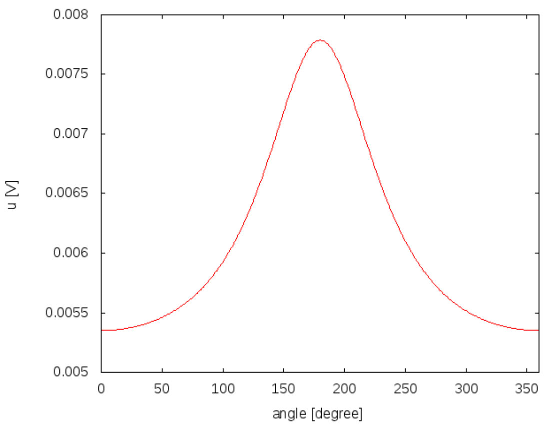
We propose a model for self-consistent computations of the magnetization dynamics in the presence of spin-polarized currents, which extends the model from [2] to full three-dimensional systems. The nonlinear system of equations consists of the Landau-Lifshitz-Gilbert equation, an elliptic equation to model the spin accumulation in the stationary regime, and an equation for the electric potential derived from the Maxwell equations. The system is discretized by a numerical method which combines finite elements and boundary elements [1], for which we show some preliminary convergence results. The presented model accounts for nonlocal spin-torque contributions due to spin diffusion and describes composite material structures in a self-consistent manner. The model solves for the magnetization dynamics as well as the electric current and spin accumulation and only requires the initial magnetization configuration and the electric potential on the boundary as input parameters.



*Switching of a multilayer structure: The computational domain (top) consists of two ferromagnetic layers (blue and red) and three nonmagnetic but conducting layers (grey). Snapshots of the field lines of the electric current (middle) and the magnetization configuration (bottom) during the switching process.*




*A circular multilayer structure with equally thick and homogeneously magnetized magnetic layers separated by a nonmagnetic layer is considered. The plot shows the potential difference applied between the top and the bottom of the structure, that is needed to retrieve a constant current flow through the sample as a function of the tilting angle of the magnetization of the two layers.*

***References:***

*[1] C. Abert, G. Hrkac, M. Page, D. Praetorius, M. Ruggeri, and D. Suess. Spin-polarized transport in ferromagnetic multilayers: An unconditionally convergent FEM integrator. Comput. Math. Appl., 68(6):639–654, 2014.*
*[2] S. Zhang, P. M. Levy, and A. Fert. Mechanisms of spin-polarized current-driven magnetization switching. Phys. Rev. Lett., 88(23):236601, 2002.*

O17 – Tuesday, 19th of May, 2015 – 15:00-15:20

# Accessing Different Spin-Disordered States Using First-Order Reversal Curves

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*(2) Department of Physics, University of Gothenburg, Gothenburg, Sweden*

*(3) Materials Physics, School of ICT, Royal Institute of Technology (KTH), Kista, Sweden*

Uncovering the mechanisms that govern hysteretic reversal is critical to their basic understanding and potential applicability. Of particular interest are ferromagnetic/non-magnetic layered structures exhibiting magnetoresistance (MR). While the first order reversal curve (FORC) technique [1] has historically been applied to a variety of magnetic systems, its applicability has been recently extended to systems exhibiting thermal, electrochemical, ferroelectric, and resistive hysteresis [2]. In addition to providing a useful qualitative "fingerprint" of the reversal mechanisms, FORC analysis has shown the ability to probe a wealth of quantitative information regarding reversible/irreversible switching, interactions, and distributions of key magnetic parameters not readily accessible from standard major loop investigations. Here, we provide a *combined* FORC analysis of the magnetization, termed M-FORC, and magnetoresistance, termed MR-FORC, to provide a comprehensive picture of the reversal mechanisms in a multilayered $[Co/Cu]_8$ film stack.

Families of M-FORCs and MR-FORCs are shown in Fig. 1(a) and 1(c), respectively. Interestingly, MR values up to 4.83% are found along selected MR-FORCs, larger than the 4.25% MR maximum of the major loop. Furthermore, the MR-FORC distribution, Fig. 1(d), reveals a different irreversibility landscape as compared to the M-FORC distribution, Fig. 1(b), as further verified in the FORC switching field distributions (FORC-SFDs), Fig. 1(e). Unlike the M-FORC measurements, which are sensitive to the macroscopic changes in magnetization, the MR-FORCs probe the microscopic domain configurations and the net spin disorder, as those are most important in determining the resultant MR value [3].

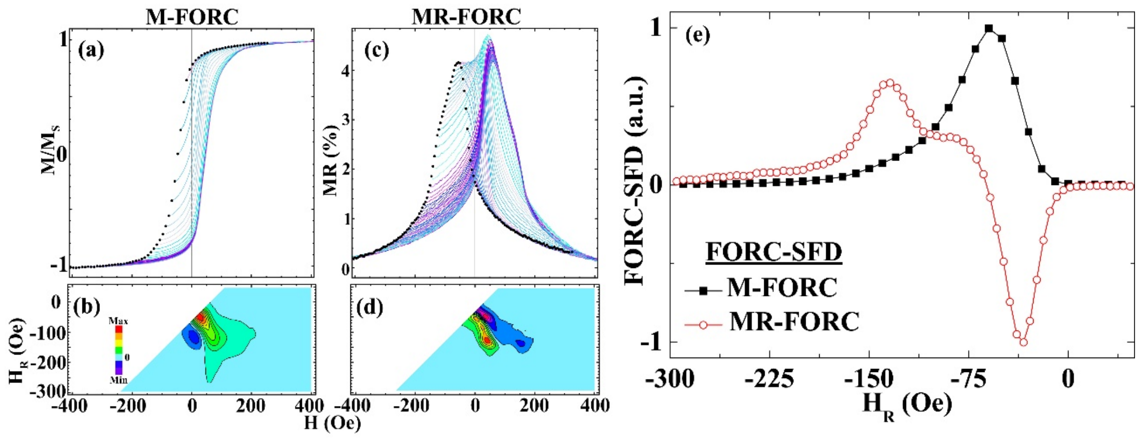


*Fig. 1: Families of (a) M-FORCs, (c) MR-FORCs, and corresponding FORC distributions are shown in (b) and (d), respectively. (e) FORC-SFDs.*

This work has been supported by the NSF (Grants No. DMR-1008791 and No. ECCS-1232275), the Swedish Research Council (VR), the Swedish Foundation for Strategic Research (SSF), and the Knut and Alice Wallenberg Foundation.

***References***

[1] C.R. Pike, et al., J. Appl. Phys. **85**, 6668 (1999); J.E. Davies, et al., Phys Rev B **70**, 224434 (2004); R.K. Dumas et al., Phys. Rev. B **75**, 134405 (2007).

[2] C. Enachescu, et al., Phys. Rev. B **72**, 054413 (2005); D. Ricinschi, et al., J. Optoelectron. Adv. M **6**, 623 (2004); J.M. Pomeroy, et al., APL **95**, 022514 (2009).

[3] R.K. Dumas, et al., Phys. Rev. B **90**, 104410 (2014).

# Better FORC Diagrams

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Since their introduction in 1999, the FORC diagrams are obtained in essentially one and the same way. It boils down to local approximation of the acquired data, $M(H_a, H_b)$, point after point, by quadratic forms, which are easy to differentiate. Then the calculation of FORC diagram is pretty straightforward: the FORC/Preisach density is proportional to the mixed second derivative of $M(H_a, H_b)$ with respect to $H_a$ and $H_b$. Unfortunately, such a procedure may introduce artifacts not present in original data and is unreliable in the vicinity of a line $H_a=H_b$. Double numerical differentiation significantly decreases the signal to noise ratio, thus some kind of smoothing seems unavoidable. It is usually implemented, somewhat arbitrarily, at the first step of calculations.

Here I present a different approach, based on 2D Fourier Transform applied to eight replicas of the original data. After suppression of high frequency components, by Wiener filter accounting for revealed noise level, the second derivative of this spectrum is computed analytically. Inverse Fourier Transform then recovers the desired FORC landscape with well defined resolution in place of smoothing factor, commonly used today. Less obvious advantage of this approach is the possibility to recover the anhysteretic part of magnetization curve directly from experiment. Currently its shape is only speculated, but this curve is a crucial component of the Jiles-Atherton model of magnetic hysteresis. It is also hoped that the Fourier Transform of FORC landscape, being insensitive to its conformal deformations, may appear more informative with respect to the physical factors behind the observed hysteresis. Last but not least: having the FORC landscape in a convenient form, and assuming some analytical form of the hysterons' lifetime, one could easily simulate hysteretic behavior of a given sample at arbitrary frequency of the driving field.

***References:***

*[1] Ch.R.Pike, A.P.Roberts, K.L.Verosub, Characterizing interactions in fine magnetic particle systems using first order reversal curves, J.Appl.Phys. 85 (9) 6660–6667 (1999)*

O19 – Tuesday, 19th of May, 2015 – 15:40-16:00

# Thermal Decoupling Of Dense-Packed Nanocrystalline Ribbons: Direct Evidence By FORC Technique

**M. Rivas, J. C. Martínez-García and P. Gorría**

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Devitrifying ferromagnetic amorphous precursors in the adequate conditions may give rise to disordered assemblies of densely-packed nanocrystals with extraordinary magnetic softness well explained by the exchange coupling of multiple crystallites [1]. Whether the exchange interaction is produced by direct contact or mediated by the intergranular amorphous matrix has a strong influence on the thermal behaviour of the system above room temperature. Bi-phase amorphous-crystalline systems dramatically harden when approaching the amorphous Curie temperature due to the hard grains decoupling, as explained by Hernando et al [2, 3] in their extension of Herzer's model.

The study of the thermally-induced decoupling of nanosized crystallites embedded in an amorphous matrix has been performed in this work by the First-Order Reversal Curves (FORC) analysis. Such technique conveniently facilitates the identification of different magnetic phases, their critical switching fields and mutual magnetic interactions.

The base amorphous alloy chosen for this work has a Curie point of 330 K, which is the cause of the noticeable differences in the FORC diagrams obtained below and above such temperature in the bi-phase nanocrystallized sample (see Fig. 1). Precise information about the grain decoupling can be inferred from the FORC diagram thermal evolution.

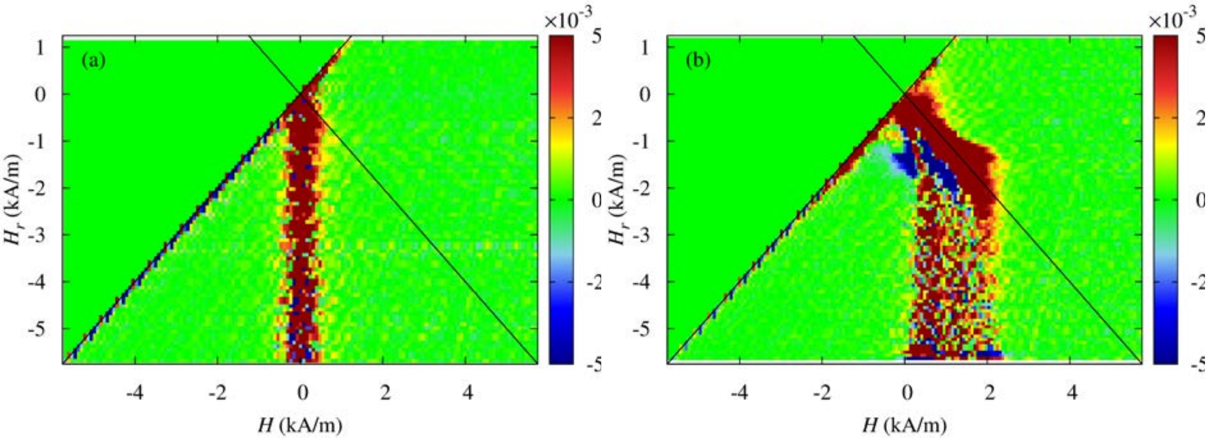


*Fig. 1: FORC diagrams of a dense-packed nanocrystallized sample at (a)* 297 *K and (b)* 390 *K*

***References***

*[1] G. Herzer, J. Magn. Magn. Mater., vol. 157/158, pp. 133–136, 1996.*
*[2] A. Hernando, M. Vázquez, T. Kulik, and C. Prados, Phys. Rev. B, vol. 51, no. 6, pp. 3581–3586, 1995.*
*[3] A. Hernando, P. Marín, M. Vázquez, J. M. Barandiarán, and G. Herzer, Phys. Rev. B, vol. 58, no. 1, pp. 366–370, 1998.*

O20 – Tuesday, 19th of May, 2015 – 16:00-16:20

# Using FORC Method For Detection Magnetic Components In $Fe_2O_3$@$BaTiO_3$ Composites With Core-Shell Structure

**L.P. Curecheriu[1], P. Postolache[2], M.T. Buscaglia[3], V. Buscaglia[3], L. Mitoseriu[1], A. Stancu[2]**

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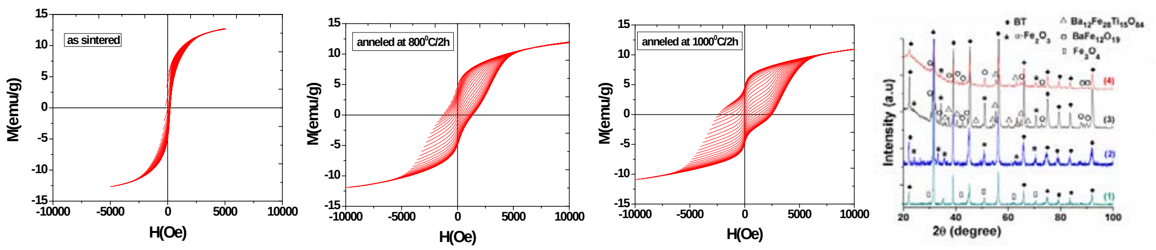
The nanoscale coating of particles with dissimilar compounds is an effective tool to engineer their surface, microstructural characteristics and functional properties. The core-shell approach and appropriate sintering is a successful route to obtain desired microstructures with various degrees of connectivity in ceramic composites. Core-shell multiferroics formed by a Fe2O3 core (with magnetic order) and BaTiO3 shell (ferroelectric order) were prepared and then densified using spark plasma sintering [1]. As result of solid state reaction at interfaces, variable amounts of secondary phases ($Fe_3O_4$, $BaFe_{12}O_{19}$ and $Ba_{12}Fe_{28}Ti_{15}O_{84}$) were induced at interfaces and they produced new functional properties of composites. Their amount was controlled by different thermal treatments and monitored by FORC and structural analysis.

Peculiar magnetic properties, including "wasp-waisted" constricted M(H) loops were determined as result of the formation of magnetic phases with contrasting magnetic coercivities (hard and soft phases) (Fig. 1 (a), (b), (c)). The macroscopic M(H) response is dominated by the high-magnetisation components. Therefore, to understand the magnetic properties induced by the formation of secondary phases, first-order-reversal FORC method was employed [2]. This method proved to be very sensitive for the direct detection of small amounts of magnetic components with contrasting coercivities formed at interfaces. The results of the FORC analysis have been confirmed by structural analysis.




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

*Fig. 1 (a), (b), (c) – FORC measured curves; (d) – XRD pattern on $Fe_2O_3$@$BaTiO_3$ ceramics calcined at various temperatures.*

**Acknowledgement:** The financial support of the PN II-PCCE-2-2011-0006 grant is acknowledged.

***References***

*[1] M.T. Buscaglia et al., Chem. Mater. 22, 4740–4748 (2010)*

*[2] A. Stancu et al., Appl. Phys. Lett. 83, 3767-3669 (2003).*

O21 – Tuesday, 19th of May, 2015 – 16:20-16:40

# Analytical Solution Of Precessional Switching In Nanomagnets Driven By Hard-Axis Field Pulses

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The high-speed and energy-efficient switching of magnetic particles is a central issue in magnetization dynamics for its application to magnetic recording nanotechnologies [1].

Several strategies have been analysed in recent years in order to circumvent the slow relaxation that occurs in switching an anisotropic nanomagnet by means a large enough external field opposite to the initial magnetization. This process has been often referred to as damping switching [2]. Possible more efficient alternatives include microwave-assisted switching [3] and precessional switching [4]. In particular, the latter occurs through the application of a field perpendicular to the initial magnetization and directed along the intermediate anisotropy axis of the particle. This method has been shown, both theoretically and experimentally, to yield much smaller switching times than conventional switching with significantly lower external field amplitudes [4].

Nevertheless, in order to guarantee successful switching, an extremely precise timing of the field pulse has to be designed in order to switch off the field at the right moment [5].

Recently, it has been also shown that ultra-fast and reliable precessional switching can be realized in anisotropic magnetic nanodots by using applied field pulses with two components: the larger one, directed along the particle hard-axis superimposed to a small bias field of appropriate amplitude [6]. This bias field can make quasi-random relaxation deterministic [7].

In this work, we propose an analytical study of precessional switching of nanodots driven by hard-axis field pulses. In particular, we analytically derive closed-form expressions for critical fields, magnetization dynamics, pulse durations and timing tolerances for successful switching as function of material and geometrical parameters. Macrospin and micromagnetic simulations are performed to check the accuracy of the theoretical predictions. It is expected that this study will be instrumental to develop novel ultra-fast and reliable magnetization switching strategies.

***References***

*[1] J-P. Wang, Nature Materials 4, 191 - 192 (2005).*
*[2] J.C. Mallinson, IEEE Trans. Magn. 23, 2003 (1987).*
*[3] C. Thirion, W. Wernsdorfer, D. Mailly, Nature Mater. 2, 524 (2003).*
*[4] S. Kaka, S.E. Russek, Appl. Phys. Lett. 80 (2002) 2958.*
*[5] G. Bertotti, I. D. Mayergoyz, C. Serpico, and M. d'Aquino, IEEE Trans. Magn. 39, 2501 (2003).*
*[6] M. d'Aquino, S. Perna, C. Serpico, G. Bertotti, I.D.Mayergoyz, IEEE Trans. Magn. 50, 7100504 (2014).*
*[7] G. Bertotti, C. Serpico, I.D.Mayergoyz, Phys. Rev. Lett. 110, 147205 (2013).*

# Chaotic Assisted Switching Of Magnetic Spin-Valves

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Magnetization dynamics driven by microwave excitations has been extensively studied in connection with the phenomenon of ferromagnetic resonance[1] and, more recently, in connection with the possibility of using microwave field and microwave injected currents to achieve magnetization reversal under substantially reduced coercive fields [2,3]. In this paper, by using analytical techniques, we study the role of microwave excitations in assisting magnetization switching of a magnetic spin-valve-like nano-structure subject to both DC and microwave fields and injected currents. Magnetization dynamics is analyzed by means of the Landau-Lifshitz equation appropriately generalized to include the effect of spin-polarized currents. It is shown that a special role in the microwave excited dynamics is played by the presence, in the precessional dynamics, of saddle equilibria. The microwave perturbations of the dynamics around these saddle equilibria, at sufficiently large microwave excitations, give rise to homoclinic and heteroclinic phenomena. These phenomena produce chaotic type dynamics and, as a consequence of that, yield an effective reduction of the switching field. The analytical derivation of this reduction is the focus of this paper. The starting point is the characterization of homoclinic and heteroclinic trajectories of the unperturbed conservative dynamics by using elliptic functions. Then, the influence of the microwave excitations on the conservative dynamics is studied through an appropriate Melnikov function. By using this method, it is possible to determine the threshold values of microwave excitation amplitudes for producing heteroclinic and homoclinic entanglement. Then, by using the concept of lobe dynamics and basin erosion, we connect the reduction of coercive field to the presence of chaotic dynamics (see Fig.1). The results of this treatment are instrumental to estimate the switching field by computing and measuring the extension of heteroclinic/homoclinic entanglement and basin erosion.

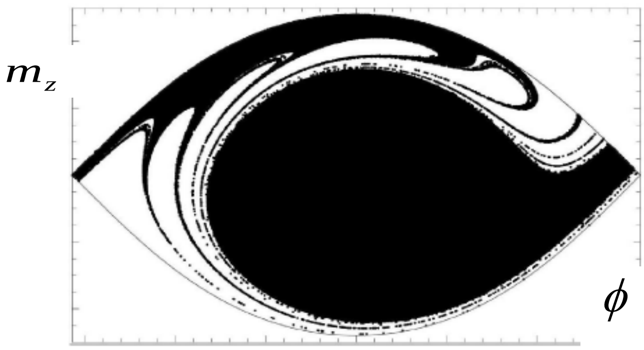


*Fig.1: Erosion basin due to heteroclinic entanglement in the (mz, □) plane.*

***References:***

[1] P. E. Wigen (ed.), Nonlinear Phenomena and Chaos In Magnetic Materials, World Scientific Publishing, Singapore (1994)
[2] C. Thirion et al., Nature Mater. 2, 524 (2003)
[3] G. Bertotti et al., J. Appl. Phys. 105, 07B712, (2009)

O23 – Wednesday, 20th of May, 2015 – 11:40-12:00

# Charge transport phenomena in molecular spin crossover materials: DC and AC analysis.

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Spin crossover (SCO) complexes of 3d4-3d7 transition metal ions are known to display a bistability between their high spin (HS) and low spin (LS) electronic configurations [1]. The spin-state switching in these compounds can be induced by various external stimuli such as temperature, pressure, magnetic field, light irradiation or gas sorption and leads to a significant change of magnetic, optical, mechanical and electrical properties [1-3].

In this work we have investigated the DC and AC charge transport properties of the SCO compound [Fe(Htrz)2(trz)](BF4) which displays a spin state dependence, i.e. a hysteretic behaviour, of various material dependent electrical parameters, such as electrical conductivity, electric modulus [4] or cut-off frequency. These results provide appealing perspectives for nanoscale switching and memory applications.

**Acknowledgements:** This work was supported by the bilateral grant of the Romanian National Authority for Scientific Research (CNCS–UEFISCDI) and Agence Nationale de la Recherche (ANR), Contract number: 9RO-FR/01.02.2013.

***References***

*[1] A. Bousseksou, et al., Chem. Soc. Rev., 40, 3313-3335 (2011).*
*[2] A. Rotaru et al., Chem. Comm., 48, 4163 (2012).*
*[3] A. Rotaru et al., Adv. Mater., 25, 1745 (2013)*
*[4] C. Lefter et al., Physica Status Solidi – RRL, 8, 191-193 (2014)*

# Vortex Nonlinear Dynamics

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This work is devoted to the analysis of spin-torque nano-oscillators (STNOs) based on spin-valve structure with the free layer in a vortex state. This type of STNO promises to have an important role in forthcoming microwave communication technologies [1],[2]. It is crucial to gain an understanding of the dynamics of these oscillators in regimes where the vortex is driven far from equilibrium, in nonlinear regimes. In this paper, we present a theoretical treatment of injection locking and nonlinear resonance of vortex oscillations, driven by AC injected currents and fields, based on Thiele-like model of vortex core dynamics. By exploiting separation of time scales and using averaging technique [3], we derive equations which are applicable to the study of phase-locking for arbitrary large vortex core motion. Bifurcation diagram of nonlinear vortex core dynamics is obtained which enables one to have a comprehensive understanding of phase-locking and nonlinear resonance phenomena (see Fig.1).

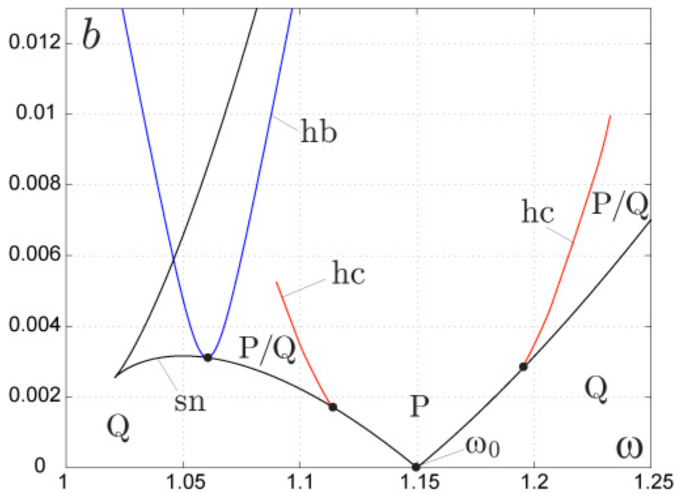


*Fig.1: Bifurcation diagram in the (ω,b)-plane (ω and b are normalized frequency and amplitude of ac excitations). The curves indicated by 'sn' are saddle-node bifurcation curves, the ones indicated by 'hb' are Hopf bifurcation curves, while homoclinic connection bifurcation curves are indicated by 'hc'. The letter P and Q indicate the presence and possibly the coexistence of periodic and quasiperiodic regimes.*

### *References*

*[1] D. C. Ralph and M. D. Stiles, J. Magn. Magn. Mater.* ***320****, 1190 (2008).*

*[2] P. Villard et al. IEEE J. Solid-State Circuits* ***45****, 214*

*[3] N. N. Bogoliubov and Yu. A. Mitropolskii, Asymptotic Methods in the Theory of Nonlinear Oscillations. New York: Gordon and Breach, 1961.*

O25 – Wednesday, 20th of May, 2015 – 12:20-12:40

# Advances In Spin-Torque Diode Sensitivity: Theory And Experiments

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Microwave detectors based on the spin-transfer torque diode effect are among the key emerging spintronic devices. By utilizing the spin of electrons in addition to charge, they have the potential to overcome the theoretical performance limits of their semiconductor (Schottky) counterparts, which cannot operate at low input power. We have demonstrated nanoscale magnetic tunnel junction microwave detectors, exhibiting record-high detection sensitivity of 75400 $mVmW^{-1}$ at room temperature, without any external bias fields, for input microwave power down to 10 nW. This sensitivity is 20× and 6× larger than the state-of-the-art Schottky diode detectors (3800 $mVmW^{-1}$) and existing spintronic diodes with greater than 1000 Oe magnetic bias (12000 $mVmW^{-1}$) respectively.

Figures 1a and 1b show the detected voltage curves as a function of the microwave frequency, at a low input microwave power of 10 nW, for the range of d.c. bias current from -0.40 to + 0.25 mA. Positive d.c. currents were found to suppress the detection voltage, because STT increases the damping of the magnetization precession and the perpendicular anisotropy in the free-layer. For a range of negative currents ($-0.32 < I_{dc} < -0.22$ mA), the detection voltages were significantly enhanced. Micromagnetic simulations supported by microwave emission measurements reveal the essential role of the injection locking mechanism to achieve this sensitivity performance. The results enable dramatic improvements in the design of low-input-power microwave detectors, with wide-ranging applications in telecommunications, radars, and smart networks.

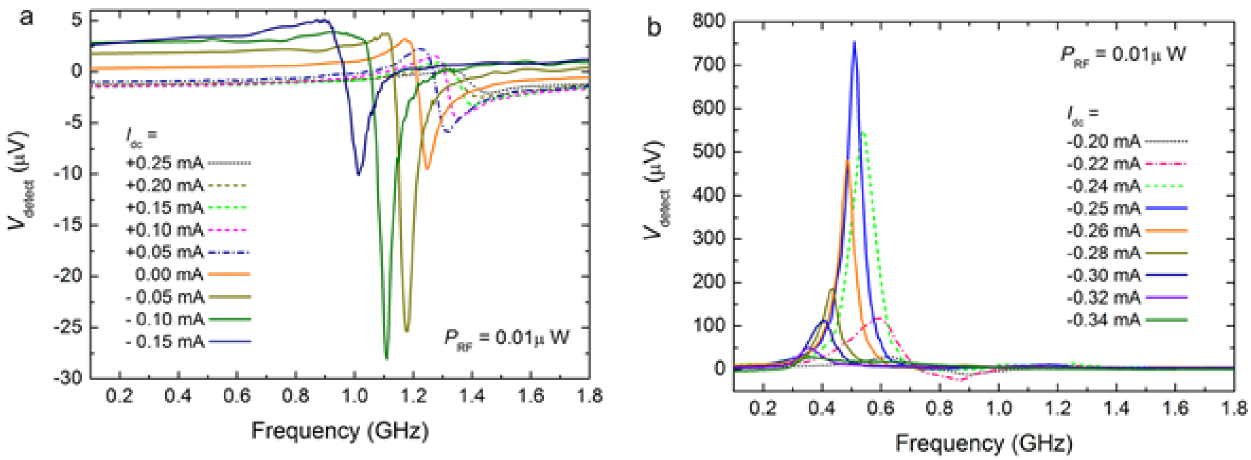


*Fig. 1: a, b, $V_{dc}$ as a function of microwave frequency under various d.c. bias currents ($I_{dc}$). The microwave input power (PRF) is 0.01 µW. The d.c. bias was found to significantly affect the $V_{dc}$.*

# Spin Dynamics Of Skyrmionic Magnetic Bubbles

**B. Krüger[1], F. Büttner[1,2], C. Moutafis[3], M. Schneider[2], C. M. Günther[2], J. Geilhufe[4], C. von Korff Schmising[2], J. Mohanty[2], I. Makhfudz[5], O. Tchernyshyov[5], B. Pfau[2], S. Schaffert[2], A. Bisig[1], M. Foerster[1], T. Schulz[1], C. A. F. Vaz[1,6], J. H. Franken[7], H. J. M. Swagten[7], S. Eisebitt[2,4], and M. Kläui[1]**

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In nano patterned magnetic thin-film elements topological defect spin structures such as Skyrmions, vortices, and domain walls emerge. These structures possess a high stability and their dynamics resembles that of a composite quasi-particle. The dynamics of these structures is of key importance for magnetic memories and logic devices but also contains exciting physics and has received enormous scientific interest in recent years.

In a magnetic vortex state the magnetization curls in-plane around a center region, in which the magnetization points out-of-plane. Whereas its dynamics has been widely investigated [1,2], much less is known about the dynamics of the magnetic bubble, a counterpart of the vortex in a magnetic material with easy-axis perpendicular anisotropy. The magnetization in the bubble points out-of-plane. In the remaining part, the magnetization points in the opposite direction. These two domains are separated by a Bloch-type domain wall in which the magnetization curls in plane. Magnetic bubbles are Skyrmions characterized by the spherical topology of their spin vector field that can be useful for memories [3].

Here, we study the GHz gyrotropic motion of a Skyrmion, which has recently been found from micro-magnetic simulations [4]. Our analytical model [5] describes this motion in terms of two waves that travel along the domain wall that confines the bubble and the position of the bubble is then determined by the superposition of the two waves. This results in a finite momentum of the bubble quasi particle which does not exist for a magnetic vortex. The analytical model further shows that the sense of free gyration of a bubble depends on its initial state, that is, the wave with the largest amplitude dominates. We performed simulations with different sizes of the film element and included pining via local variations of the anisotropy constant. It is found that these changes have only a small effect on the inertia of the bubble.

Experimentally we observed the motion of a bubble using pump-probe X-ray holography and we track the bubble position with 3 nm accuracy and report the first experimental observation of the GHz gyrotropic motion of a Skyrmion. The trajectory of the Skyrmion's position is accurately described by our quasi particle equation of motion [5]. From a fit we are able to deduce the inertial mass of the magnetic bubble and find it to be much larger than inertia found in any other magnetic system. We attribute the large mass to the non-trivial topology, making the results also relevant for other Skyrmionic spin structures sharing the same topology [6].

***References***

*[1] B. Van Waeyenberge, et al. ,Nature 444, 461 (2006).*
*[2] B. Krüger, et al., Phys. Rev. B 76, 224426 (2007).*
*[3] A. Fert, et al., Nature Nanotech. 8, 152 (2013).*
*[4] C. Moutafis, et al., Phys. Rev. B 79, 224429 (2009).*
*[5] I. Makhfudz, et al., Phys. Rev. Lett. 109, 217201 (2012).*
*[6] F. Büttner, et al., Nature Phys. advanced online publication DOI: 10.1038/NPHYS3234 (2015).*

O27 – Wednesday, 20th of May, 2015 – 15:30-15:50

# Hysteresis Loop-Based Identification Of Thermal Switching Field Distributions In Magnetic Granular Systems

**S. Ruta[1], O. Hovorka[2], K. Wang[3], G. Ju[3], R. Chantrell[1]**

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The intrinsic switching field distribution (SFD) is a fundamental characteristic of granular magnetic materials determining the quality of recording media used in hard disk drives. Being able to evaluate the thermal SFD of a system of coupled grains dominated by thermally activated hysteresis behaviour remains a challenge and is an essential practical step for developing and optimising the present-day and future magnetic recording technology.

SFD is defined as a distribution of irreversible switching events of magnetic grains in the absence of inter-granular interactions, in which case it corresponds directly to the differentiated hysteresis loop. If thermal relaxation is absent, then the SFD provides direct information about the distributions of intrinsic material properties of grains, such as anisotropy and volume. This relatively simple physical picture becomes complicated 1) by the presence of thermal relaxation, when the SFD also includes a component from thermal activation and becomes non-linearly dependent on the sweep rate of external field applied during the hysteresis loop measurement, and 2) by inter-particle interactions leading to correlated switching of magnetic grains, when the intrinsic switching thresholds of individual grains can no longer be resolved.

In this work we compare the applicability of two methods that have been widely used to extract the SFDs in magnetic granular materials, the so-called FORC method [1] and the $\Delta H(M, \Delta M)$-method [2]. Both methods are based on the measurement of hysteresis loops and the corresponding first order reversal curves, and identify the SFD as an inverse problem analogous to identifying the Preisach 'hysteron' distribution in the well-known Preisach and mean-field Preisach models, respectively.

As a benchmark for validating the methods we consider a kinetic Monte-Carlo (kMC) model of exchange and magnetostatic interacting Stoner-Wohlfarth grains, including self-consistently the volume and anisotropy distributions, and thermal activation. We quantify the limiting model parameter range of the FORC methods and the refined mean-field $\Delta H(M, \Delta M)$ method and demonstrate, for example, that FORC methods apply only when interaction induced correlations are negligible. We show, that solving the problem of identifying the SFD from such hysteresis loop measurements in the parameter range relevant in applications fundamentally requires applying the inverse problem solving techniques, essentially inverting the kinetic Monte-Carlo model in its full complexity.

***References***

*[1] A. Stancu, C. Pike, L. Stoleriu, P. Postolache, and D. Cimpoesu, "Micromagnetic and Preisachanalysis of the First Order Reversal Curves (FORC) diagram," Journal of Applied Physics, vol. 93, no. 10, p. 6620, 2003.*

*[2] O. Hovorka, Y. Liu, K. Dahmen, and a. Berger, "On the ability to determine intrinsic switching field distributions from hysteresis loops in the partially correlated magnetization reversal regime," Journal of Magnetism and Magnetic Materials, vol. 322, pp. 459– 468, Feb. 2010.*

# Motion Of Domain Walls In The Magnetic Peierls Potential

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The dynamics of magnetic domain walls is a topic of great technological interest, with potential applications in devices for magnetic data storage and logic. In this presentation, we link this topic to wider questions about the dynamics of topological defects in condensed matter. In particular, we consider the effect of the discreteness of the crystal lattice on domain-wall dynamics.

It has been predicted that a domain wall with a width comparable to the lattice parameter feels the crystal lattice as a periodic variation of its energy as a function of position, creating a relief of energy barriers. An analogous effect, the Peierls potential, is well known in the theory of dislocations (crystal plasticity). The authors of Ref. [1] were able to observe a magnetic Peierls potential as a very fine and regular staircase pattern (different from Barkhausen jumps) in the hysteresis curve measured by a sensitive Hall probe placed directly on top of a domain wall in a perpendicular-anisotropy film.

When a domain wall crosses a Peierls barrier, it creates kinks in its profile to maximize the areas which lie in a valley of the Peierls potential. Once formed, such kinks can slide freely along the domain wall. A key question is what happens when two kinks of opposite sign collide. If kinks can be seen as sine-Gordon solitons, they do not annihilate but pass through each other and continue their motion, taking a part of the domain wall to the next Peierls valley. Solitonic kinks can also form long-lived excitations known as breathers (bound kink-antikink pairs).

In this presentation, we show that domain-wall kinks can display solitonic behaviour when certain conditions on the material are met [2]. We establish the key dynamical characteristics of kinks, such as limiting velocity and effective mass, in excellent agreement with our micromagnetical simulations. We predict that long-lived breathers may exist for realistic material parameters.

***References***

*[1] K.S. Novoselov, A.K. Geim, S.V. Dubonos, E.W. Hill, I.V. Grigorieva, Nature 426, 812 (2003).*
*[2] F. J. Buijnsters, A. Fasolino, M. I. Katsnelson, Phys. Rev. Lett. 113, 217202 (2014).*

O29 – Wednesday, 20th of May, 2015 – 16:30-16:50

# Comparison Of Prandtl-Ishlinskii And Preisach Modeling In Micro-Positioning Control Systems Applications

**M. Al Janaideh[1], D. Davino[2], P. Krejci[3], and C. Visone[2]**

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Hysteresis of smart actuators, such as piezo-ceramics and magnetostrictive actuators, causes oscillations in micro- positioning open-loop systems, or poor tracking performance and potential instabilities in closed-loop systems [1]-[2]. In order to improve the performances of these systems, in terms of tracking and stability, a number of hysteresis models have been proposed to model and compensate hysteresis nonlinearities in smart micro-positioning actuators. The paradigm of hysteresis models for control as for magnetics tasks is represented by the Preisach model, (PM), [3] which guarantees several features but results a bite more complex with respect other approaches based on Play superposition, such as the Prandtl-Ishlinskii (PI) model. This conditions fostered the spread of several approaches based on PIs operators, which provide the compensator in a closed form. As a preliminary point we should stress that PI and PM are strictly linked and that PI represents a special case of Preisach operator. For this reason, the aim of this study is to analyze in detail in which conditions a simplified version of PM could be suitable to describe micro-positioning devices, based on magnetostrictive actuators. The PI operator, as proposed in [4], in the Preisach formalism has a simplified distribution function of the form: $\mu(\alpha,\beta)=\rho\big(g(\alpha)-g(\beta)\big)g'(\alpha)g'(\beta)$. Conversely, the most general Preisach Distribution Function can be in principle written as: $p(\alpha,\beta)=-\frac{\partial^2 E(\alpha,\beta)}{\partial\alpha\partial\beta}$ with $E(\alpha,\beta)$ the Everett function directly related to measured first order reversals, as shown in Fig. 1, that can be written as: $p(\alpha,\beta)=\kappa(\alpha,\beta)\left[\rho\big(g(\alpha)-g(\beta)\big)g'(\alpha)g'(\beta)\right]$. Now expanding $k(\alpha,\beta)$ in Taylor series: $\kappa(\alpha,\beta)\approx k_0+\frac{\partial\kappa}{\partial\alpha}\Delta\alpha+\frac{\partial\kappa}{\partial\beta}\Delta\beta$ a comparison between the PM and GPI is straightforward. In fact a perturbation of the function k allows to leave the condition which guarantees a perfect correspondence between PM and GPI and to estimate the modeling error (an example is provided in Fig. 2 ), with different distribution functions.

In the full paper a thorough discussion on the conditions within the GPI provides accurate results will be drawn in the frame of micro-positioning applications.

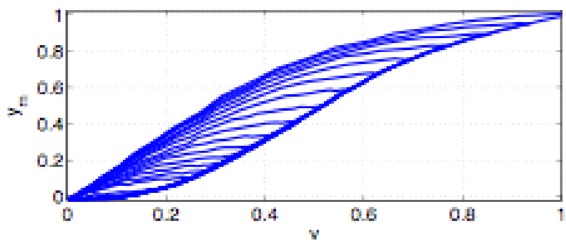


*Fig. 1*

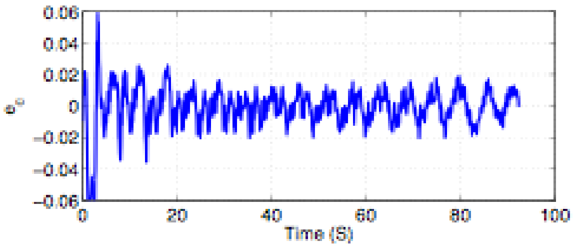


*Fig. 2*

***References***

[1] *X. Tan and J. Baras, Automatica, vol. 40, pp.1469-1480, 2004.*
[2] *Y. Li and Q. Xu, IEEE Transactions on Industrial Electronics, vol. 58, pp. 3601-3615, 2011.*
[3] *I. Mayergoyz, Mathematical Models of Hysteresis, Elsevier, New York, 2003.*
[4] *C. Visone and M. Sjostrom, Physica B, vol. 343, pp. 148-152, 2004.*

# Inverse Opal-Like Structure – 3D Antidot Array Exhibiting Spin Ice Behavior: Micromagnetic Study

**I. S. Dubitskiy[1,2], A. V. Syromyatnikov[1,2], N. A. Grigoryeva[1], A. A. Mistonov[1,2], I. S. Shishkin[1,2], and S. V. Grigoriev[1,2]**

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Artificial spin ice systems have attracted much attention in recent years [1]. They can be used as a model objects for the study of frustration phenomenon and magnetic excitations similar to those observed in pyrochlore spin ice materials. Most of artificial spin ice systems are two dimensional. Inverse opal-like structures (IOLS) are promising candidates to become first 3D artificial spin ice [2].

IOLS can be fabricated from opals by filling the voids between microspheres with another material (Co or Ni in our case). Later microspheres can be removed. Thus IOLS can be considered as a set of submicron metallic particles connected to each other via thin and long crosspieces ("legs"). The shapes of such particles resemble the shapes of the voids of face centered cubic (FCC) structure of opal and have quasi cubic and quasi tetrahedral forms (fig. 1). Such spatially ordered 3D structure of IOLS leads to a complex distribution of the magnetization in the sample [2,3]. One can think IOLS as 3D antidot array.

We perform a micromagnetic calculation of magnetization distribution in IOLS unit cell using Nmag software [4]. External magnetic field was applied along IOLS principal axes and corresponding hysteresis curves were calculated. Results are in good quantitative agreement with experimental data (SQUID measurements) and suggest that IOLS exhibit spin ice behavior i.e. spin ice rule is fulfilled in quasicubes and quasitetrahedra in a wide range of magnetic field values.

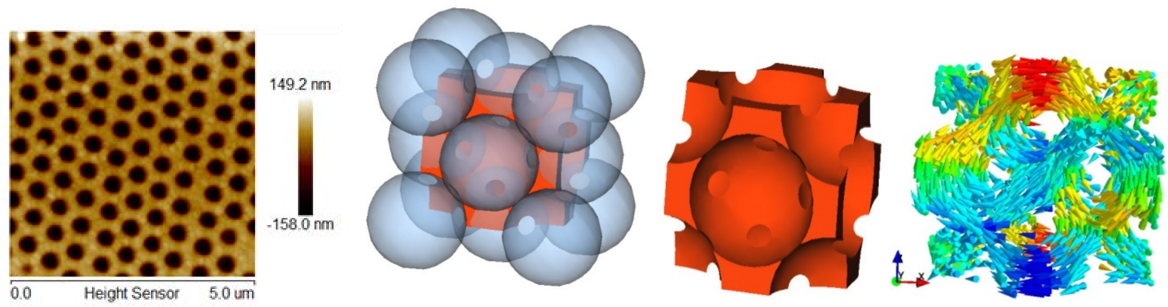



*Fig. 1. AFM image in (111) plane, model of IOLS unit cell (with and without surrounding microspheres) and magnetization distribution in unit cell (color indicates x-component of magnetization)*

### References

*[1] C. Nisoli et al. Reviews of Modern Physics, 85(4), 1473, (2013)*
*[2] A. A. Mistonov et al. Physical Review B, 87(22), 220408, (2013)*
*[3] S. V. Grigoriev et al. Phys. Rev. B 79, 045123 (2009)*
*[4] T. Fischbacher, M. Franchin, G. Bordignon, H. Fangohr,. Magnetics, IEEE Transactions on, 43(6), 2896-2898, (2007)*

O31 – Wednesday, 20th of May, 2015 – 17:10-17:30

# Quantifying History Dependence Of Thermal Relaxation In Clusters Of Magnetic Nanoparticles

**O. Laslett[1], S. Ruta[2], J. Barker[3], G. Friedman[4], R. Chantrell[2] and O. Hovorka[1]**

*(1) Engineering and the Environment, University of Southampton, SO16 7QF, Southampton, UK*
*(2) Department of Physics, University of York, York, YO10 5DD, UK*
*(3) Institute for Materials Research, Tohoku University, Sendai, 980-8577 Japan*
*(4) Electrical and Computer Engineering Department, Drexel University, Philadelphia, PA 19104, USA*

In this talk we discuss our recent study [1] of the effects of dipolar interactions on the long-time thermal activation in clusters of magnetic nanoparticles. Our work is motivated by the need to understand the properties of inverse problems for developing enhanced magnetic particle detection for applications in biomedicine [2]. Applying the Néel-Arrhenius transition state theory (Figure 1), formulated in terms of coupled many-body master equations shows that the resulting magnetization decay follows the stretched exponential behaviour, with parameters dependent on the geometrical symmetries of clusters. Moreover, the relaxation rates are shown to be determined by the hysteresis process applied to initialize the system prior to relaxation. Combining this symmetry and initialization dependent behaviour could serve for improving the sensitivity for distinguishing between particle cluster types, thus enhancing the degree of resolution in magnetic particle detection beyond the standard use of non-interacting particle systems. We further discuss our ongoing work that aims to validate these findings using the refined Langevin dynamics formalism.

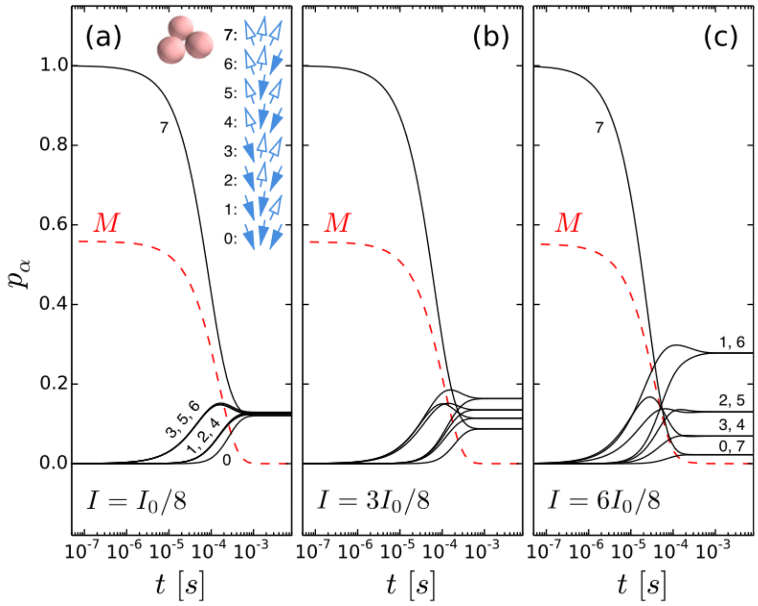



*Fig. 1: Calculation of time dependent probabilities of discrete state configurations of three particle clusters using the Néel-Arrhenius transition state theory, for increasing inter-particle interaction strength I in (a)-(c). In all cases the system has been initialised in the remanent state (7) by decreasing the external field from saturation to zero. Applying different field histories enables the system to be initialised in different state configurations, which affects the relaxation rates gowerning the approach to equilibrium.*

### *References*

*[1] O. Laslett, S. Ruta, J. Barker, R. W. Chantrell, G. Friedman, and O. Hovorka. Interaction effects enhancing magnetic particle detection based on magneto-relaxometry. Applied Physics Letters, 106(1):012407, 2015.*
*[2] Frank Wiekhorst, Uwe Steinhoff, Dietmar Eberbeck, and Lutz Trahms. Magnetorelaxometry assisting biomedical applications of magnetic nanoparticles. Pharmaceutical Research, 29(5):1189-1202, 2012.*

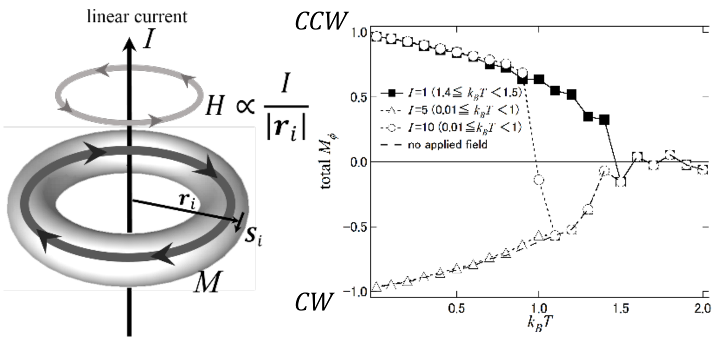
O32 – Wednesday, $20^{th}$ of May, 2015 – 17:30-17:50

# Monte Carlo Simulation For Thermal Assisted Reversal Process Of Micro-Magnetic Torus Ring With Bistable Closure Domain Structure

**K. Terashima, K. Suzuki and K. Yamaguchi**
*Fukushima University, Fukushima, Japan*

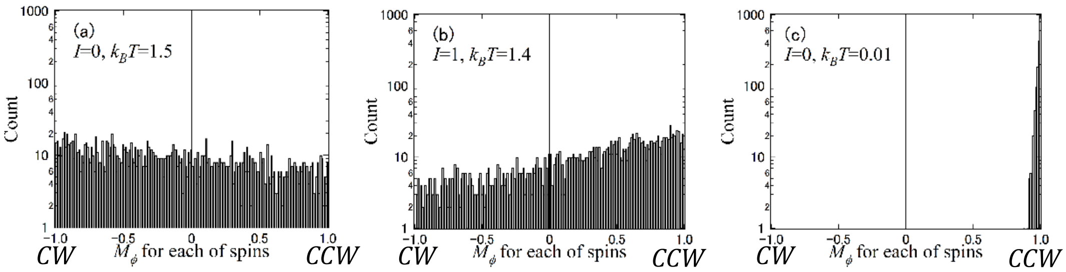
Micro magnetic torus rings like doughnut shapes have bistable closure domain (CD) structures, which have the direction along clockwise (CW) or counterclockwise (CCW). The direction of CD can be switched by rotational magnetic field due to linear current I penetrating to the center of the ring as shown in Fig. 1(a). But the stable CD structure in low temperature demands large magnetic field to reverse the direction because the process includes the generation of magnetic reversal nuclei. In this paper, we will show the easier reversal process by thermal assistance using Monte Carlo (MC) method.

Figure 1(b) shows MC simulation results using same random number series for the temperature dependences of magnetic CD parameter (total $M_\Phi$ to the lowest temperature $k_BT$=0.01 from same initial magnetic states in higher temperature $k_BT$=2.0. CD structure at kBT=0.01 is along CW under no applied magnetic field (I=0) and the structure demands larger field (I ≥10) to reverse to CCW if the field is applied in the lower temperature than $k_BT$=1.0. Weaker magnetic field (I=1), however, can satisfy the reverse condition if it is applied in around Currie temperature $T_C$ ($k_BT$~1.4). Then the distribution of $M_\Phi$ for each of spins slightly tends to CCW direction as shown in Fig.2(b) from CW direction in Fig.2(a). The tiny difference is enhanced with cooling temperature as shown in Fig.2(c), although magnetic field is not applied in the lower temperature than $k_BT$=1.3; that is, small bias to CW or CCW in the distribution for each of spins around TC decides the CD structure in low temperature. This shows easier reversal process through thermal assistance and a self-organization.




*(a) (b)*

*Figure 1: (a) Schematic view for magnetic torus ring and rotational magnetic field H due to linear current I and (b) temperature dependence of total $M_\phi$.*




*(a) (b) (c)*

*Figure 2: Distribution of $M_\phi$ for each of spins in (a) $k_BT$=1.5, (b) $k_BT$=1.4 and (c) $k_BT$=0.01.*

O33 – Wednesday, 20th of May, 2015 – 17:50-18:10

# One-Phase Flow In Porous Media With Hysteresis

**N. Botkin, E. El Behi-Gornostaeva**
*Technical University of Munich, Zentrum Mathematik, Boltzmannstr. 3, D- 85748 Garching, Germany*

The nature of flow in porous media is characterized by hysteretic effects observable on a macroscopic level. These effects have a significant influence on the behavior of the whole system, and therefore they have to be taken into account.

The aim of this work is to study an evolution problem of filtration through porous media, accounting for hysteresis in the saturation versus pressure constitutive relation.

The mass conservation and Darcy's laws yield a nonlinear diffusion equation coupled with Neumann and Signorini boundary conditions imposed on different parts of the boundary. The relationship between the saturation and the capillary pressure is modeled by a Preisach hysteresis operator.

We present an existence and uniqueness result for a weak formulation in the framework of Sobolev spaces under the assumption that solutions remain in the convexity domain of the Preisach operator.

Moreover, we show numerical simulations conducted using the Finite Element program Felics developed on the Chair for Mathematical Modelling, M6, of the Technical University of Munich.

It should be noticed that a very rapid algorithm for computing output signals of the Preisach operators attached to each node of a 3D computantional domain is utilized.

Numerical simulations substantiate the theoretical result.

***References***

*[1] F. Bagagiolo, A. Visintin, Porous media filtration with hysteresis, Adv. Math. Sci. Appl., vol. 14 (2004), 379-403.*
*[2] D. Flynn, H. McNamara, J. P. O'Kane, A.Pokrovskii, Application of the Preisach model to soil-moisture hysteresis, in The Science of Hysteresis, vol. 3 (2006), 689--744.*

# POSTER SESSION

Tuesday, 19th of May 2015

17:00-19:00

# Vector Hysteresis Moving Model Identification For Fe-Si Thin Films From Micromagnetic Simulations

**S. Quondam Antonio[1], A. Faba[1], G. Carlotti[2], E. Cardelli[1].**
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*(2)University of Perugia, Department of Physics and Geology, Via A. Pscoli, Perugia, Italy.*

Vector hysteresis modeling to macroscopic scale attracts a lot of interest for the design and the optimization of electrical machines. Common phenomenological methods are inspired to stochastic distributions of hysteresis operators and they can reproduce magnetization processes with local memory in macroscopic systems [1]. One of the most promising approaches is the Vector Hysteresis Moving Model (VHMM), based on vector hysteresis operators, called hysterons, that are circles on $Hx - Hy$ plane. Each hysteron is characterized by a center $\boldsymbol{h_i}=(hx_i, hy_i)$, a radius $u_i$ and a weight $P_i$ and the total magnetization, for a given applied field $\boldsymbol{H_{ext}}$, is the weighted sum of the single hysteron contributions [2]. In order to represent a more general kind of magnetization processes, “moving technique” is implemented. It consists in a variation of the weight associated to each hysteron with the total magnetization.

In spite of the already shown potentiality of the above approach, it is clear that it would be highly desirable to connect the mathematical properties of the model (number and distribution of hysterons, radii, weights, etc.) to the physical properties of the magnetic material under investigation. To this aim, here we first exploit a micromagnetic approach[3], using the commercial software Micromagus [3] [4], to perform “virtual experiments” on polycrystalline thin films of iron-like media, with either randomly or preferentially-oriented crystalline uniaxial anisotropy (set to the value of Si-Fe steel with 4%Si in Fe)[5]. We calculate the hysteresis cycles and systematically vary the grain size, the exchange interaction at gran boundaries and the value of the anisotropy constant and its orientation (either random or preferencial). We also consider the presence of a global uniaxial anisotropy to take into account the effect of rolling processes during steel lamination. Because of the computation limitations of the micromagnetic approach, the simulated area is limited to a square of 2.5μm ×2.5μm while the average grain size is between a few tens and a few hundreds of nanometers. Then we study the relationship between VHMM parameters and the physical characteristics of the considered iron-like media. VHMM identification is performed considering both scalar and rotational cycles calculated with micromagnetic approach, and the above mentioned systematic variation of relevant physical parameters.

***References***

*[1] E. Della Torre, E. Pinzaglia, E. Cardelli, Physica B, Vol. 372, pp. 111-119, 2006.*
*[2] E. Cardelli, E. Della Torre, A. Faba, IEEE Trans. on Magn., Vol. 46, n. 12, pp. 3990-4000, 2010.*
*[3] J. Azpiazu , Phd Thesis, University of Vigo 2014.*
*[4] http://www.micromagus.de/*
*[5] R. M. Bozorth, IEEE Press, 1993.*

P2

# Simulation Of Established Linear And Nonlinear Hysteretic Loops


**D.Y. Danailov**

*Todor Kableshkov University of Transport, 158 Geo Milev Street, Sofia 1574, Bulgaria*



The paper considers a model for the simulation of an established linear and nonlinear symmetric hysteretic loop. The base magnetic material curve $B_\mu\left(H_\mu\right)$, as well as magnetic chain active resistance, assigned by the $B_r\left(H_r\right)$ curve, are used in its construction. It is possible to determine remagnetization and iron losses. Hysteresis is presented by means of pulsing functions of the type $\overset{*(p)}{b} = \vartheta\left[\overset{*(p)}{h}\right]$, where flux density $\overset{*(p)}{b}\left[t, b_r(t), b_\mu(t)\right]$ and magnetic field strength $\overset{*(p)}{h}\left[t, h_r(t), h_\mu(t)\right]$ are preliminarily expanded into two components $\left(b_r(t); b_\mu(t)\right)$ and $\left(h_r(t); h_\mu(t)\right)$. Parametric functions $b_r(t), b_\mu(t), h_r(t), h_\mu(t)$ are trigonometric.

A software product for the assignment of symmetric loop family has been created according to the mathematical model of hysteretic process description. Fig. 1 and fig. 2 show obtained hysteretic loop families, of linear and nonlinear hysteretic loops. The model can be also applied in dynamic hysteretic process research (fig. 3).


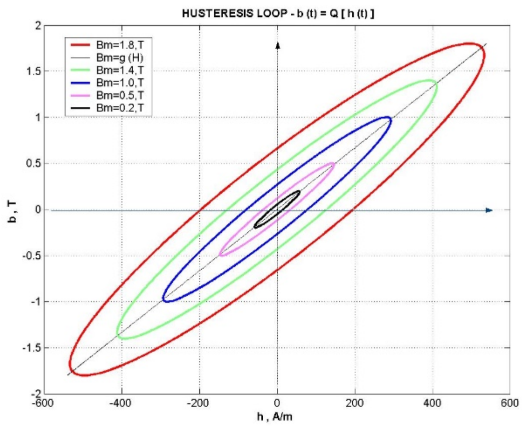


*Fig. 1*

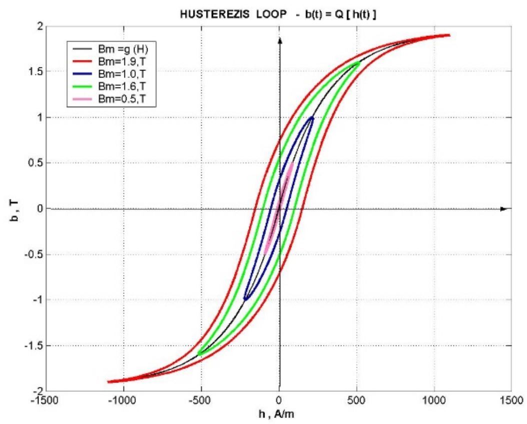


*Fig. 2*

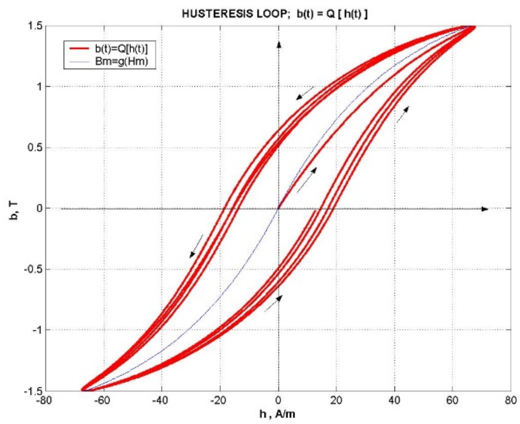


*Fig. 3*

# An Experimental Evaluation Of The Fully Coupled Hysteretic Electro-Mechanical Behaviour Of Piezoelectric Actuators

**M. Butcher[1], D. Davino[2], A. Giustiniani[1], A. Masi[1]**

*(1) CERN EN/STI/ECE, Switzerland;*

*(2) University of Sannio, Italy*

Piezoelectrics are, among the multifunctional "smart" materials, the most well-known and widespread in industrial applications, because of their relatively low cost and ease of use in electric and electronic oriented applications [1]. Moreover, they are a fundamental element in precision goniometers for crystal based beam collimation at CERN [2]. Piezoelectrics have four external variables involved in the electromechanical characteristics. For example, assuming here, as a reference, a linear description is:

$$S_3 = s_{33}^E T_3 + d_{33}^T E_3$$

$$D_3 = d_{33}^E T_3 + \varepsilon_{33}^T E_3$$

$S_3, T_3, E_3, D_3$ are the strain, the mechanical stress, the electric field and the electric displacement, respectively. $s_{33}^E, d_{33}^T, d_{33}^E, \varepsilon_{33}^T$ are the compliance at constant field, the piezoelectric coupling coefficient at fixed stress, the piezoelectric coupling coefficient at fixed electric field and the permittivity, respectively. Usually, piezoelectrics and, more recently, multilayer stacks are employed as one-input / one-output systems in actuation or sensing. The other variables effect is then just neglected. This approximation holds as long as those variables do not change within the application operating range.Conversely, few papers report experiments investigating the effect of applied mechanical stress on piezoelectric actuator performances [3-4]. The modeling of this effect can be important when the actuator is employed in dynamic conditions where the applied force can be higher than the mechanical prestress, so the control system can be challenged and the material damaged. It is therefore important to characterize and model the effect when 2-input variables are involved, e.g. electric field and mechanical stress. The aim of this paper is to present a complete electro-mechanical characterization of a piezo stack actuator in "33" mode (i.e. the electric field axis along the mechanical load one), see Fig.1. The full paper will discuss useful indications for the design and the analysis of piezo based devices (Coupling coefficients, Blocked force, Young's modulus and elastic working load), see Figs.2-3. For example, Fig.3 shows that the characterization can be useful to find the working stress point to achieve the maximum strain performance.

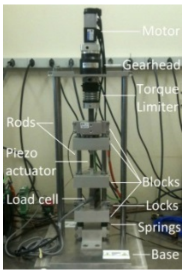


Fig. 1 Experimental Setup

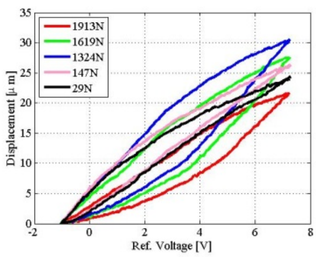


Fig. 2 Displacement vs Voltage, with varying the mechanical load.

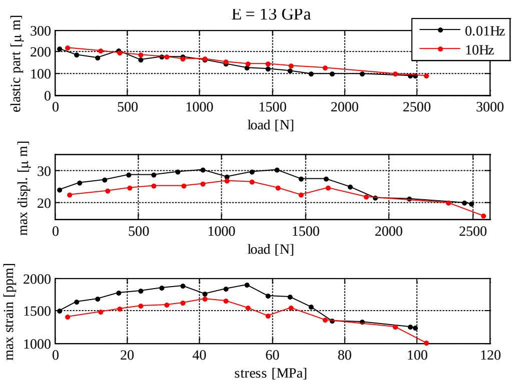


Fig. 3 .Maximum strain at different mechanical loads. Two different frequencies for the applied sinusoidal voltage are considered

## *References*

*[1] M. Biggio et al., Elsevier Phys. B., 435 (2014), pp. 40–43.*

*[2] W. Scandale et al., JINST, (2011),* ***6,*** *T10002.*

*[3] M. Mitrovic, et al., Elsevier Int. J. Solids Struct., 38 (2011), pp. 4357–4374.*

*[4] J. Fan et al., Elsevier Acta Mater., 47 (1999), pp. 4415-4425.*

P4

# On The Identification Of Hammerstein Systems In The Presence Of An Input Hysteretic Nonlinearity With Nonlocal Memory: Piezoelectric Actuators – An Experimental Case Study

**M. Butcher, A. Giustiniani, A. Masi**

*CERN EN/STI/ECE - Switzerland*

The use of piezoelectric materials for active sensing and actuating purposes is becoming more and more widespread in both research and industry [1]. However, as for almost all the other materials belonging to the larger family of "smart" materials, they show complex nonlinear behaviour, like non local memory hysteresis. This characteristic often represents a severe limitation to their use, demanding greater modelling efforts and the definition of advanced control strategies. In this paper the modeling and identification of a piezoelectric actuator is addressed and discussed. For the description of the actuator under study a Hammerstein – like structure is assumed, see Fig.1.

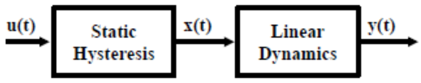


*Fig.1. Hammerstein – like structure for the piezoelectric actuator.*

This choice is motivated by the availability of models of nonlocal memory hysteresis (e.g. Preisach, Play based ones) for the static input nonlinearity that can offer a good description of the material behavior in the low frequency limit. Moreover, this structure intrinsically decouples the identification problem leaving the identification of the latter block (linear dynamics) to a second step. Referring to Fig.1, it is clear however that the internal variable x(t)(the driving signal of the linear part) is not directly available. A careful choice of the true input signal u(t) should therefore be made. In literature, this problem has only been outlined and addressed for memory-less input functions or for single hysteresis operators with local memory, [2].

The aim of this paper is to propose an identification method of the linear part considering the input hysteretic nonlinearity to have the nonlocal memory feature. In particular, it will be shown that Pseudo Random Binary Sequences (PRBS and square wave-like signals in general) are useful for this task, decoupling totally the problem. In fact, assuming a PRBS for u(t), then the internal signal x(t) will also be a PRBS, with similar characteristics. This property does not, however, apply to other typical excitation signals such as sine waves or stochastic noise [3]. The linear identification results are then related to the main properties of the hysteretic block (bias dependence for a given history, cancellation and congruency, Figs. 3-4).

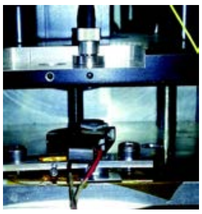

*Fig. 2.Experimental Setup.*

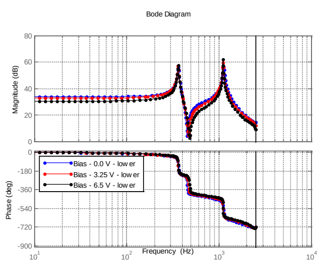


*Fig. 3. Identified transfer functions – Bias dependence for minor loops attached on the lower branch of the major one.*

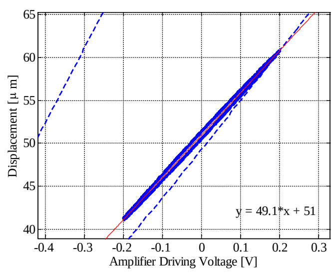


*Fig. 4. The DC gain of the identified transfer function can be related to the slope of the relative minor loop.*

***References***

[1] M. Biggio et al., Elsevier Phys. B., vol. 435, pp. 40 43, 2014.

[2] E. W. Bai, Automatica, vol. 40, pp. 671–676, 2004. F. Giri et al., Automatica, vol. 44, p. 767775, 2008.

[3] I. D. Mayergoyz et al., J. of Phys.: Conf. Ser., vol. 22, pp. 139-147, 2005. M. Sjostrom, Trans. on Magn., vol. 35, pp. 2097-2103 1999.

# Period-Doubling Bifurcation Cascade In A Ferromagnetic Nanoparticle Under The Action Of A Spin-Polarized Current

**M. Kushnir[1], P. Horley[2], M. Morales-Meza[2], V. Rusyn[1], A Sukhov[3] and S Galyuk[1]**

*(1) Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine*

*(2) CIMAV Unidad Monterrey, Chihuahua, México*

*(3) Martin-Luther-Universität Halle-Wittenberg, Halle/Saale, Germany*

Magnetization dynamics at nano-scale attracted much scientific attention due to rich variety of precessional states [1]. By tuning parameters of the system, it is possible to switch between ordered and chaotic states [2], which can be efficiently characterized by the methods developed for study of complex dynamic systems and self-organization [3]. The accounting for non-linear magnetic behavior is important, as it may lead to spin wave instabilities [4], chaotic vortex core reversal [5] and other phenomena.

In this paper, we analyze the hysteresis curves calculated for a cascade of period-doubling bifurcations occurring in Co/Cu/Co spin-valve [6]. The bifurcation cascade was obtained for a model subjected to the simultaneous action of a constant spin-polarized current and periodic external magnetic field. We use bifurcation diagrams and Hausdorff dimension as main tools for visualization of different oscillation modes seen upon transition from ordered to chaotic states of the system. The important role of driving force frequency is illustrated with a considerable increase of field region corresponding to the cascade of period doubling bifurcations. The influence of chaotic oscillation modes is discussed in connection to a possible use of spin-valve systems for spintronic devices acting as generators of high-frequency magnetic oscillations.

With modern software environment LabView was simulated mathematical apparatus describing hysteresis and was showed circuit implementation by using Multisim [7].

The paper also describes a software package to calculate the numerical parameters of chaotic states and characteristics within studied systems. As a comparative system software environments we selected MatLab and LabView.

We gratefully acknowledge the support of this research by the CONACYT grant as the Basic Science Project 129269 (Mexico) and Erasmus Mundus Ianus II grant (Romania, 2014-2015).

***References***

*[1] M.D. Stiles and J. Miltat, "Spin transfer torque and dynamics", Topics in Applied Physics 101 (2006) 1-85*

*[2] Z. Yang, S. Zhang, and Y. Charles Li, "Chaotic dynamics of spin-valve oscillators", Phys. Rev. Lett. 99 (2007) 134101*

*[3] D. Laroze, J. Bragard, O.J. Suarez, and H. Pleiner "Characterization of the chaotic magnetic particle dynamics", IEEE Trans. Magn. (2011) CG-02.*

*[4] G. Bertotti, R. Bonin, M. d'Aquino, C. Serpico, and I. D. Mayergoyz, "Spin-wave instabilities in spin-transfer-driven magnetization dynamics", IEEE Magn. Lett. 1 (2010) 3000104*

*[5] O.V. Pylypovskyi, D.D. Sheka, V.P. Kravchuk, F.G. Mertens, and Yu. Gaididei, "Regular and chaotic vortex core reversal by a resonant perpendicular magnetic field", Phys. Rev. B 88 (2013) 014432*

*[6] S. I. Kiselev, J. C. Sankey, I. N. Krivorotov, N. C. Emley, R. J. Schoelkopf, R. A. Buhrman, and D. C. Ralph, "Microwave oscillations of a nanomagnet driven by a spin-polarized current", Nature 425 (2003) 380-383.*

*[7] M. Kuczmann "Scalar hysteresis measurement using FFT", Journal of Optoelectronics and Advanced Materials, Vol. 10, No. 7, July 2008, p. 1828-1833.*

P6

# Experimental Comparison Of Rate-Dependent Hysteresis Models In Characterizing Hysteresis Of Piezoelectric Tube Actuators

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*(3) Department of Mechatronics Engineering, The University of Jordan, Amman 11942, Jordan*

Piezoelectric tube actuators are considered attractive for micro-/nano- positioning and micro manipulating applications [1]. These actuators, however, show rate-dependent hysteresis nonlinearities that increase with the excitation frequency of the applied input. Formulating of a rate-dependent hysteresis model that can account the frequency effect of the applied input is considered essential to expect the response of the actuator at various frequencies as well as to design controllers able to improve the tracking performance of smart actuators [2]. Different methodologies have been proposed in the literature for characterization of dynamic hysteresis nonlinearities of smart materiel-based actuators. One of the the most popular methodologies is to employ a rate-independent hysteresis model (such as the classical Preisach and the classical Prandtl-Ishlinskii) coupled with linear dynamics which is the so-called Hammerstein approximation. Another methodology is to formulate a hysteresis model that can integrate the rate of the applied input in the parameters of the hysteresis model [3].

In this study, a thorough experimental study has been carried out to characterize rate-dependent hysteresis of piezoelectric tube actuator at different excitations of frequency. The experimental measurements were followed by modeling of hysteresis nonlinearities using both the rate-dependent Prandtl-Ishlinskii model and a rate-independent Prandtl-Ishlinskii model coupled with linear dynamics of the piezoelectric tube actuator. The comparison between both the models is presented and discussed along with investigating the output responses at various arbitrary excitations of frequency, which were not considered in parameters identification.

***Refrerences***

*[1] D. Habineza, M. Rakotondrabe, Y. Le Gorrec, Bouc-Wen Modeling and Feedforward Control of Multivariable Hysteresis in Piezoelectric Systems: Application to a 3-DoF Piezotube Scanner, Accepted, To appear in the IEEE Transactions on Control System Technology.*

*[2] M. Al Janaideh, S. Rakheja, and C-Y. Su, Experimental characterization and modeling of rate-dependent hysteresis of a piezoceramic actuator, Mechatronics, vol. 19, pp. 656–70, 2009.*

*[3] C. Visone, Journal of Physics: Conference Series vol.138(1), 012028, 2008.*

# Dynamical Response Of Seismic Metamaterials In Presence Of Soil Hysteresis

**O. Casablanca[1], F. Garescì[2], G. Finocchio[2], B. Azzerboni[2], M. Chiappini[1]**
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Seismic Metamaterials (SM) can be used to filter earthquake waves (S-wave mainly) showing theoretically higher potential than traditional seismic insulators and passive energy dissipation systems. To move this concept towards a practical realization, one challenge is to adapt the bandgap in order that coincides with the amplification region of the soil response where the SM is realized and to include the main resonance frequency of building.

For this purpose, we have introduced in a monodimensional model for the soil response analysis SM[1], the presence of soil hysteresis. This aspect is one of the factors that most influence the soil response, in fact in correspondence of a seismic event there is a decrease in the shear modulus, and an increase in the damping ratio with increasing shear strain. We have generalized the one-dimensional model described above including the hysteresis modeling using the Preisach model (See Figure 1). It was identified by experimental cyclic tests carried out on different soils. With this approach it is possible to obtain the degradation curve of shear stiffness and damping as a function of shear deformation. We found that it is necessary to reduce significantly the initial frequency of the bandgap. Our strategy is based on the reduction of the optical branch frequency achieved by getting closer the Bragg band gap.

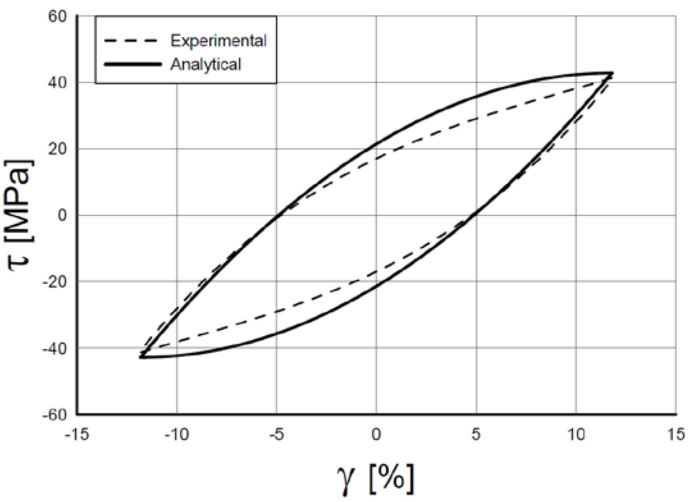


*Fig. 1: A comparison between the experimental soil hysteresis loop and the one computed with the Preisach model. τ is shear tension, γ is shear strain.*

***References***

*[1] G. Finocchio, et al, App. Phys. Lett. 104, 191903 (2014).*

# Periodic System With Hysteresis

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Periodic systems (EP) with local resonance offer an innovative way to manipulate the propagation of waves, allowing an amplitude attenuation of the perturbation in certain frequency ranges. We present the results of numerical simulation on dynamic response of a EP composed by five cells, subjected to a sinusoidal displacement. The EP was represented by a one-dimensional mass-spring system.

In the analysis we considered as external excitation, a imposed sinusoidal displacement with amplitude equal to 0.1 m and frequency equal to 3.2 Hz. This frequency was chosen within the band-gap (Figure 1). Preisach hysteresis model was considered to model the nonlinear behavior of the elements of the periodic system, found experimentally (figure 2). The analysis results showed an attenuation greater than the amplitude of the vibration in the presence of hysteresis (Figures 3 - red curve) compared to the case of the absence of hysteresis (Figure 3 - black curve).

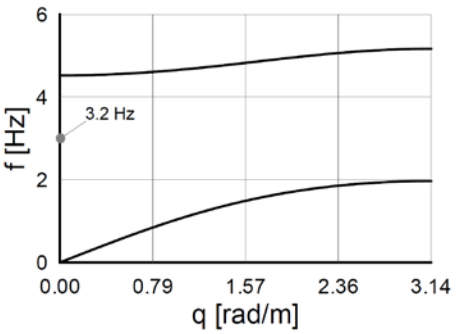


*Fig. 1: Dispersion curves of EP*

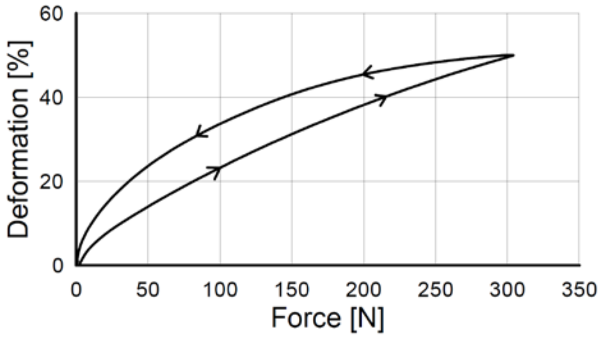


*Fig. 2: Experimental diagram force-deformation*

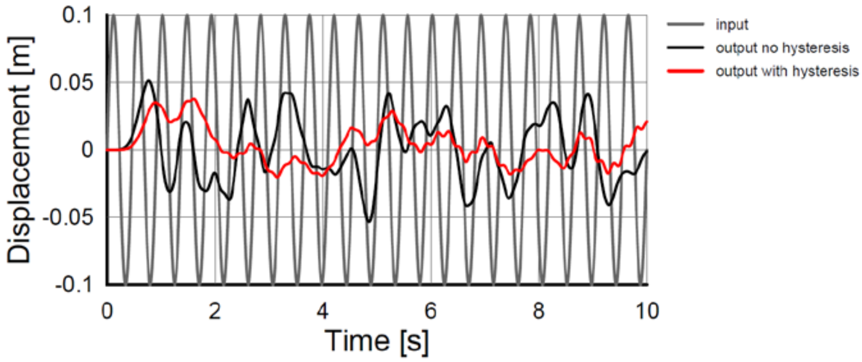


*Fig. 3: Results of numerical simulation*

# Hysteresis Modeling At Temperatures Near Curie Point Based On Mean Field Theory With Domain Structure

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This paper presents a hysteresis model to explain the thermal effect of magnetization curves near the Curie point $T_C$. According to a kinetic mean field theory, the magnetization $M_{in}$ of a uniaxial ferromagnet as a function of magnetic field $H$ and temperature $T$ satisfies following TDGL equation[1]: $\frac{dm_{\mathrm{in}}}{d\bar{t}} = -m_{\mathrm{in}} + B_S\left[\frac{3S}{S+1}\frac{1}{\varepsilon+1}\left(m_{\mathrm{in}}+h\right)\right]$ ,where $B_S[x]$ is the Brillouin function of $x$, and $m_{in}$, $h$, and $\varepsilon$ are dimensionless variables defined by $m_{in}=M_{in}/M_s$, $h=H/H_s$, $\bar{t}=t/\tau$, and $\varepsilon=T/T_C-1$, where $M_s$ is the saturation magnetization, $H_s=\alpha M_s$ is the saturation mean-field, $\alpha$ is the mean-field constant, and $\tau$ is the average relaxation time of spins. Below $T_C$, $m_{in}$ has two values at fields lower than the coercivity $|h_c|$. On soft magnetic materials, such a hysteretic curve cannot be observed using usual techniques because of the domain structure. We assume that the observed magnetization $m_{an}$ is a weighted average of $m_{in\pm}$ inside of domains separated by a domain wall as follows: $m_{an}=w_+m_{in+}+w_-m_{in-}$, where $w_\pm= w_\pm(h)$. If the wall motion is not frictional, $m_{an}$ becomes anhysteretic. To add the frictional effect to $m_{an}$ at $|h|<a_c h_c$, we adopt the Jiles-Atherton's reversible ($m_{rev}$) and irreversible ($m_{irr}$) magnetizations as follows[2]: $\frac{dm_{\mathrm{irr}}}{dh} = \frac{m_{\mathrm{an}}-m_{\mathrm{irr}}}{\delta K-\left(m_{\mathrm{an}}-m_{\mathrm{irr}}\right)}$, $m_{\mathrm{rev}} = c_1[\left(m_{\mathrm{an}}-m_{\mathrm{irr}}\right)+c_3\left(m_{\mathrm{an}}-m_{\mathrm{irr}}\right)^3]$, where a dimensionless parameter $K$ is linked to the average pinning site energy, the directional parameter $\delta=$ Sgn($dh/dt$), and $c_3$ is a parameter introduced to enhance the reversible contribution. When the magnetic field $h$ is applied, the model generates magnetization $m(=m_{irr}+m_{rev})$ curves on the both sides of $T_C$ (Fig. 1). In addition, the frequency-dependent magnetization $m(t)$ is obtained as a solution of following equation[3]: $\frac{d^2m(\hat{t})}{d\hat{t}^2} + \Lambda\frac{dm(\hat{t})}{d\hat{t}} + m(\hat{t}) = m$, where $\hat{t}$ is a dimensionless time defined by $\hat{t}=\omega_n t$ and $\Lambda$ is dimensionless parameters defined by $\Lambda=2\lambda/\omega_n$, where $\omega_n$ is the natural frequency, which generally satisfies $\omega_n \ll 1/\tau$ , and $\lambda$ is a damping factor of the domain-wall displacement. Magnetization curves at various frequencies and at various temperatures near $T_C$ will be shown in the full paper.

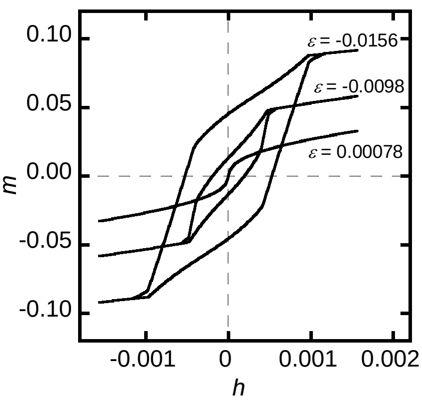


*Fig. 1: Magnetization curves calculated at a field amplitude $h_0$= 0.00156 and at various temperatures near $T_C$ with following values of the parameters: $S=\infty$, $\tau=0$, $K=0.137$, $c_1=0.2$, $c_3=5.0\times10^{-12}$, $a_c=1.2$, and $w_\pm(h)=(1\pm h/h_c)/2$.*

***References***

[1] T. Tome and J. de Oliveira, Phys. Rev. A41, 4251 (1990).
[2] D. C. Jiles, and D. L. Atherton, J. Magn. Magn. Mater. 61, 48 (1986).
[3] D. C. Jiles, IEEE Trans. MAG 29, 3490 (1993).

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# Analysis And Simulation Of Magnetic Hysteresis Using Scalar Preisach-Model And Finite Element Method

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The manuscript basically deals with the numerical simulation of the acting of ferromagnetic materials, focused on the ferromagnetic hysteresis. The implementation of the scalar Preisach-model of the nonlinear, multivalued function defined between the magnetic field intensity and the magnetic flux density is introduced by applying Everett-function set up from concentric hysteresis curves measured by using toroidal transformer. A brief survey of the measurement method is offered, and an expansive overview of the attendance of the staircase line over the Preisach-triangle is presented, and its connection with the output of the model by using matrices to store the past condition of the hysteresis-described system is paraphrased as well.

Besides the generic integral-determined model output, a dealable output-calculation method is summarized in connection with the matrix-stored staircase line by using triangle area ratio-theory, and the section also touch on the question of model verification. After this part, a short exposit of the Maxwell-equations is given in reference to the ferromagnetic hysteresis, wherein likewise the appropriate constitutive equations are outlined.

A short résumé of the finite element method is given, its principle, the steps of the method, the scalar form functions in one and two dimensions, the discretization and the way of solving the equations. In the next part of the manuscript, a possible solution of the fitting of Preisach-model into the finite element method simulation is explained. In the apropos of this, the fixed-point iteration technique and the polarization method is familiarized briefly, thus creating connection between the numerical manner and the acting model of the ferromagnetic materials.

In the last part of the matter, the problems observed and simulated in connection with the above mentioned theory by means of the solvers implemented in Matlab environment are presented. The simulation of the magnetic field intensity with one and two dimensional models observing a ferromagnetic material placed in homogeneous magnetic field is exposited, along with the calculation method of magnetic flux density: a bovrilized deduction of the partial differential equation and its weak formulation, and also the numerical implementation. With that, the results and the characteristics of modelling and simulation are briefly evaluated.

Last, but not least the partial differential equation of A-formulation is overviewed, its weak formulation, the numerical implementation by using a two dimensionally modelled example. Through a particular case the procedure of the solver operation is outlined, and the results are presented concisely.

# Hysteresis Model And Statistical Interpretation Of Energy Losses In Non Oriented Steels

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In this paper the hysteresis energy losses in two non oriented industrial steels (M400-65A and M800-65A) were determined, by means of an efficient classical Preisach model, which is based on the Pescetti-Biorci method for the identification of the Preisach density. The excess and the total energy losses were also determined, using a statistical framework, based on magnetic object theory.

The hysteresis energy losses Wh, in a non oriented steel alloy, depend on the peak magnetic polarization Jp and they can be computed using a Preisach model, due to the fact that in these materials there is a direct link between the elementary rectangular loops and the discontinuous character of the magnetization process (Barkhausen jumps). To determine the Preisach density it was necessary to measure the normal magnetization curve and the saturation hysteresis cycle. These data must contain 3N points, N points on the normal magnetization curve and 2N points between the positive and negative saturation values. Therefore a system with 3N equations was deduced and the Preisach density was calculated for a magnetic polarization Jp = 1.5 T; then the hysteresis cycle was reconstructed. Using the same pattern for the Preisach distribution, it was computed the hysteresis cycle for Jp = 1 T. Despite the fact that this classical model does not calculate exactly the saturation point, it approximates very accurate the area of the hysteresis cycle, so it is suitable to determine the hysteresis energy losses, which are independent of the frequency.

The classical losses were computed using a well known formula and the excess energy losses were determined by means of the magnetic object theory, which consists of n active magnetic objects in direct connection with the magnetic domain walls. The total energy losses were mathematically reconstructed and compared with those, measured experimentally.

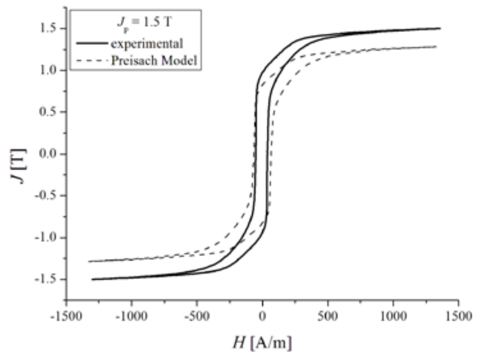


*Fig. 1. Comparison between the experimental and modeled hysteresis cycle in the case of M400-65A steel.*

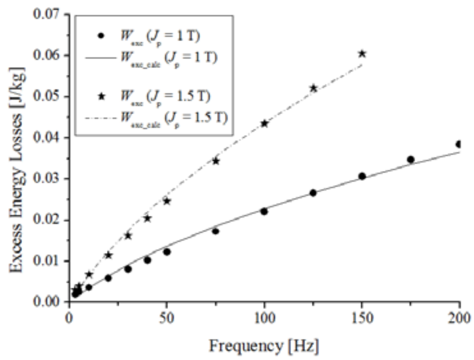


*Fig. 2. Comparison between the experimental values (Wexc, Wtot) and the predicted (Wexc_calc, Wtot_calc) behavior of the excess and total energy losses in M400-65A NO FeSi.*

**Acknowledgement:** The work of Veronica Mănescu (Păltânea) was supported by Project SOP HRD – PERFORM/159/1.5/S/138963 and the work of Horia Gavrilă and Gheorghe Păltânea by a grant of the Romanian Ministry of National Education, UEFISCDI, project number PN-II-PT-PCCA-2011-3.2-0373.

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# Preisach Engine In The Presence Of Arbitrarily-Oriented Hysteresis Loops

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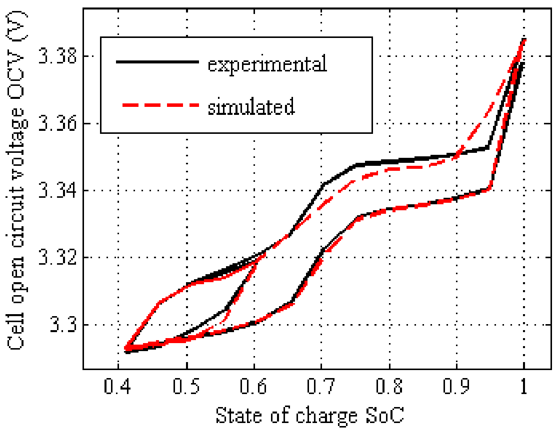
The classical approach to hysteresis modelling refers traditionally to magnetic systems where the Magnetization vs. Magnetic field is of concern. In this specific case, we observe counter-clockwise loops and monotonic increasing hysteresis branches. As well known, the paradigm for hysteresis modelling is the Preisach operator that, in these specific conditions, exhibits a positive distribution function μ [1]. Compensators for feedback control of hysteretic systems and Shape Memory Alloys (SMA) modelling required the ability to describe asymmetric and/or clockwise loops. A lithium-ion battery is another example where the classical approach to hysteresis modeling needs a modification. Indeed, a hysteretic behaviour of the State-of-Charge (SoC) versus Open Circuit Voltage (OCV) is observed [2] so that, if plotted in the SoC-OCV plane, the hysteresis is characterized by clockwise loops with strictly increasing branches. This phenomenon has strong evidence in Lithium-Iron-Phosphate (LFP) batteries [3], as depicted in the figure. Modelling LFP battery hysteresis requires going beyond literature approaches [4-5], where a simple modification of the Preisach engine is proposed.

We will discuss on a general Preisach formalism able to describe hysteresis phenomena, whatever the orientation of loops or monotonicity of branches are assumed. The question is whether it is possible to model a CW process with hysteresis as the superposition of CCW-oriented ideal relay contributions, weighted with a suitable μ. This problem can be easily solved by using, if necessary, a reversible term to the overall response. The key point to solve the problem is to relate the slopes of Everett integrals E and the density function μ. The Everett integrals are defined as $E(\alpha,\beta)=\int_{T\alpha\beta} \mu \, d\alpha d\beta$, where $T\alpha\beta$ is the integration triangle having one vertex in $(\alpha,\beta)$ in the Preisach domain. It can be proven that the slopes of the Everett function in the presence of monotone increasing branches can never be compatible with CW loops, unless we assume that μ has an impulsive component: $\mu(\alpha,\beta) = \mu_{reg}(\alpha,\beta)+ f\, \delta(\alpha,\beta).\delta(\alpha-\beta)$, where δ is the Dirac delta function and $\mu_{reg}$ the regular term of the density. However, the knowledge of the density function μ is not required. Indeed, the formalism of Everett functions for Preisach modelling is exploited as its value can be computed from the measurement of the First-Order Reversal (FOR) curves. An example is given in the figure for an LFP battery, whose major loop is reported in [3] and an arbitrary hysteretic response is plotted in the figure. The loop is drawn with the correct orientation on the basis of the identification procedure outlined above. Simulations based on the approach presented are also compared to the experimental data measured with pulsed current tests, showing satisfactory results.




***References***

[1] *I. Mayergoyz, Mathematical Models of Hysteresis, Elsevier, New York, 2003.*
[2] *M. A. Roscher et al. International Journal of Electrochemistry, Vol. 2011, pp. 1-6, 2011.*
[3] *F. Baronti, N. Femia, R. Saletti, C. Visone and W. Zamboni, IEEE Trans Magn, Vol. 50(11), 7300704, 2014.*
[4] *A. Ktena et al., Physica B,Vol. 306, pp. 84-90, 2001.*
[5] *I. D. Mayergoyz and P. Andrei, J. Appl. Phys., Vol. 91, No. 10, pp. 7645-7647, 2002.*

# The Effect Of Field Non-Uniformity On The Magnetic Susceptibility Of Superconductors

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Important properties of superconductive materials can be extracted from probing the magnetic susceptibility of their Meissner state. One of such properties is the London penetration depth which is directly related to the superfluid density and can give valuable information about the pairing symmetry.

By measuring the susceptibility of superconductive samples at low temperatures, the London penetration depth can be directly extracted. Typically, the samples under study, especially high Tc superconductors, are crystalline and have slab shapes of rectangular cross section.

An analytical formula, correlating the measured susceptibility of such samples with the London penetration depth, has been obtained by means on analytical and numerical calculations by Prozorov et. al. [1]. However, the probing magnetic field has to be uniform and perpendicular to the sample. This scenario can straightforwardly be achieved if large solenoid coils are being used to produce the probing field for relatively small samples. In order to achieve maximum output, the filling factor of the coil-sample ensemble has to be maximized [2] which in terms means that the sample will be subjected to a non-uniform field.

The aim of our work is to study the influence of non-uniform magnetic field profiles on the measured susceptibility of typical shapes superconductive samples in Meissner state. We investigate, by means of analytical methods and numerical calculations, the diamagnetic susceptibility response under the influence of realistic magnetic field profiles as those produced by commonly used susceptometer coils.

***References:***

*[1] Prozorov, R., Giannetta, R. W., Carrington, A., & Araujo-Moreira, F. M. (2000). Meissner-London state in superconductors of rectangular cross section in a perpendicular magnetic field. Physical Review B, 62(1), 115.*
*[2] Prozorov, Ruslan, and Russell W. Giannetta. "Magnetic penetration depth in unconventional superconductors." Superconductor Science and Technology 19.8 (2006): R41.*

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# On The Origin Of Stepwise Spin Transition Behaviour In 1d Nanoparticles

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The lasts years have bring new directions regarding the study of FeII spin crossover (SCO) complexes, one of these being the synthesis of switchable nanoparticles [1,2]. Investigating these materials at a reduced scale became a priority, in order to analyze their capacities to be used as active elements in potential nano-electronic and spintronic devices [3,4]. Besides the potential applications of SCO nanomaterials, their fascinating switching phenomenon using various stimuli (temperature, pressure, magnetic field, light irradiation) has drawn a considerable interest over the years for both physicist and chemist communities.

In order to investigate the spin state switching mechanism in molecular spin crossover (SCO) nanoparticles, a special attention is given to the reproduction of an unprecedented multi-step thermally induced spin crossover behavior tremendously awaited in 1D chains [5]. Using three types of interactions in the Ising Hamiltonian and an individual switching process which does not depend on the physical factors of the system, we show that multi-steps hysteretic behavior can be obtained in the thermal behavior of a 1D SCO system. Furthermore, the relation between a polymeric matrix and the particular multi-step spin crossover phenomenon is discussed. Finally, the environment influence on the SCO system size is analyzed as well.

**Acknowledgements:** the work at Suceava was supported by a grant of the Romanian National Authority for Scientific Research, CNCS–UEFISCDI, project number PN-II-RU-TE-2011-3-0307.

***References***

*[1] A. Bousseksou, et al., Chem. Soc. Rev., 40, 3313-3335 (2011).*
*[2] P. Gütlich, A. B. Gaspar, and Y. Garcia, Beilstein J. Org. Chem. 9, 342-391 (2013).*
*[3] A. Rotaru et al., Eur. Phys. J. B, 84, 439-449 (2011)*
*[4] A. Rotaru et al., Adv. Mater. 25, 1745-1749 (2013).*
*[5] D. Chiruta et al., Eur. J. Inorg. Chem, 5086-5093 (2013)*

# The Analysis Of Light-Induced Hysteresis For Spin-Crossover System Under Noise

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Spin-crossover (SC) solids are examples of “switchable” molecular magnetic materials, which provide a wide range of potential applications in contemporaneous nanoelectronics. Multifunctional properties of spin-crossover compounds may be considered for designing a new generation of optical data storage, processing devices, sensors, and visualization systems. The practical value of these materials lies on their response to the various external perturbations, such as temperature or light irradiation, leading to the switching of SC solids from a low-spin (LS) state to a high-spin (HS) state and vice versa [1]. Photoexcitation is one of the promising external fields to control the bistable properties of these materials, and thus their usage as optical controlled data storage and recording systems. In such applications, the stability of metastable states becomes extremely important, especially to thermal fluctuations.

We study the stochastic macroscopic kinetics of photoinduced phase transitions in spin-crossover compounds assisted by white and colored Ornstein-Uhlenbeck noise described by the following equation:

$$\frac{dn}{dt}=\beta(1-n)-n\exp[-\alpha n]+(1-n)\eta(t)+\xi(t), \qquad (1)$$

where $n$ is HS fractions of SC molecules, $\beta$ control parameter describing light irradiation, $\alpha$ is self-acceleration factor. The stochastic processes $\eta(t)$ and $\xi(t)$ corresponds to multiplicative and additive noises. Starting from this general form of a phenomenological master equation obtained in the mean-field approach, the phase diagram is constructed based on the associated Lyapunov function. The stochastic behavior is then analyzed in the Langevin framework based on the corresponding Fokker-Planck equation of the following general form:

$$\frac{\partial P(n,t)}{\partial t}=\frac{\partial}{\partial n}F(n)P(n)+\frac{\partial^2}{\partial n^2}G(n)P(n) \qquad (2)$$

The expressions for functions $F(n)$ and $G(n)$ depend on the particularly examined noise environment [2]. The noise color is introduced in the system through description of autocorrelation functions of stochastic processes $\eta(t)$ and $\xi(t)$ [3].

Both white and colored noise are considered as additive and multiplicative noise and, by solving the Fokker-Plank equations, the stationary probability densities are found along with the noise-assisted light induced hysteretic loops. The noise influence on the light-induced hysteresis characteristics is also determined and the qualitative differences between the actions of the additive and multiplicative noises on photoinduced hysteresis are analyzed analytically and numerically. By using the Kramers formalism, we also focus our attention on the escape time problem in these noise perturbed systems.

***References***

*[1] Spin-Crossover Materials: Properties and Applications, ed. by M. A. Halkrow (John Wiley & Sons, Chichester, UK, 2013).*
*[2] Iu. Gudyma, A. Maksymov, M. Dimian, Phys. Rev. E 88, 042111 (2013).*
*[3] Iu. Gudyma, A. Maksymov, C. Enachescu, Eur. Phys. J. B 78, 167 (2010).*

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# Hysteresis Modeling Of Spin-Crossover Solids Under Pressure

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The molecular complexes of transition metals with the electronic configuration d4−d7 can have both high spin (HS) and low spin (LS) central ions and are called spin crossover (SCO) solids. The setting of spin-state is related to the balance between the orbital energy, which is necessary for populating the all 3d sublevels, and the average energy of the Coulomb interaction between electrons on the d-levels. The compressible model of spin-crossover compounds we consider in simplest way enables to combine statistical and thermodynamic approach. This is the Ising-type model for simple statistical and thermodynamic description. The deformations are homogeneous and isotropic and are the result of changes in molecular volume at the spin transition [1]. Our work's aim was examined theory model of compressible spin-crossover solids and hysteresis simulation of the fraction of molecules in the HS state.Thermal and pressure induced behavior of SCO system, has been modeled in the framework of Ising-like model:

$$H = -h\sum_{i} s_i - \sum_{\substack{i,j \\ i\neq j}} J_{ij} s_i s_j + \frac{1}{2} K V_{LS} \xi^2 \ , \qquad (1)$$

where $s_i$ is a fictitious classical spin, which has two eigenvalues $\pm 1$, corresponding to the HS and LS states, respectively, and $\xi = \left(V(T) - V_{LS}\right)/V_{LS}$ indicates the relative change of the volumes in these states. Here, *K* is the bulk modulus of the lattice, $V_{LS}$ is the volume of unit cell in LS state at T=0. The third term is the elastic energy of the lattice. The second term in the Hamiltonian (1) describes the intermolecular interactions of elastic origin through a phenomenological parameter accounting the ferromagnetic coupling (J>0) between neighboring spins i and j in Ising form. This is the simplest way to express the co-operativity between magnetic molecules [2, 3]. The first term describes a "magnetic" energy or a contribution of ligand field. The basic variables defining the state of the system are the "magnetic" field h and the temperature T. We describe what happens by looking at the fraction of molecules in the HS state.

By using this model can be effectively studied the influence of pressure on the spin transition. The obtained numerical results enable us to construct the phase diagram in "magnetic field"-temperature plane, which in turn confirm the presence of first and second order phase transitions in such compounds. The dependence of the critical temperature and the coefficients of Landau expansion of the Gibbs free energy on the external pressure are derived. Phase transition kind depends generally on the magnitudes inter-ion interaction and crystal field of ligand. Obtained results show that the increasing the strain of system lead to a forthcoming of first-order phase transition. Finally, the phase diagram which characterizes the system is examined numerically. The conditions for obtaining hysteresis and the dependence of its shape under pressure studied in detail. The temperature-induced transitions in spin-crossover solids with breathing ligand field studied in details. The transition temperature under pressure to be increased and the width of the hysteresis should be reduced. The possibility to address spin states (HS state and LS state in considering model) through external stimuli opens the perspectives to construct new kinds of switches and magnetic storage.

***References***

*[1] Spin-Crossover Materials: Properties and Applications, ed. by M. A. Halkrow (John Wiley & Sons, Chichester, UK, 2013).*

*[2] Iu. Gudyma, V. Ivashko, J. Linares, J. of Appl. Phys. 116, 173509 (2014).*

*[3] Iu. Gudyma, A. Maksymov, C. Enachescu, Phys. Rev. B 89, 224412 (2014).*

# Micromagnetic Study Of Laterally Coupled Magnetic Waveguide

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Modern progress in the investigation of the coupled magnetic structures lead to miniaturize passive microwave components [1]. A number of linear and nonlinear devices (microwave phase shifters, filters, delay lines and resonators) can be fabricated using the layered structures. The characteristics of such devices can be tuned using both the static magnetic over a wide frequency range.

Here we report experimental and numerical investigations of spin-electromagnetic waves propagating in the laterally coupled yttrium iron garnet (YIG) finite-width waveguides. Numerical simulation was provided by the developped finite-element method (FEM) of electromagnetic eigenspectrum calculation [3] and FDTD simulation of LLD equation. Experimental study of eigenmodes of laterally confined YIG waveguides was performed by using space-resolved Brillouin light scattering (BLS) spectroscopy [4, 5]. We show that the spatial distribution of magnetization of the width-modes in laterally confined structure changes due to the electrodynamic coupling between the spin waves (SW) (Fig. 1). Moreover the effectiveness of coupling depends on the mode number, propagating in the layered structure. By using space-resolved BLS spectroscopy, we map the spatial distributions of the intensity of the propagating electromagnetic spin waves and measure directly their wavelength and spatial attenuation. We demonstrate the possibility of efficient SW excitation and propagation in the laterally coupled finite-width magnetic waveguides.

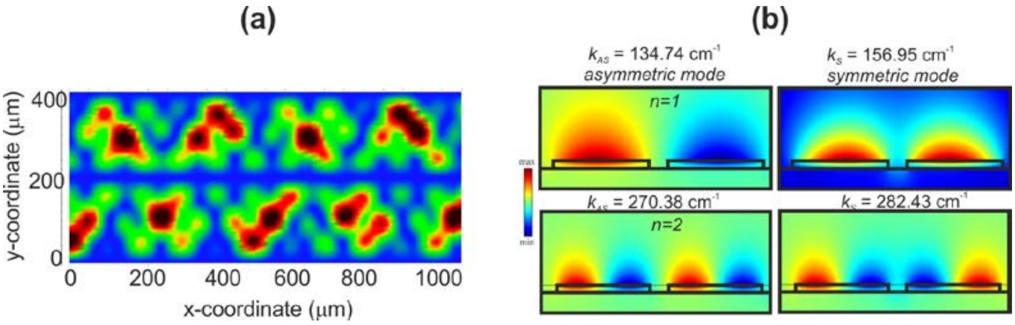


*Fig.1. FDTD calculation of |mz|2 in coupled magnetic waveguides (a) and FEM calculation of electrodynamic characteristics of the first and second symmetric and asymmetric modes (b)*

This work was partially supported by the Grant from Russian Science Foundation (Project # 14-19-00760), by the Russian Foundation for Basic Research (Grant # 13-07-12409, 14-02-00976, 15-07-05901).

***References***

*[1] U. Ozgur, Ya. Alivov, H. Morkoc, J. Mater. Sei.: Mater. Electron., 20, 911-952, (2009).*
*[2] V. E. Demidov, B. A. Kalinikos, P. Edenhofer, J. Appl. Phys. 91,10007 (2002).*
*[3] E. N. Beginin, A. V. Sadovnikov, Yu. P. Sharaevskii, S. A. Nikitov, Bulletin of the Russian Academy of Sciences. Physics, 77(12) 1–3, (2013).*
*[4] S. O. Demokritov and V. E. Demidov, IEEE Trans. Magn., 44(6), (2008).*
*[5] E. N. Beginin, A. V. Sadovnikov, Yu. P. Sharaevskii, S. A. Nikitov, Solid State Phenomena, 215, 389-393, (2014).*

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# Effect Of The Shape And The Lateral Dimensions On The Magnetization Reversal In Permalloy Nanofilms

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Thin ferromagnetic films are used for making magnetic memory, recording and reading devices. Application of the thinner films and the miniaturization of structural elements allow one to increase the recording density. However, the magnetization reversal process in small samples differs crucially from the reversal in the bulk ones as it becomes dependent not only on the characteristics of the material, the shape and dimensions of the samples, but also on the characteristics that are difficult to take into account like the roughness of the surface, the quality of interface between the film and substrate, the misfit stresses, and other factors. In this work the magnetization reversal in permalloy nanofilms has been simulated numerically and studied experimentally. The experiments were performed with magnetron-deposited films shaped by the lift-off lithography as the disks and rings with the diameters from 10 to 200 μm, the stripes from 2 to 200 μm wide and the waved strips of different curvatures 10 μm wide. The magnetization reversal was observed by Bitter decoration and magneto-optic visualization by indicator yttrium-iron garnet films techniques. Micromagnetic simulation was performed using the standard OOMMF package.

In the simulation of the biggest samples, we observed the classical process of the magnetization reversal, i.e. the domains form at the edges, grow to the sample interior and then expand to the whole sample. The change in the reversal scenario occurred when the lateral dimensions were diminished to a hundred of nanometers. The domain formation was changed by the appearance of a couple of vortices at the edges of the disc, which move along the periphery, providing a non-uniform rotation of the magnetization in the submicron disks. Further decrease in the disc diameter was shown to result in the magnetization reversal via formation of one vortex only that moves through the disc center. In the experiments the change in the magnetization reversal scenario was observed already in the structures by two orders of magnitude larger than was predicted by simulation, i.e. in the structures with the lateral dimensions of tens of microns. Unexpectedly large value of the critical dimensions could be explained taking into account an abnormally large width of real domain walls in permalloy, which could be a consequence of the polycrystalline film structure or is related to the film surface roughness being of about 1-6 nm, which could be in turn the cause of the appearance of perpendicular anisotropy.

Observation of the domain structure by Bitter technique confirmed the basic magneto-optical conclusions, and revealed some new features like the appearance of ripple of magnetization and near-surface labyrinth domain pattern before the magnetization reversal, Fig.1. It should be noted that the magnetic liquid affects some parameters of the magnetization reversal, in particular the coercivity value. Therefore, we cannot exclude that to some extend the effects are the consequence of interaction of magnetic fluid with magnetic films.

This work is partially supported by Russian Foundation for Basic Research (project 15-02-065743) and RAS program.

*(a)* *(b)*

*Fig.1: The labyrinth domain pattern in the beginning of the magnetization reversal of the strip: Bitter image of the structure, (a) and the sketch of the structure (b); the arrows show supposed in-plane components of magnetization direction that are separated by domain walls with perpendicular alternating up and down magnetization.*

# Synchronization Of Spin-Hall Oscillators: A Micromagnetic Study

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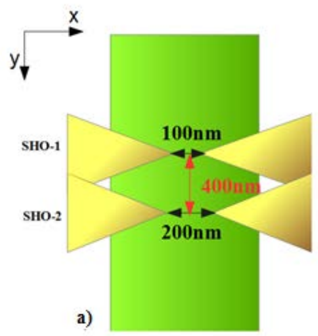
Experimental [1] and theoretical [2] studies of bilayers composed by a heavy metal film coupled with a thin ferromagnet have opened a way for the development of new spintronic devices. In those samples, the spin-orbit interaction in the bilayer drives the magnetization to precessional states where the magnetic losses are fully compensated by the torque due to the spin-Hall effect generated by the current flowing in the heavy metal. Here, we study a different geometry to excite propagating spin-waves and get the synchronization between two spin-Hall oscillators.

The system is composed by two contacts placed in the center of the device, 400 nm away from each other, while two pairs of tips are 100 nm and 200 nm away from the two spin-Hall oscillators SHO-1 and SHO-2, respectively (Fig.1a). The Au (150 nm) triangular contacts are positioned above the bilayer CoFeB(1 nm)/Pt(8 nm).The current is injected along the x-direction via the two gold contacts. When the current is injected only through a contact, localized modes and propagating spin waves have been observed for a magnetic field applied in-plane and out of plane, respectively [2]. With this in mind, the device described above has been studied to obtain the synchronization between two spin-Hall oscillators when the current is injected through the two contacts at once. Fig. 1b summarizes the oscillation frequency of the excited mode as a function of the current, for different out of plane external fields. Those results refer to the current region where the two oscillators are synchronized. Fig. 1c shows the snapshots of the magnetization for the points A, B, C and D as displayed in Fig. 1b. As the field is reduced, the wavelength of the excited spin-waves increases (for H=800mT a clear identification of the two sources of spin-waves can be observed, for H=200mT the wavelength of the propagating modes becomes comparable with the distance between the two oscillators giving rise to an excitation pattern where the two contacts cannot be identified anymore).



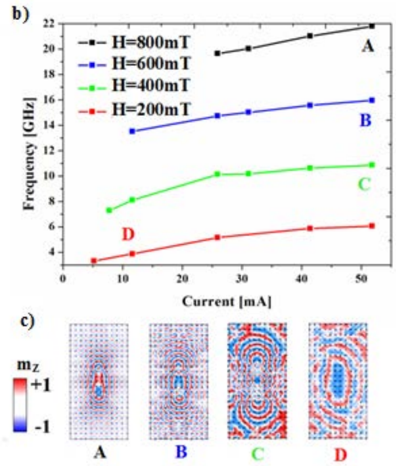




*Figure 1 - a) Example of the device structure, in the plane x-y. b) Oscillation frequency vs. current for different out-of-plane fields. c) Example of propagation pattern of spin-wavesrelated to the points A, B, C and D as displayed in Fig. b.*

***References***

*[1] V. E. Demidov, et al., Nat. Mater. 11, 1028-1031, 2012*
*[2] A. Giordano, et al., Appl. Phys. Lett. 105, 042412 (2014)*

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# Micromagnetic Modelling Of The Exchange-Coupled Stoner–Wohlfarth Ensemble

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Numerical and analytical studies of magnetization processes in the exchange-coupled Stoner-Wohlfarth (SW) ensemble have been performed. The space-filling ensemble was corresponded to nanoparticles of the same size with the isotropic distribution of easy magnetization axes. For each magnitude of an external magnetic field the equilibrium configuration of magnetic moments was evaluated from minimum of the following energy: $\varepsilon = \sum_{i=1}^{N}\left[-(\vec{\mu}_i \cdot \vec{n}_i)^2 - 2\vec{\mu}_i \cdot \vec{h} - \frac{\alpha}{2}\sum_{j=1}^{N_n}\vec{\mu}_i \cdot \vec{\mu}_j\right]$, where for $i$ particle $\vec{\mu}_i = \vec{M}_i/M_S$ is magnetization reduced to the spontaneous magnetization $M_S$, $\vec{n}_i$ – unit vector along the easy magnetization axis, $\vec{h} = \vec{H}/H_a$ is magnetic field reduced to the anisotropy field $H_a = 2K/M_S$, $K$ – uniaxial magnetic anisotropy constant. Parameter $\alpha$ is defined as interaction parameter $\alpha = J_{IEI}S/KV$, where $J_{IEI}$ – intergrain exchange interaction constant, $S$ and $V$ – the surface area between particles and the volume of one respectively. The contribution of the magnetostatic energy is neglected in this work.

The aim of the studies was to develop the estimation methods of intergrain exchange interaction constant for the isotropic exchange-coupled SW ensemble. These were considered two principal options for it: the quantitative analysis of Kelly plots [1] and the analysis of magnetic susceptibility measured in transverse and longitudinal direction to the remnant magnetization. Kelly plots are based on the comparison of a normalized dc demagnetization remanence $m_d(h)$ dependency on isothermal remnant magnetization $m_r(h)$ with the one for SW ensemble. The discrepancy is characterized by $\delta m(h)$. Micromagnetic modelling (fig. 1) revealed functional relation between the maximum value of the $\delta m(h)$ curve and microscopic parameters of the ensemble [2]: $\max(\delta m) = 2\left[1 - \exp\left(-\frac{26 J_{IEI} \cdot S}{V \cdot K}\right)\right]$. The second option originated from the analytical minimization of the energy for the remnant magnetization state of the ensemble with a weak coupling approximation [3]. Each of the methods allow us to estimate the intergrain exchange interaction constant for nanostructured highly anisotropic ferromagnets if there are known parameters of narrow particle size distribution and magnetic anisotropy constant. The last is not necessary for combined usage of them.

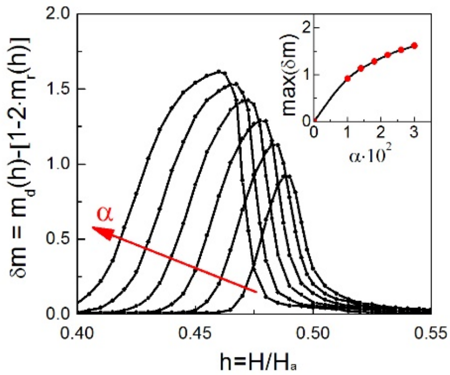


*Fig.1. Kelly plots for the isotropic exchange-coupled Stoner-Wohlfarth ensemble; inset - the $\delta m(h)$ maximum dependence on the interaction parameter $\alpha = J_{IEI}S/KV$ magnitude. The arrows indicate the direction of interaction parameter $\alpha$ increase.*

***References***

[1] P.E. Kelly, K. O'Grady, P.I. Mayo and R.W. Chantrell, IEEE Trans. Magn. 25 (1989) 3881-3883.
[2] A.S. Bolyachkin, A.S. Volegov, N.V. Kudrevatykh, J. Magn. Magn. Mater. 378 (2015) 362–366.
[3] R. Skomski, Simple Models of Magnetism, Oxford University Press, New York, 2012.

# A Neural-FEM Tool For The 2-D Magnetic Hysteresis Modelling

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The aim of this work to present a new tool for the analysis of magnetic field problems considering 2-D magnetic hysteresis. In particular, this tool makes use of the Finite Element Method to solve the magnetic field problem in real device, and fruitful exploits a Neural Network (NN) for the modelling of 2-D magnetic hysteresis of materials. The NN has as input the magnetic inductions components B at the k-th simulation step and returns as output the corresponding values of the magnetic field H corresponding to the input pattern [1]. It is trained by vector measurements performed on the magnetic material to be modelled. This input/output scheme can be directly implemented in a FEM code employing the magnetic potential vector A formulation [2]. The FE solution of the above equation can be performed by adopting Newton-Raphson method (NRM) or Fixed-Point technique (FPT) [2-3]. In this way the computing process is fast, and the FEM-NN tool can be used to reproduce the magnetic behaviour of complex devices, such as electrical machines or magnetic sensors. As an example, Fig. 1 shows a 2-D mesh of the asynchronous machine used for measurements and the magnetic field computed at the centre of the rotor for a Not Oriented Grain (NOG) magnetic steel core, excited by a circular magnetization. Validations through measurements on a real device have been performed.

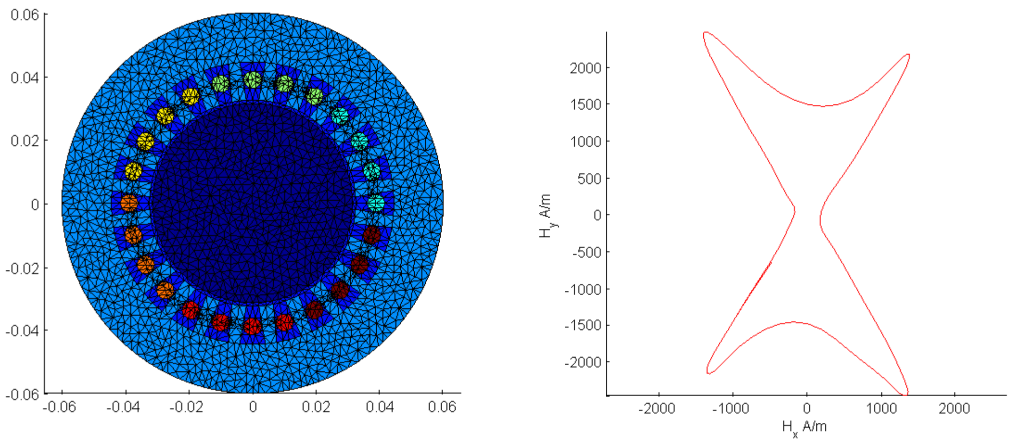


*Fig. 1: 2-D mesh of the asynchronous machine and the magnetic field computed at its centre for a Not Oriented Grain (NOG) magnetic steel core.*

***References***

*[1] E. Cardelli, A. Faba, A. Laudani, F. Riganti Fulginei, and A. Salvini (2015), "A neural approach for the numerical modeling of two-dimensional magnetic hysteresis", Journal of Applied Physics, in press.*
*[2] S. Coco et al. (2013), "Neural-FEM approach for the analysis of hysteretic materials in unbounded domain" COMPEL - The international journal for computation and mathematics in electrical and electronic engineering, Vol. 32, N. 6, pp. 1964-1973*
*[3] J. Saitz, (1999), "Newton-Raphson Method and Fixed-Point Technique in Finite Element Computation of Magnetic Field Problems in Media with Hysteresis", IEEE Trans. on Magnetics, 35(3), pp. 1398-1401.*

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# Two-Dimensional Magnetic Modeling Of Ferromagnetic Materials By Using A Neural Networks Based Hybrid Approach

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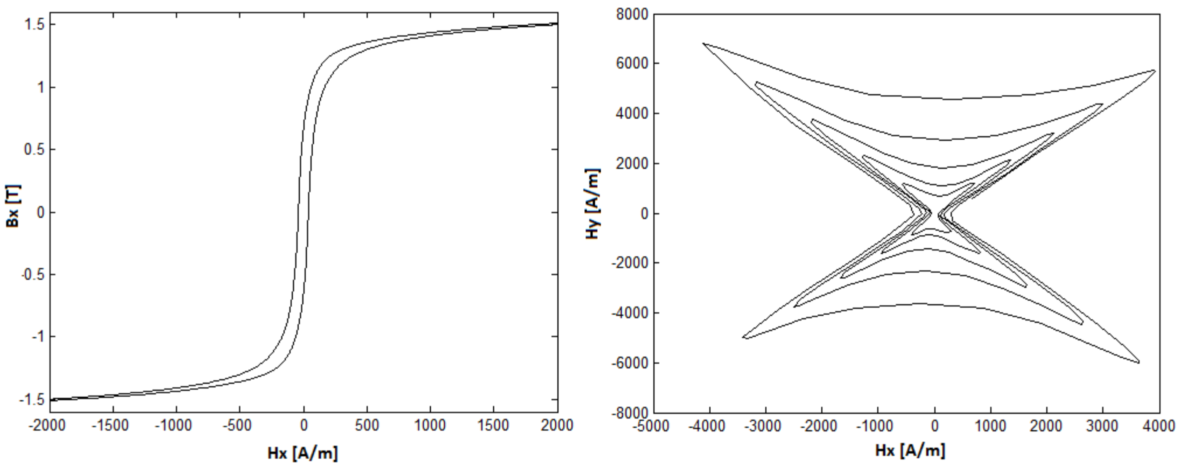
In this work a hybrid approach based on neural networks for modeling the two-dimensional ferromagnetic hysteresis is proposed. Several authors have proposed many different numerical procedures and models in literature [1 - 4]. Our aim is to obtain a new numerical approach consisting entirely of neural networks able to predict both circular polarization and scalar hysteresis loops. That neural system (NS), trained on measurements performed on the ferromagnetic sample to be modelled, exploits the synergy of two different subsystems: one for the prediction of the magnetic field under circular polarization of the magnetic induction and one for the prediction of the scalar hysteresis loops. In particular, the last one takes into account the hysteresis effects of the whole ferromagnetic material. The presented NS approach has been validated by predicting the components of the magnetic field on both Not Oriented Grain (NOG) and Oriented Grain (OG) electric steel core under circular and linear polarizations of the magnetic induction (see Fig. 1).




*(a)* *(b)*

*Fig. 1: Example of prediction the magnetic field components in the cases of: (a) linear polarization of the magnetic induction along the x axis for an OG electric steel core; (b) circular polarization of the magnetic induction for an NOG electric steel core.*

***References***

*[1] A.A. Adly, S K. Abd-El-Hafiz, "Efficient modeling of vector hysteresis using a novel Hopfield neural network implementation of Stoner–Wohlfarth-like operators", Journal of Advanced Research., 4, 4, 403–409, 2013.*

*[2] E. Cardelli, A. Faba, "Numerical two-dimensional modeling of grain oriented steel", Journal of Applied Physics 115, Article number 17A327, pages 17A327 - 17A327-3, 2014*

*[3] F. Riganti Fulginei, A. Salvini and G. Pulcini, "A neural approach for the numerical modeling of two-dimensional magnetic hysteresis ". 59th Annual Magnetism and Magnetic Materials (MMM) Conference, Honolulu, Hawaii, Nov. 3-7, 2104*

*[4] F. Riganti Fulginei, A. Salvini, "Neural Network Approach for Modelling Hysteretic Magnetic Materials under Distorted Excitations", IEEE Transactions On Magnetics, vol. 48, p. 307 -310, 2012.*

# Noise-Induced Effective Potential For Analisys Of Switching In Spin-Valves

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The magnetization dynamics in the nanosystems relevant to magnetic recording and spintronics technologies are stochastic in nature due to the presence of thermal fluctuations. This stochastic nature manifests itself in random transitions among coexisting steady states such as metastable magnetic equilibria or self-oscillatory regimes driven by spin-polarized currents. In this context there is a growing interest in studying the effects of fluctuations over a wide range of temperature across which the magnetic system undergoes superparamagnetic-like transitions [1]. In this paper, we carry out the analysis of a single-domain uniaxial nanomagnet subject to external fields and spin-polarized currents while in contact with a thermal bath. Our starting point is the stochastic Landau-Lifshitz (LL) equation appropriately generalized to take into account the effect of spin polarized currents [2,3]. We show that key information can be obtained by studying the properties of the noise-dependent effective potential that naturally arises from the averaging, with respect to rotations around the symmetry axis, of the Fokker-Planck equation [3] associated with the stochastic LL equation. The potential contains a fluctuation-dependent part which is related to the presence of a noise-induced drift in the Fokker-Planck equation. The competition between deterministic and fluctuations-dependent contributions to the potential gives rise to bifurcations that provide the skeleton of the thermally-induced transitions, such as those of interest in thermally assisted current or field switching [4]. The region of the control plane corresponding to the presence of either one minimum or two minima of the effective potential are separated by an Astroid-like curve which enables to computed the values of injected current needed to switch the nanomagnet as function of temperature. In this paper, the limit of applicability of the theory is studied by comparing the Astroid-like curve obtained by the effective potential analysis with the one determined numerically by estimating the switching values of the injected current computed at different temperatures and different rates of variation of the current itself.

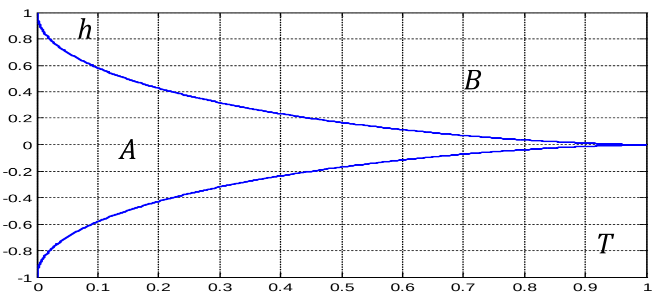


*Fig.1: Astroid-like curve: the solid line represents the normalized switching field ( h ) as function of normalized temperature ( $\tilde{T}$). The effective potential has two minima in region A and one minimum in region B.*

***References***

*[1] W. F. Brown, Phys. Rev. 130, 1677 (1963)*
*[2] R. Bonin et al. Eur. Phys. J. B 59, 435 (2007)*
*[3] G. Bertotti, C. Serpico, I. D. Mayergoyz, Nonlinear Magnetization Dynamics in Nanosystems, Elsevier, Oxford (2009).*
*[4] J. P. Liu, E. Fullerton, O. Gutfleisch, D. J. Sellmyer (eds), Nanoscale Magnetic Materials and Applications,Springer, New York (2009)*

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# Geometry Dependent Ferromagnetic Resonance Phenomena In Three Dimensional Magnonic Crystals

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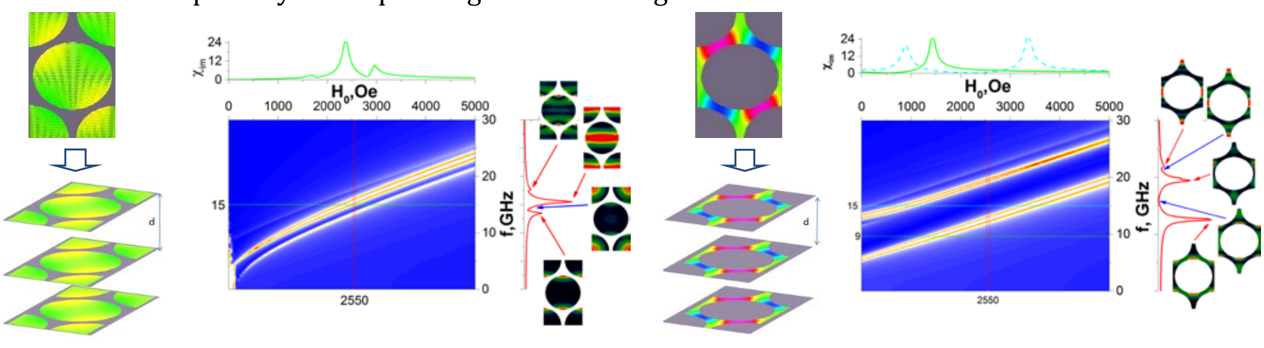
Magnonic crystals (MC) are artificial assembly of "man-made" building blocks with tailored properties via their geometrical shaping and compositional modulation. This fact makes possible the confinement of solid state excitations and formation of a discrete spectrum of the allowed modes. Magnonic crystals open huge possibilities for device application as the frequency and strength of resonances related to the propagation of the magnons can be controlled by the geometry and magnetization configuration of meta-atoms [1].

In this work we use micromagnetics simulations to find the spectra and spatial profiles of collective spin-wave excitations in various three-dimensional (3D) arrays of magnetic nanoelements. Complicated shapes of magnetic elements forming three-dimensional magnonic crystals determine a rather complex structure of a spin wave spectrum of these individual nanosized elements. Thus, full scale micromagnetic simulations that go beyond the macrospin approximation are needed to accurately evaluate the structure of spin wave modes in these elements. The magnetization dynamics in nanosized magnetic elements is described by the Landau Lifshitz-Gilbert (LLG) equation that is solved using a Finite Difference Time Domain (FDTD) method. Commercial (LLG Micromagnetics Simulator) [2]) and open-source (mumax [3]) software packages was used for this purpose. While the commercial micromagnetics code offers the advantages of an advanced graphical user interface and integrated data analysis functions, mumax, which is a GPU-accelerated micromagnetics code, brings the high computation speed necessary for the simulation of larger scale systems.

A static magnetic field selects different ground states of the system while a transverse picosecond exponential magnetic pulse determines the magnetization dynamics in the system. The frequency and field dependence of the imaginary part of magnetic susceptibility is obtained from spectral analysis of the time dependent magnetization. A special attention was paid to the influence of the magnetic system ground state on the properties of the collective resonance modes, i.e. the possibility to dynamically reconfigure a ground state of 3D MCs. The frequency response of a 3D MC was extracted from the spatially and temporarily resolved data produced by micromagnetic simulations. In the Fig. 1 are presented examples of such results for 3D array of dots and antidots are shown. The spatial profiles of resonance frequencies distribution is presented for the main modes of susceptibility corresponding to a static magnetic field of H0 = 2500 Oe.




*(a)* *(b)*

*Fig. 1 The feromagnetic resonance spectra for 3D arrays of dots (a) and antidots (b).*

***Refrences***

*[1] M. Krawczyk and D. Grundler, J. Phys.-Condes. Matter, vol. 26, p. 32, Mar 2014.*

*[2] M. R. Scheinfein, " LLG Micromagnetics Simulator," http://llgmicro.home.mindspring.com.*

*[3] A. Vansteenkiste, J. Leliaert, M. Dvornik, M. Helsen, et al, AIP Adv., vol. 4, p. 22, Oct 2014.*

# Fast And Accurate Calculation Of The Demagnetization Tensor For Systems With Periodic Boundary Conditions

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Micromagnetic simulations are an important tool for the investigation of magnetization dynamics. In micromagnetic simulations, the magnetization in one simulation cell is acted upon by the demagnetization field that is generated by all simulation cells. In numerical simulations with periodic boundary conditions (PBC) long-range interactions between the sample and each of its repetitions have to be included in the computation. This leads to an infinite number of interactions to be taken into account. Since the dipolar interaction decreases with increasing distance it is in principle possible to calculate the occurring infinite sum by neglecting all cells beyond a certain distance. However, this cutoff range has to be very large which renders this method impracticable. This problem is similar to the Madelung sum in solid state physics [1] where the electrostatic interaction in a periodic crystal is calculated. For the demagnetization interaction with one dimensional PBC it has been demonstrated that a useful approach in real space is to calculate the first terms exactly and to use an approximation for the terms that correspond to more distant cells [2].

In this work, we present a scheme to calculate the demagnetization interaction with one and two-dimensional PBC fast and accurately [3]. The method has been implemented in a micromagnetic simulation tool. For a reasonable accuracy and two-dimensional periodic boundary conditions the presented method is about six orders of magnitude faster than the straightforward method in which all cells beyond a certain distance are neglected (see figure 1). In principle this method can also be applied to other long-range interactions like the Oersted field and the electrostatic interaction [1].

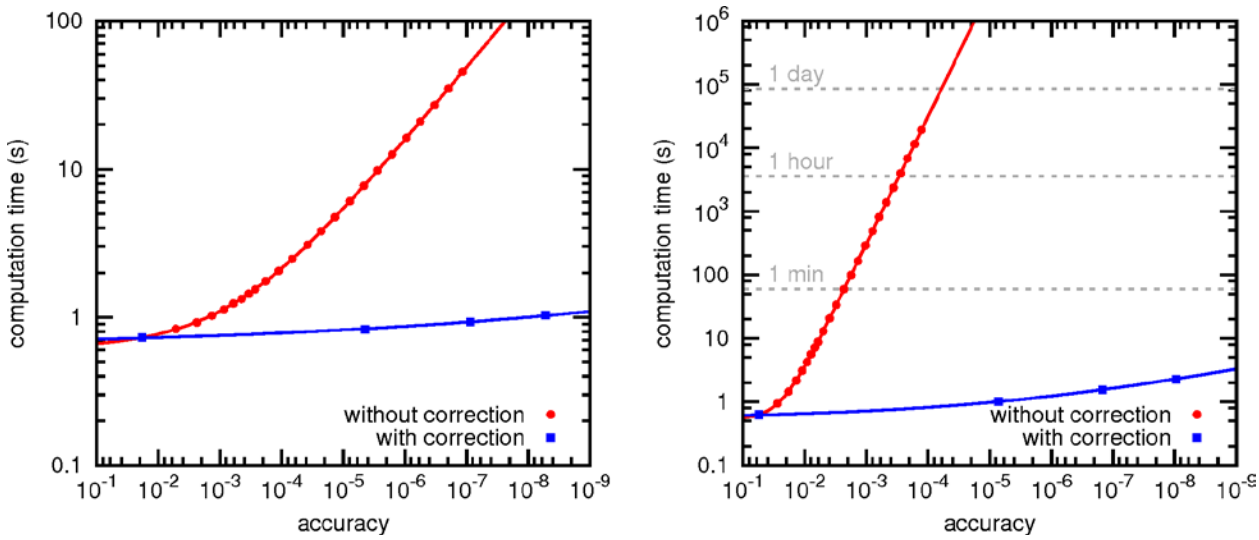


*Fig. 1: Computation time that is needed for the calculation of the demagnetization tensor with one dimensional (left) and two dimensional (right) PBC using the straightforward method (discs) and the developed corrections (squares). The gray lines in the right figure denote computation times of one minute, one hour, and one day.*

***References***

[1] *E. Madelung, Physik. Zeitschr., 19, 524 (1918).*
[2] *K. M. Lebecki, et al., J. Phys. D: Appl. Phys., 41, 175005 (2008).*
[3] *B. Krüger, et al., IEEE Trans. Mag. 49, 4749 (2013).*

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# Exchange Bias Effect In Hybrid Magnetic Nanoparticles

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*(4) Department of Physics, University of South Florida, Tampa, FL-33620, USA*
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Solution chemistry methods provide a versatile bottom-up approach for the growth of nanoparticles with tailor-made of sizes, shapes and material combinations. In the present work we use solution chemistry methods to grow $Fe_2O_3$/CoO hybrid nanopartices with both the direct (FM grown on AF) and the inverted (AF grown on FM) morphology and various sizes. We use a combination of imaging techniques (TEM), magnetometry (SQUID) and computer simulations to understand the factors controlling the exchange bias effect in these hybrid nanoparticles. We observe an interesting behavior at low temperatures exhibiting strong time dependent phenomena (initial curves lying out of the hysteresis loop) and supression of the exchange bias effect below a certain particle size.

We model the morphology of the hybrid nanoparticles by two partialy overlapping spherical particles of FM and AF material, described by a classical classical Heisenberg Hamiltonian with different local anisotropy terms for the core, the (free) surface and the interface region of each constituent spherical particle. We obtain the isothermal magnetic hysteresis after field-cooling using the Metropolis Monte Carlo algorithm and investigate the dependence of the exchange bias effect on the different geometrical lengths characterising the hybrid nanostructure (particle diameters, center-to-center distance) and the material parameters (exchange and anisotropy energy). Our simulations show that the exchange bias field: (i) shows a non-monotonous dependence on the degree of overlap between two spherical particles of fixed radii, following the change of the interface-to-volume ratio. (ii) shows a non-monotonous dependence on the ratio of the particles radii ($R_{FM}/R_{AF}$) , (iii) vanishes below a critical value of the AF radius. Our simulation results support adequately the experimental measurements.

**Acknowledgment:** the authors from ASPETE, NCSR "Demokritos", University of Ioannina, ICMM and University of Delaware acknowledge financial support by the European Social Fund and Greek national funds through the Research Funding Program *ARCHIMEDES-III*.

# Inertial Mass Of Magnetic Domain Wall Under Magnetic Pulse Fields

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We have analysed inertial mass of the magnetic domain wall in ferromanetic nanowire under magnetic pulses by means of micromagnetic simulations [1,2] Due to an increasing request for a high speed operation, spintronic devices based on domain wall motions should utilizing a domain wall speed faster than 1000 m/s, where the exact consideration of the domain wall mass becomes essential. We have observed that domain wall motion initiated by a strong magnetic pulse field of few nanoseconds, the domain wall keeps its motion after switching off the field pulse. We have systematically changed material parameters such as a damping parameter and exchange coefficient. The inertial mass of the domain wall under various configurations are numerically calculated, where the domain wall motion is explained based on a simple 1-D damped motion.

***References***

*[1] M. J. Donahue and D. G. Porter, OOMMF User's Guide, http://math.nist.gov/oommf (2002).*

*[2] H.-G. Piao, J.-H. Shim, D. Djuhana, and D.-H. Kim, Appl. Phys. Lett. 102, 112405 (2013).*

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# New Thermodynamic Paradigms in Low Dimensional Magnetic Structures Far from Equilibrium

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Using light (a few tens of femtoseconds laser pulses) processing information speed can be increased by orders of magnitude, which was considered impossible just a few years ago [1]. This phenomenon was recently revealed in ferromagnets [2] and in antiferromagnetically coupled multilayers and heterostructures [3] fully compatible with the manufacturing methods in the market. The major challenge now is to realize such ultra-fast switching of a bit of information at the nanoscale. A promising idea is to design bits in the form of topologically protected nanometre structures which can be moved using polarized currents of very low intensity [4].

Ultra-fast processes in condensed matter with advanced non-equilibrium states are a completely new area in physics. We are forced to use concepts from Equilibrium Thermodynamics (ET) as the electrons, phonons or magnons temperature as well as thermal energy exchange between these reservoirs. Also, when we are dealing with a small number of particles relative to Avogadro's Number (AN), methods of Statistical Mechanics become unusable.

Several new paradigms are analysed in this work in order to extend the ET laws (with the focus on the second law) to the (basically quantum) systems in the conditions described above. For example, an interesting concept is entropic torque [5,6] which seems to be larger than the angular momentum transfer from the magnon current in various magnetic textures and driving forces. This concept is particularly addresed in this work in the case of ultrafast dynamics and/or a small number of particles relative to AN, asking that is there a second law of thermodynamics in this regime. Numerical simulations are provided and principles of good practices in the use of the new concepts are stated in relation with the multiscale approach in the presented models [7,8].

**Acknowledgment:** This work was financially supported by a grant of the Romanian National Authority for Scientific Research, CNCS-UEFISCDI Project PN-II-RU-TE-2012-3-0439 [DYNAMIC]

***References:***

*[1] A. Kirilyuk, et al., Rep. Prog. Phys. 76, 026501 (2013)*
*[2] C-H. Lambert, et al., Science 345, 1337 (2014)*
*[3] S. Mangin, et al., Nature Mater. 13, 286 (2014)*
*[4] J. Sampaio, et al., Nature Nanotech. 8, 839 (2013)*
*[5] S. Wienholdt, et al., Phys. Rev. B 88, 020406(R) (2013)*
*[6] F. Schlickeiser, et al., Phys. Rev. Lett. 113, 097201 (2014)*
*[7] E. Oniciuc, et al., Appl. Phys. Lett. 102, 022405 (2013)*
*[8] E. Oniciuc, et al., Appl. Phys. Lett. 104, 222404 (2014)*

# Simulations Of The Heating Processes Of Magnetic Nanoparticles Suspended In A Viscous Fluid

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Few decades have passed since the idea of using magnetic nanoparticles in hyperthermic treatment of cancer was introduced to the scientific community. Since then, an important effort has been oriented towards the understanding of the physical mechanism that governs the response of the magnetic nanoparticles under various external conditions. The small size of the nanoparticles situates these structures at the border between quantum and classical physics, so the properties of the nanoparticles are quite different from the properties of bulk structures. In studies concerned with magnetic hyperthermia one aims to maximize the efficiency of this therapeutical procedure in order to diminish the negative effects [1].

In the heat generation mechanisms in a magnetic nanoparticle (MNP) under varying external magnetic field, we distinguish between losses due to friction between the MNP and the environment (Brownian relaxation) [2] and losses due to the rotation of the magnetic moment of the nanoparticle relative to the MNP's lattice (Neel and hysteresis losses) [3]. For systems of nanoparticles with relative high coercivity suspended in a fluid with low viscosity frictional losses are expected to dominate. The cases in which only one of the above processes prevails are theoretically studied but the results apply only to oversimplified physical systems.

In this work we aim to simulate the coupling of magnetic moment of a non-interacting system of MNPs in a viscous fluid with the time variable external field, in order to determine the specific power loss (SPL). We establish a system of differential equations containing the LLG-type equation for the magnetic moment (macrospin) dynamics and the mechanical rotation movement of one MNP. In the theoretical model we propose will include both Neel and Brown relaxation processes of the nanoparticles in Brownian motion. One goal of our study is to determine the frequency range in which each of the processes mentioned above prevails. We determine the characteristic time of the relaxation processes and compare them with known experimental and theoretical results. We compute the dissipated energy specific to each of the described processes.

**Acknowledgment:** This work was financially supported by the grants of the Romanian National Authority for Scientific Research Parteneriate - HYPERTHERMIA Project No. 148/2012 and CNCS-UEFISCDI Project PN-II-ID-PCE-2011-3-0794 [IDEI-EXOTIC No. 185/25.10.2011]

***References***

*[1] S. Dutz, R. Hergt, J. Mürbe, J. Töpfer, Robert Müller, M. Zeisberger, W. Andrä, and M.E. Bellemann, Magnetic nanoparticles for biomedical heating applications, Zeitschrift für Physikalische Chemie, 220(2/2006):145–151, 2006.*
*[2] Lev D. Landau and Evgeny Mikhailovich Lifshitz, Fluid Mechanics: Landau and Lifshitz: Course of Theoretical Physics, volume 6, Elsevier, 2013.*
*[3] Giorgio Bertotti, Hysteresis in magnetism: for physicists, materials scientists, and engineers, Academic press, 1998.*

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# Magnetic Eigenmodes Excited By Spin Hall Effect In Transversely Magnetized Rectangular Nife Dots

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Recent studies have demonstrated the possibility to reduce (or increase) the effective magnetic damping in ferromagnetic materials by means of a pure spin current, generated by the spin Hall effect (SHE).[1,2,3,4] This discovery opened a new range of opportunities in the field of spintronic envisioning new ways to exploit spin waves (SWs) for high-frequency signal transmission and processing.

In the present work we employed micro-focused Brillouin light scattering (micro-BLS) to study the amplification of thermal SWs by means of a pure spin current, generated by SHE, in a Pt(4nm)/NiFe(4nm)/SiO2(5nm) layered dot of rectangular shape and lateral dimensions ranging from 300x600 to 1000x1500 nm$^2$. Measurements have been performed by applying an external field both in-plane and out of the sample plane ($\theta$=0° and $\theta$=70° away from the sample surface). In both geometries the in-plane component of the field is parallel to the rectangle shorter side and perpendicular to the direct current (IDC), which flows along the longer side of the Pt rectangle. The frequency of both the center (fundamental) and the edge SW modes has been measured by micro-BLS as a function of IDC. The frequency of both modes exhibits a clear redshift on increasing IDC. A linear extrapolation of the inverse of the SW intensity, integrated in the whole frequency range, as a function of IDC accounts for a threshold value for IDC ranging from 1.3 to 6.6 mA and proportional to the area of the rectangle section. Interestingly, just above the threshold value a third mode, localized in the central part of the rectangle appears at higher frequency values in the 500x750 nm$^2$ device. Micromagnetic simulations were used to quantitatively reproduce the experimental results and to investigate the appearance of this extra mode above the IDC threshold.

***References***

*[1] K. Ando, et al. Phys Rev. Lett. 101, 036601 (2008).*
*[2] R. Liu, et al. Phys. Rev. Lett. 110, 147601 (2013).*
*[3] V.E. Demidov, et al. Nature Mater. 11, 1028 (2012).*
*[4] V.E. Demidov, et al. Appl. Phys. Lett. 104, 152402 (2014).*

# Magnetostatic Bias And Athermal Demagnetization In Kagome Artificial Spin Ice Systems

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The magnetostatic bias in elongated nanomagnetic elements arranged in Artificial Kagome spin ice arrays is studied by micromagnetic simulations using the Nmag package. The reversal of a given element has been simulated under the influence of its four nearest neighbors with their magnetic states fixed in all possible configurations. This includes 24=16 sates which can be classified under five different cases. The hysteresis loop of each element is greatly influenced by the magnetic state of the nearest neighbors not only by the expected shift due to dipolar interaction bias, but as it regards the loop shape and width itself. This presents a correction to the usual macrospin calculation assumptions in which the effect of interparticle interactions is taken on account by simply calculating the total dipolar (plus external) field at a specific element and checking if it exceeds its coercivity. The latter is equivalent to the assumption that the loop is shifted by a biasing field (equal to the local dipole field) but the loop width (and shape in general) does not change. The long range of dipolar interactions creates an overall magnetizing effect with remanence enhancement of the order of 8% above the expected value. Kagome systems serve as models for the study of geometrically frustrated magnets for which the ability to achieve the low-energy states athremally via demagnetization drastically decreases as the system size (number of elements) and consequently degeneracy increases. It is shown that rotation in angular steps a little less than 180o is the most effective process in accessing the largest possible number states before ending up near the ground state even in the absence of any disorder which is shown to represent the most unfavorable case.

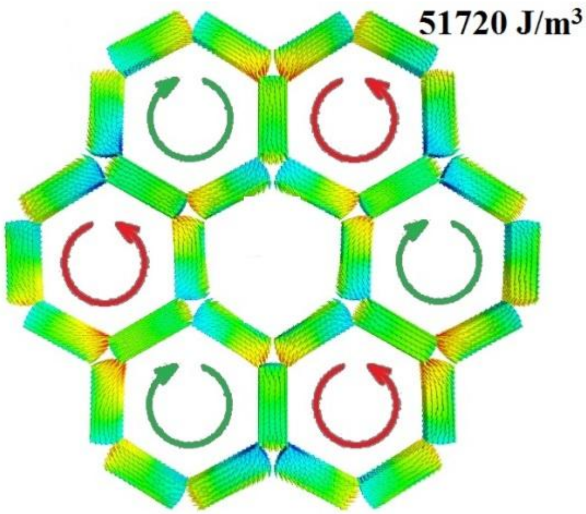


*Fig. 1: Characteristic micromagnetic state for an array of 30 elements arranged in seven hexagonal rings having the outer rings in states of alternating chirality. The pseudocolor corresponds to the scalar magnetic potential.*

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# Magnetic Field, Current And Voltage-Induced Ferromagnetic Resonance In Magnetic Tunnel Junctions: Micromagnetic Spatial Analysis

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In order to perform an advanced analysis of complex magnetization dynamics induced by phenomena such as Spin-Transfer-Torque (STT) [1] or voltage-controlled anisotropy changes [2,3], a spatial distribution of power spectral density obtained from micromagnetic simulations is often needed [4]. We use a specially designed open-source tool that utilizes parallel computing in order to create spectral density maps with frequency domain analysis conducted separately for each cell [5]. We examine the distribution of FFT amplitude for the respective frequencies of identified peaks in a nanooscillator based on a magnetic tunnel junction (MTJ). An example result calculated for a constant current STT-induced resonance in the free layer is presented in Fig. 1. The differences in localizations of two modes are clearly visible, allowing for more detailed analysis of the junction behavior and peaks origin.

Using such an approach, we compare localization of frequency modes excited by: single pulses of magnetic field, alternating magnetic field, constant spin-polarized current flow, alternating current (via spin-diode effect) and alternating voltage which induces anisotropy changes. Obtained results will be presented and used in attempt to optimize excitation types as well as geometrical and material parameters of experimentally investigated MTJs. We also discuss opportunities for further analysis based on our approach combined with wavelet transform in case of non-stationary dynamic processes in MTJs.

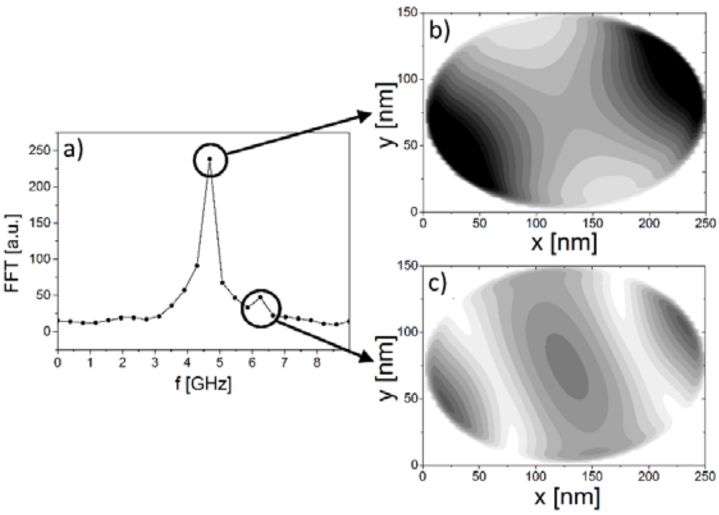


*Fig. 1. Spectral analysis of 250×150 nm spin-torque oscillator based on MTJ under constant magnetic field. a) overall FFT spectrum b) FFT spectrum density, f=4.7 GHz. c) FFT spectrum density, f=6.2 GHz.*

Project was co-financed by the Polish Ministry of Science and Higher Education - Diamond Grant DI2011001541 and Polish National Science Center grant Harmonia-DEC-2012/04/M/ST7/00799.

***References***

*[1] J.C. Sankey et al. Nature Physics 4, 67 - 71 (2008).*
*[2] T. Nozaki et al. Nature Physics 8, 491–496 (2012).*
*[3] W. Skowroński et al. Applied Physics Letters 105, 072409 (2014)*
*[4] A. Giordano et al. Appl. Phys. Lett. 105, 042412 (2014).*
*[5] M. Frankowski, J. Chęciński et al. Computer Physics Communications 189, 207–212 (2015).*

# Switching Properties Of Perpendicular STT-MRAMs With Second Order Anisotropy

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Magnetic tunnel junctions (MTJs) are very promising devices for several technological applications, such as spin-torque nanoscillators, microwave detectors and Spin-Transfer torque MRAMs. In particular, they could be used as "universal memories", being fast, thermally stable and easily included in the conventional CMOS technology [1]. A huge step ahead towards the improvement of the STT-MRAMs performances has been done by the discovering of the interfacial perpendicular anisotropy (IPA) [2], in MTJ with an iron-rich CoFeB free layer and a MgO tunnel barrier, due to electrostatic interaction arising at the CoFeB/MgO interface. This effect can be modeled micromagnetically as an additional thickness dependent perpendicular magnetic anisotropy field added to the total effective field. The most promising advantage of the IPA should be the lower switching current densities (SCD) ($<10^6$ A/cm$^2$) and energetic consumption obtained in in-plane MTJs [3]. The IPA strongly depends on the free layer thickness, decreasing when the thickness increases. Therefore, over a critical value of the thickness, the easy axis of the magnetization will be in-plane. However, if the thickness is critical, also the effect of the second order anisotropy [4] has to be considered and it crucially influences the SCD.

In this work, we investigated the SCD of a CoFeB/MgO MTJ with a perpendicular easy axis of the free layer magnetization, including both the first and the second order magnetocrystalline anisotropy. The SCDs were determined analytically and verified by micromagnetic simulations. The analytical predictions and numerical simulations have been made under the assumption of uniformly magnetized particles.

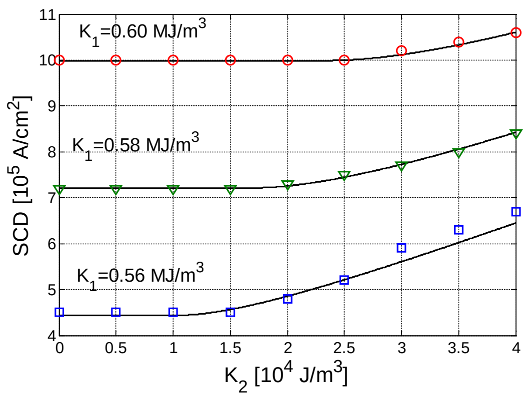


*Fig. 1: SCDs as a function of $k_2$ for $k_1$=0.60, 0.58, and 0.56 MJ/m$^3$ (Dotted-line analytical results , circles, triangles and squares respectively, micromagnetic results.*

***References***

*[1] J. Åkerman, "Toward a universal memory" , Science, 308, 508–510,( 2005).*
*[2] S. Ikeda et al., "A perpendicular-anisotropy CoFeB–MgO magnetic tunnel junction", Nature Mater., 9, 721–724, (2010).*
*[3] R. Tomasello et al. "Switching properties in magnetic tunnel junctions with interfacial perpendicular anisotropy: Micromagnetic study", IEEE Trans. Magn., 50, 7100305, (2014).*
*[4] Juan G. Alzate et al. "Voltage-Induced Dynamics in Nanoscale Magnetic Tunnel Junctions: Higher-order Anisotropy Contributions to Ferromagnetic Resonance and Switching", IEEE*

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# Magnetic Anisotropy Of Obliquely Deposited Thin Films Evaluated By Micromagnetic Modeling

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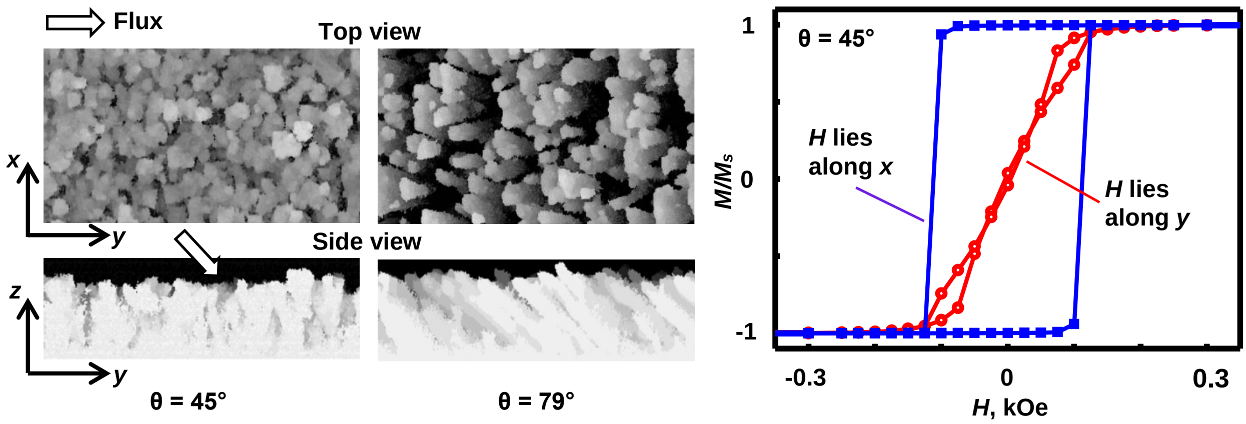
Thin ferromagnetic films have a wide range of applications such as magnetic recording heads, microwave noise filters, microwave inductors, and others. One of the methods for producing samples that helps to tune easily their characteristics is oblique deposition. The shadowing effect, which occurs in such films, induces anisotropy in their macroscopic properties [1]. In this paper, we theoretically investigate the structure and hysteresis loops of obliquely deposited films. We used micromagnetic modeling in conjunction with Monte-Carlo simulation of films growth to explain the magnetic anisotropy induced by oblique deposition. We used our own micromagnetic simulation software for modeling static and dynamic magnetic properties of magnetic nanostructures [2]. We also developed 3D Monte-Carlo simulator for modeling thin film deposition that was based on known algorithms [3].




Calculations showed that the columnar structure of the films had an anisotropic shape which depended on the deposition angle θ (see Fig. (a)). The non-uniform structure of the film led to the formation of demagnetizing fields in it. As a result, magnetic uniaxial anisotropy was induced. This was confirmed by calculated hysteresis loops with high squareness (see Fig. (b)). It has been found that for a particular deposition angle the symmetry of particles conglomerations changed. Due to the change in the symmetry, the direction of the shape induced uniaxial anisotropy made a 90° turn. The obtained theoretical results agree well with experimental data [1, 4] which implies that the proposed method is efficient and can be used for evaluation of magnetic properties of thin films with a complicated structure.

***References:***

*[1] H. Kranenburg, C. Lodder, RII (1994) p. 295-354*
*[2] B. A. Belyaev, A. V. Izotov, An. A. Leksikov, Phys. of the Solid State, 52 (2010), p.1664–1672*
*[3] T. Karabacak, J. of Nanophotonics, 5 (2011) p.052501*
*[4] K. Ozawa, T. Yanada et al., JMMM, 35(1983), p. 289-29*

# Unified Model Of Hyperthermia Via Hysteresis Heating In Systems Of Interacting Magnetic Nanoparticles

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A promising methodology for cancer treatment is magnetic hyperthermia. Understanding the mechanisms of magnetic heating is crucial for synthesizing the optimal particles and to control the heating inside the human body. Full understanding of the hyperthermia heating process requires a model incorporating these key elements: it must span the full range of applicability beyond the linear response regime, 2) include the effects of intergranular interactions, 3) take into account the distribution of properties (size, anisotropy, easy axis orientation, etc.), and 4) be fully time-quantified to allow frequency dependent studies. Although individual investigations incorporate some of these factors, a generalised model unifying all the key factors for hyperthermia is needed if hyperthermia is to be developed and optimised as a therapy.

Our study is based on the kinetic Monte-Carlo [1] modelling and contains all the complexity mention above. We explore the limitations of the linear response theory developed by Rosensweig [2] (LRT), which is practically always used in the technology design and optimization. We demonstrate, for the first time, that there is a formal link between the LRT and the kMC approach via the underlying master equation formalism, which gives a mathematically consistent modeling method essential for unified description of fast and slow time scales relevant in the superparamagnetic and hysteretic regimes of nanoparticle systems.

We show that the magnetic behaviour can be categorized in 3 regions in terms of the applied field: a) the low field region where the linear response theory approximation, developed in previous studies, can be used, b) the large field region where full hysteresis models are applicable and c) an intermediate region where the transition between the two behaviour occurs and the conventional approaches no longer apply. In this way, our work leads to a discovery of importance of the transition region between the superparamagnetic and the fully hysteretic behaviour for maximizing the heating power in applications.

The investigation reveals some 'simplicity within the overall complexity", in particular the importance of two homogeneous scaling parameters between the interaction energy, anisotropy energy and thermal energy, which gives rise to different effects of interactions in the 'superparamagnetic' and fully hysteretic regimes.

***References***

*[1] R. Chantrell, N. Walmsley, J. Gore, and M. Maylin, "Calculations of the susceptibility of interacting superparamagnetic particles," Physical Review B, vol. 63, p. 024410, Dec. 2000.*
*[2] R. Rosensweig, "Heating magnetic fluid with alternating magnetic field," Journal of Magnetism and Magnetic Materials, vol. 252, pp. 370–374, Nov. 2002.*

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# Stiff Modes In Spinvalve Simulations With OOMMF

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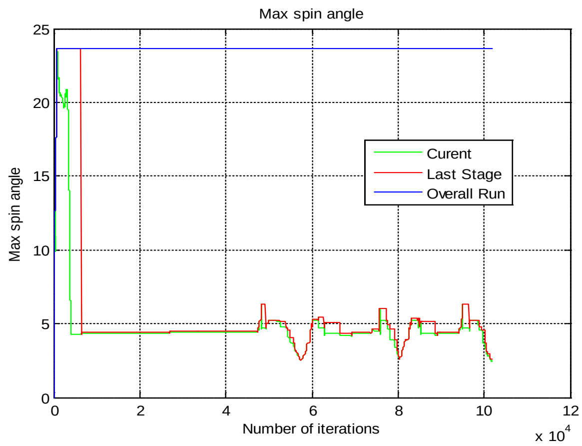
Micromagnetic software uses various techniques to solve differential equations, partial or ordinary, involved in the dynamic simulations. Euler, Runge-Kutta, Adams, BDF methods are some of the methods used for the above mentioned purpose. Some of them are suitable for non stiff problems, whereas some others are appropriate for stiff problems. Stiff modes where investigated first in micromagnetics by Della Torre and co-workers [1,2]. Della Torre [2] mentions that stiff modes in micromagnetics are involved when cooperative rotation of the magnetization of many cells appears. On the other hand, numerical analysts mention that stiffness appears when there are two different time scales in the problem, which is translated to large number of time steps taken to solve the problem. In this work it has been investigated the existence of stiffness in spinvalve simulations. Initial calculations show that there exist stiff modes in such simulations. A number of simulations were run with OOMMF [3] and are presented in the paper. For example, it is found that in the case of antiferromagnetic exchange coupling between the lower surface of the “top” layer and the upper surface of the “bottom” layer, across a middle “spacer”' layer the iterations needed for the convergence with a nonstiff method were 37629, whereas with a stiff method were 26466. The max spin angle for this case is given below in the Figure. More results will be presented in the paper.

**Acknowledgment:** one of us (VT) acknowledges financial support by the European Social Fund and Greek national funds through the Research Funding Program ARCHIMEDES-III.




***References***

*[1] D. Lewis and E. Della Torre, “Identification of Stiff Modes in Micromagnetic Problems,” CEFC, Okayama, Japan, March 19, 1996.*
*[2] E. Della Torre, "Stiff modes in numerical micromagnetic problems," IEEE Trans on Magn. Vol. 29, No. 6 1993, pp. 2371.*
*[3] M.J. Donahue and D.G. Porter, “OOMMF User's Guide”, Version 1.0, Interagency Report NISTIR 6376, National Institute of Standards and Technology, Gaithersburg, MD (Sept 1999).*

# Travelling Spin Wave Mode During Vortex Core Gyration Under Alternating-Current Magnetic Fields

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Recently, much attention has been drawn to the excited vortex core motion under profiled magnetic fields in various ferromagnetic nanopatterns. We have carried out micromagnetic simulations based on the Landau-Lifshitz-Gilbert equation [1,2] to explore the magnetic vortex dynamics on the ferromagnetic nanodisk under alternating current (AC) magnetic fields. Interestingly, we have observed that there exists a persistent spin wave excitation around the gyrating core, travelling along the opposite way compared to the core gyration. The spin wave mode travelling oppositely to the core can be clearly observed under AC field excitation, whereas the spin wave emitted from the excited core dissipates rapidly due to destructive interferenceces from a disk boundary in case of conventional pulsed field excitations. The oppositely travelling spin wave mode is explained based on the angular momentum conservation of the whole disk, which could be utilized in understanding and designing AC-operating magnetic devices based on vortex core motion.

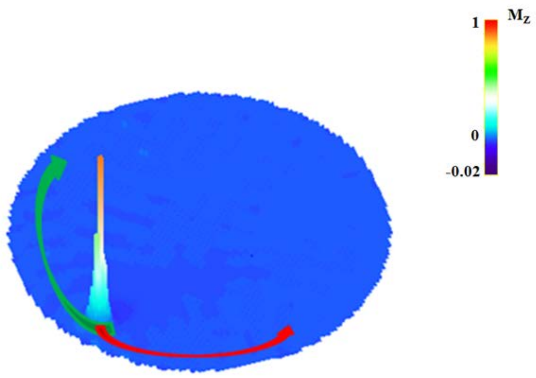


*Fig. 1. Snapshot of magnetic vortex core dynamics with core gyration.*

***References***

[1] M. J. Donahue and D. G. Porter, OOMMF User's Guide, http://math.nist.gov/oommf (2002).
[2] J.-H. Shim, et al Appl. Phys. Lett. 99, 142505 (2011).

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# Single Bubble Formation In Patterned Dot Array Under In-Plane Magnetic Field

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Several numerical analyses and theoretical studies have recently predicted that magnetic soliton states observed in systems with perpendicularly anisotropy (PMA), i.e. bubbles and droplets, would have the potential to significantly widen the scope for recording and dynamics of existing spintronic devices [1-3]. In our presentation, we will discuss the formation conditions of magnetic bubble through in-plane field demagnetization in array of Co/Ni circular dots. Based on magnetic force microscopy, we will demonstrate high success rate in nucleating stable bubble (up to 90%). An example is given in Fig. 1 for 1.25 μm dots etched from Ta(5nm)/Pt(10nm)/[Co(0.2nm)/Ni(0.6nm)]10/Pt(5nm) deposited on thermally oxidized Si wafers by magnetron sputtering. After in-plane AC-demagnetization, MFM image shows that about 80% of bubbles coexist with 5% single domain state and 15% multiple domains state. The efficiency of single bubble formation depends not only on the static energy of the bubble, which is a function of dot size, material thickness and intrinsic material parameters (e.g. anisotropy), but also on the bubble nucleation mechanism. Experimental Phase diagrams consisting in region with single domain state, single bubble and multi-domain state will be presented, and compared with micromagnetic simulations, to highlight the influence of starting in-plane field amplitude and dipolar interactions during the demagnetization process.

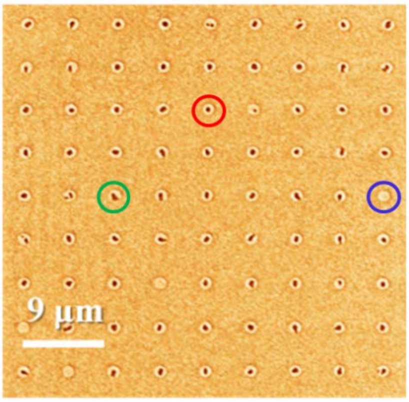


*Fig. 1: 45×45 µm2 MFM images of the [Co/Ni]10 of 1.25 µm dots arrays after demagnetization under AC in-plane field. The red, blue and green circles show single bubble state, single domain state, and multi-domain state, respectively.*

***References***

*[1] J.-V. Kim et al., Phys. Rev. B 90, 064410 (2014).*
*[2] G. Finocchio et al., J. Appl. Phys. 114, 163908 (2013).*
*[3] J. Sampaio et al., Nature Nano 8, 839 (2013).*

# Recovering Ancient Magnetic Field Intensities From Rocks Using FORC Measurements

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Igneous rocks record a thermoremanent magnetization (TRM) on formation. This remanent magnetisation is often magnetically and chemically stable on geological timescales up to the age of the Earth or longer. Recovering the direction of the ancient magnetisation is relatively straightforward; however, determining the ancient magnetic field intensity (palaeointensity) is much more problematic. The standard methods of determining the palaeointensity rely on replicating TRM acquisition in a known field in the laboratory. There are two main problems: 1) many rocks are dominated by multidomain grains (mostly small vortex structures) and are imperfect recorders, and 2) the magnetic minerals under investigation often chemically alter during the palaeointensity experiment, that lead to low success rates (between 10 and 80%). This is particularly troublesome, as palaeointensity experiments are very time consuming, e.g., two weeks intensive laboratory work to process 40 samples.

We have developed a non-heating palaeointensity protocol. This involves measuring the original natural remanent magnetisation of a sample, then using first-order reversal curve (FORC) measurements to generate a Preisach distribution. We then use a thermally activated Preisach model to estimate the TRM intensity required to produce the measured natural remanent magnetisation. We have tested this on over 300 historical lavas, where the actual field intensity is known. And applied the method to real geological and meteoritic problems; meteoritic samples are particularly suited to this method, as the samples are very chemically unstable to heating, and standard loan agreements from museums do not allow heating. Here we report new revisions to this method.

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# Thermal Hysteresis Kinetic Effects Of Spin Crossover Nanoparticulated Systems Studied By FORC Diagram Method On An Ising-Like Model

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The scientific community is manifesting a higher research interest on spin crossover compounds (SCO) and recently synthesized nanoparticles, for their bistability and for displaying two states in thermodynamic competition: a diamagnetic low spin state (LS) and a paramagnetic high spin state (HS), interswitchable by temperature or pressure changes, light irradiation or magnetic field. The utility of SCO compounds covers a broad area of applications, from the development of more efficient designs of temperature and pressure sensors to automotive and aeronautic industries and even a new type of molecular actuators [1]. We are proposing in this work a study regarding the kinetic effects and the distribution of reversible and irreversible components [2] on the thermal hysteresis of spin crossover nanoparticulated systems. For that, we are considering tridimensional systems with different sizes and also systems of nanoparticles with various Gaussian size distributions, simulated with both open boundary conditions or using an additional interaction between the molecules from the margins with the ones of the embedding surfactant [3]. The correlations between the kinetics of the thermal hysteresis, the distributions of sizes and intermolecular interactions and the transition temperature distributions were established by using the FORC (First Order Reversal Curves) method using a Monte Carlo technique within an Ising-like system.

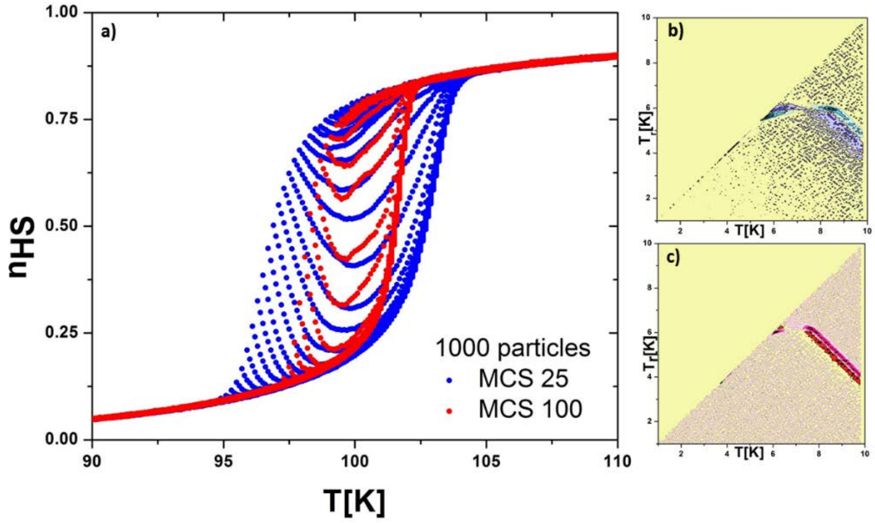


*Fig.1: FORC curves simulated for a system with 1000 particles and their specific FORC diagrams for both 25 MCS (b) and 100 MCS (c).*

***References:***

[1] H.J. Shepherd, I. A. Gural'skiy et al., Nature Communications 4, 2607, 2013.

[2] R. Tanasa, J. Laisney, A. Stancu, ML. Boillot, C. Enachescu, Appl. Phys. Lett. , 104 (3), 2014.

[3] A. Atitoaie, R. Tanasa, A. Stancu, C. Enachescu, J. Magn. Magn. Mater. 368, 12-18, 2014.

# Size Effect In Spin Crossover Compound Investigated By FORC Diagram Method

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The miniaturization of the "new generation" of multifunctional materials towards the nanometric scale, in order to insert them into electronic devices, such as thin films and nanoparticles, opens new research subjects in the spin crossover (SCO) field. One of the most interesting issues is the effect of the system size reduction on the cooperative effect. Indeed, following a simple analogy to the super-paramagnetic behaviour, the first theoretical [1-2] or experimental [3-6] investigations of spin crossover nanoparticles have shown that the thermal hysteresis loop width is strongly affected by size reduction. Thus, the loop vanishes below a critical value of the particle size, which in principle should depend on the time scale of the experiment (or simulation).

In this work we report on a further application of the FORC (First-order Reversal Curves) technique to spin crossover hysteresis, suitable to the case of broad distributions of size in nanoparticle systems. We have recorded, by magnetic measurements, a family of FORCs at the thermal transition of the [Fe(NH2-trz)3](Br)2.3H2O.0.03(surfactant) (NH2-trz)=4-amino-1,2,4-triazole Surfactant = Lauropal) spin crossover compound using samples with various particle sizes (70, 90 nm in average) and bulk for comparison. The widening of the FORC diagram with the particle size decrease has been explained by taken into account the surface energy of the SCO particles.

**Acknowledgements:** The work at Suceava was supported by a grant of the Romanian National Authority for Scientific Research, CNCS–UEFISCDI, project number PN-II-RU-TE-2011-3-0307.

***References***

*[1] T. Kawamoto, S. Abe, Chem. Commun. 31, 3933 (2005)*
*[2] C. Enachescu, L. Stoleriu, A. Stancu, A. Hauser, Phys. Rev. Lett. 102, 257204 (2009)*
*[3] T. Forestier, et al., Chem. Commun. 36, 4327 (2008)*
*[4] I. Boldog, et al., Angew. Chem. Int. Ed., 47, 6433 (2008)*
*[5] F. Volatron, et al., Inorg. Chem., 47, 6584 (2008)*
*[6] A. Rotaru et al., Eur. Phys. J. B, 84, 439-449 (2011)*

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# FORC Diagram: Coercivity, Interactions And Switchings' Multiplicity

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In the last fifteen years the first-order reversal curves (FORC) diagram technique has been and continues to be an important method of study for a wide class of hysteretic physical processes. Based on the Preisach model (1935) and on the identification procedure proposed by Mayergoyz (1985) for the classical Preisach model [1], the FORC method became extensively used after 1999 when Pike and collaborators disconnected the method from the aforementioned model [2]. FORC diagram method was seen as an experimental tool providing a fingerprint of the hysteretic processes in different types of samples and has been used as such, without a rigorous quantitative interpretation based on switching events. In order to provide quantitative analyses of the FORC diagram, we have used a perfect 2D network of magnetic wires with diameter in the range of tens of nanometers and lengths in the micrometer range. The advantage of these magnetic systems lies in the fact that each isolated wire has a rather well established simple hysteretic behaviour described by a rectangular symmetrical loop. The inter-wire interactions are changing the loop symmetry and the loops are like in the fundamental image described by the Preisach model in its simplest form. We have observed in our study that even if these systems are so similar to a Preisach one, the hysteretic behaviour of individual loops of the interacting wires is sometimes far from the Preisach hypothesis. We observe essentially two categories of effects of the interactions: wires with the loop shifted along the interaction axis without a significant change in the coercivity and wires with the increased coercivity without a significant change in the loop symmetry [3]. To make the analysis quantitative, instead of the smoothing techniques in the FORC diagram analysis we obtain information directly from the FORC histogram represented in the coercivity/interactions Preisach plane [4]. Due to the interactions the hysteresis loop is changing and we have shown that both the symmetry and the coercivity can be affected in magnetization processes [4]. We also have shown that most of the physical hysterons are producing multiple "images" within the FORC diagram. In this study we present a systematic analysis of the multiplicity parameter as a function of particles intrinsic coercivity, wires' length and position in the sample. Each type of wire contribution was accounted on each region in the histogram and the correspondence between the physical wires switchings and the FORC distribution is discussed. We assess in this case the limits of the usual interpretation of the experimental FORC distribution directly in terms of Preisach distribution.

**Acknowledgment:** This work was financially supported by the grants of the Romanian National Authority for Scientific Research, CNCS-UEFISCDI Projects PN-II-RU-TE-2012-3-0439 [DYNAMIC] and PN-II-ID-PCE-2011-3-0794 [IDEI-EXOTIC No. 185/25.10.2011].

***References***

*[1] I. D. Mayergoyz, J. Appl. Phys. 57, 3803 (1985).*
*[2] C. R. Pike, A. P. Roberts, K. L. Verosub, J. Appl. Phys. 85, 6660 (1999).*
*[3] C. I. Dobrotă, A. Stancu, J. Appl. Phys 113, 043928 (2013).*
*[4] C. I. Dobrotă, A. Stancu, Physica B 457, 280 (2015).*

# Disentangling Between Static And Kinetic Effects On Mirroring Hystereses In Spin Crossover Compounds Using Forc Method

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Spin transition molecular magnets are inorganic compounds, commutable between two states in thermodynamic competition: the low spin state (LS) and the high spin state (HS). The commutation is accompanied by various hysterees, such as thermal, light induced or pressure hysteresis. The thermal hysteresis (TH) accompanies the variation of temperature for interactions higher than a threshold and it is independent on the temperature sweeping rate. The commutation between LS and HS states can be equally realized by a light irradiation. The competition between the irradiation and the temperature dependent HS-LS nonradiative relaxation results in the Light Induced Thermal Hysteresis (LITH), which is highly affected by kinetics. FORC (First Order Reversal Curve) method [1, 2] is well known for its capacity to provide information about the intrinsic properties of these molecular compounds. Here, we use this method not only to infer the domains distribution, but also to disentangle between kinetic and static components of the LITH. Understanding kinetic aspects of the hysteresis reflected in FORC diagrams is important for a larger class of magnetic materials exhibiting kinetic effects. We have measured TH and LITH major loops and FORCs for the pollycristalline Fe(II) spin crossover compound Fe Zn (bbtr) (ClO) [3], either in a pure state (x=0) or doped with Zn impurities (x=0.33) for LITH we have considered different sweeping rates. From the FORC distributions we estimated the changes in the intermolecular interactions introduced by dopants. We also determined the relationship between FORC distributions in the case of TH (fig. 1c) and LITH (fig. 1a). Using a multi variance mean field model we propose an algorithm to disentangle between static and kinetic effects on LITH.

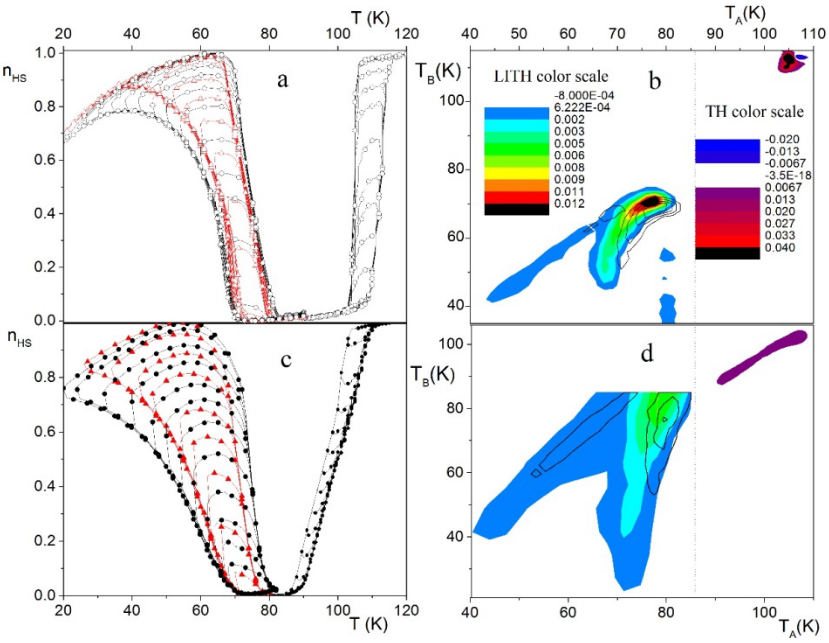


*Fig.1 TH and LITH FORCs for pure (a) and diluted (c) compound (left); Corresponding FORC distributions (b, d)*

***References***

*[1] C. Enachescu, R. Tanasa, A. Stancu, F. Varret, J. Linares, E. Codjovi, Phys. Rev. B **72**, 054413 (2005).*
*[2] R. Tanasa, J. Laisney, A. Stancu, M. L. Boillot, C. Enachescu, Appl. Phys. Lett. **104** (2014).*
*[3] R. M. Stan, R. Gaina, C. Enachescu, R. Tanasa, A.Stancu, R.Bronisz , J. Appl. Phys, in press*

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# Experimental Frequency Dependent Dynamic FORC In Ferromagnetic Wires

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Ferromagnetic wires are interesting systems both from theoretical point of view and for their potential technological applications (miniaturized sensors, filters, or in modern spintronic devices to store, transfer and manipulate information). Their magnetic domain structure mainly consist of axially magnetized domains and magnetization process takes place through domains wall propagation on large scales (few centimeters) along the entire wire. The switching field at which the domain wall starts to propagate as well as the domain wall dynamics is dependent on the external parameters like frequency of the applied magnetic field (i.e. field sweep rate), temperature, or mechanical stress. The performance of the devices using magnetic wires relies on their switching characteristics. The magnetization switching is experimentally studied in this paper using the first-order reversal curve (FORC) method [1]. The FORC technique is typically used to evidence the intensity of interactions between the switching physical entities in ferromagnetic samples, and also the distribution of coercivity.

In order to acquire the dynamic FORC, an ac magnetometer based on the induction coil principle [2] was constructed, in which two identical detection coils differentially connected measure the sample's magnetic response by detecting the induced voltage across the detection coils due to the changing magnetic moment of the sample which is placed within one of the coils. The coils geometry can be optimized for various conformations of the sample. Detection coils assembly is centered in a solenoid which provides the nearly uniform external excitation field through a function/arbitrary waveform generator and a high speed, broad band and high slew rate bipolar amplifier. A high power and low inductance (over a wide frequency range) resistor connected in series with the solenoid allows to measure the electric current that flows through the solenoid and generates the external magnetic field. The capability of supplying high output voltage and high power of the amplifier allow us to obtain up to 200 Oe. Time variation of the applied field (which is proportional with the voltage/potential difference across the low inductance resistor) and of the induced signal were digitized and acquired through a high resolution digital oscilloscope synchronized with the waveform generator, and then sent to a computer for software signal processing. Average acquisition mode was used to obtain the average value for each record point over many acquisitions in order to reduce random noise. To further reduce the noise we have used the advantage of digital/numerical filtering which improves signal-to-noise performance over analog filters, which have to sacrifice accuracy in order to perform over a wide frequency band. No external amplifier was used for the induced voltage, only the internal amplifier of the oscilloscope. All the instrumentation are interconnected with a computer. The high speed acquisition allows fast and detailed dynamic FORC diagrams measurement in a wide range of the applied field sweep rate values. With this setup we measured FORC diagrams for different field rates and we were able to evidence significant changes in both coercivities and interactions. This complex experimental tool opens the possibility to evidence in details how the switchings of domains and grains in soft magnetic materials are influenced by the field rate. A detailed analysis of the FORC diagrams together with a description of the methods used in numerical analysis will be presented in the full paper.

**Acknowledgment:** This work was financially supported by the grants of the Romanian National Authority for Scientific Research Parteneriate - HYPERTHERMIA Project No. 148/2012 and CNCS-UEFISCDI Projects PN-II-RU-TE-2012-3-0439 [DYNAMIC], PN-II-ID-PCE-2011-3-0794 [IDEI-EXOTIC No. 185/25.10.2011] and PN-II-RU-TE-2012-3-0449.

***References***

*[1] I. D. Mayergoyz, J. Appl. Phys. 57, 3803 (1985); C. R. Pike, A. P. Roberts, and K. L. Verosub, J. Appl. Phys. 85, 6660 (1999).*

*[2] F. Beron, G. Soares, and K. R. Pirota, Rev. Sci. Instrum. 82, 063904 (2011).*

# Combined FORC And X-Ray Microscopy Study Of Magnetisation Reversal In Antidot Lattices

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First-order reversal curves (FORC) are increasingly utilised in laboratories to investigate complex magnetisation reversal processes. Especially in the field of nano- or microstructured magnetic materials the interest has surged as FORC promises distinction of individual microscopic magnetisation states without the need to laterally resolve the individual nano- or micromagnets [1]. However, it has recently been discussed that the interpretation of the physical meaning of the peaks appearing in FORC diagrams is not straight forward [2,3].

Here, we present an approach combining FORC measurements with X-ray microscopy with magnetic contrast to investigate a nanostructured magnetic system. Our magneto-optical Kerr effect based FORC measurement scheme allows fast acquisition and a lateral constraint of the sample area contributing to the FORC diagram from 1 $\mu m^2$ to 25 $mm^2$ [4]. X-ray microscopy, on the other hand, allows for direct visualisation of the microscopic magnetic processes involved into the magnetisation reversal.

As a model system we used nanoscaled hexagonal antidot lattices. These antidot lattices were prepared both in in-plane (Fe) and out-of-plane (GdFe) magnetised host materials. The magnetic properties of antidot lattices and thus the microscopic magnetic interactions can easily be tuned by variation of hole size and spacing, and the orientation of the applied magnetic field [5]. Their very complex magnetisation reversal strongly depends on these parameters and features up to six individual microscopic processes. Accordingly, the FORC diagrams strongly differ, showing both FORC peaks with and without interaction field. Furthermore, the FORC diagrams exhibit features with narrow and broad distributions both in interaction field and coercivity.

Using detailed X-ray microscopy analysis we deduce a physical interpretation and show the microscopic origin of all features in these FORC diagrams. In this context we also discuss the influence of magnetisation rotation and reversible/irreversible domain wall movements on FORC peak height; the influence of domain size and the surrounding stray field landscape on the interaction fields; and microscopic features leading to narrow and broad distributions in FORC diagrams.

***References***

*[1] Béron, F., K. R. Pirota, et al. (2011). New Journal of Physics 13(1): 013035.*
*[2] Dobrotă, C.-I. and A. Stancu (2013). Journal of Applied Physics 113(4): 043928*
*[3] Dobrotă, C.-I. and A. Stancu (2015). Physica B: Condensed Matter 457(0): 280-286.*
*[4] Gräfe, J., M. Schmidt, et al. (2014). Review of Scientific Instruments 85(2): 023901.*
*[5] Wang, C. C., A. O. Adeyeye, et al. (2006). Nanotechnology 17(6): 1629-1636.*

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# FORC Analysis Of Ferro-Ferro Exchange Bias In Nanocrystalline Ribbons

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Horizontal shift and distortion of the hysteresis loops can be induced in some Co-based nanocrystalline systems in which soft and hard ferromagnetic phases coexist. As all the aspects of the phenomenon can be well explained in terms of the exchange interaction between the two phases, it has been identified as an induced ferro-ferromagnetic exchange bias [1]. In this work we use the differential analysis based on first-order reversal curves (FORC) to analyze this particular kind of exchange bias.

The study has been carried out on several samples obtained by isothermal annealing of amorphous ribbons of $Co_{70}Fe_5Si_{15}B_{10}$. The annealing temperature was kept in all cases below the first crystallization point, leading to a series of samples with different crystallization degrees. The annealed samples consist of ferromagnetic hard crystallites embedded in the soft residual amorphous matrix. Although the hard phase is ferromagnetic, it can only be observed as a spot in the FORC diagram when the amount of crystallites is significant. As can be viewed in Fig.1, in such case a couple of blue/red linear spots appear in the FORC diagram ($0 \lesssim H \lesssim 10$ kA/m), corresponding to the soft phase, while the magnetically hard phase shows up as a red spot ($10 \lesssim H \lesssim 25$ kA/m). The mutual exchange interaction between both phases is revealed by the spreading of the corresponding spots in the intermediate region.

Contrarily, for a low concentration of crystallites, the spot of the harder phase cannot be observed. Despite this, its interaction with the soft matrix is visible in the FORC diagram as a yellow spreading of the positive soft spot towards the position where the hard spot would appear if its concentration were greater (see Fig. 2). In this case, tracing the hysteresis loop with a field amplitude of $H \sim 10$ kA/m (see superimposed squares in Fig. 1 and 2) gives rise to a remarkable horizontal exchange bias.

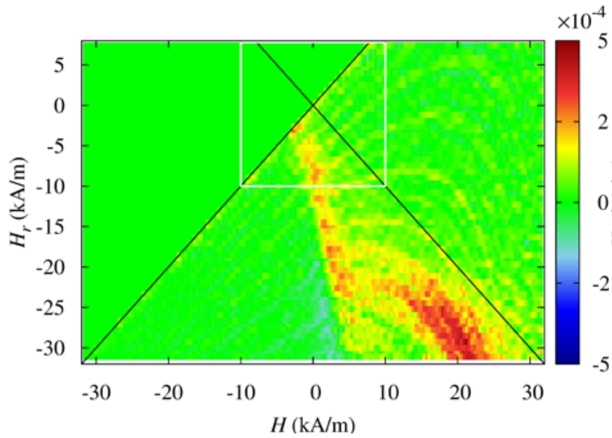


*Fig.1: FORC diagram of a sample with a significant concentration of crystallites.*

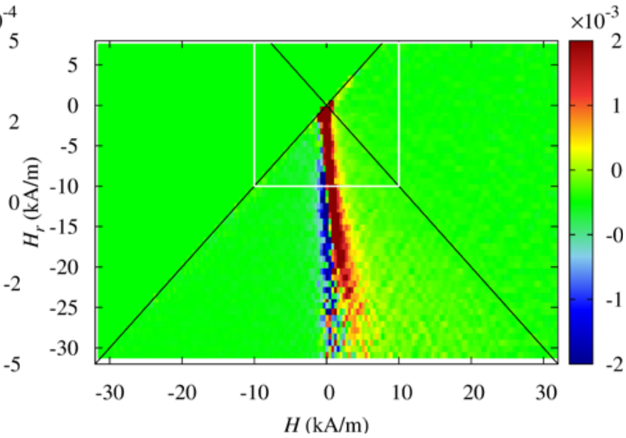


*Fig. 2: FORC diagram of a sample with an amount of crystallites enough to interact with the soft matrix.*

***References***

*[1] J.C. Martínez-García, M. Rivas, J.A. García. Induced ferro-ferromagnetic exchange bias in nanocrystalline systems, J. Magn. Magn. Mat. 377 (2015) 424–429*

# Investigation Of Magnetic Frustrated Networks Using FORC Analysis

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First-order reversal curves (FORC) method [1-3] gained a strong visibility in the last decade as a technique to get insight information on switching processes taking place in many kind of systems with hysteretic behaviour – from a wide range of magnetic materials to temperature or pressure hysteresis in spin transition materials.

Recent contributions [4] clearly demonstrated that classical interpretation of the FORC diagram in terms of interaction and coercive field distribution is not always valid – especially for samples with high degrees of order. Nevertheless, even in this case, after a correct understanding of the intimate processes taking place in the sample, the FORC diagrams can give interesting information on magnetic interactions or switching behaviour.

In this paper we propose a study of magnetically frustrated networks of spins (Fig. 1) using FORC diagrams. Starting from FORC diagrams computed on networks of interacting macrospins, described by Landau Lifshitz Gilbert equation, we discuss how spatial arrangement, interactions and external field direction influences different features of the FORC diagrams.

**Acknowledgment:** This work was financially supported by the grant of the Romanian National Authority for Scientific Research, CNCS-UEFISCDI Project PN-II-ID-PCE-2011-3-0794 [IDEI-EXOTIC No. 185/25.10.2011]

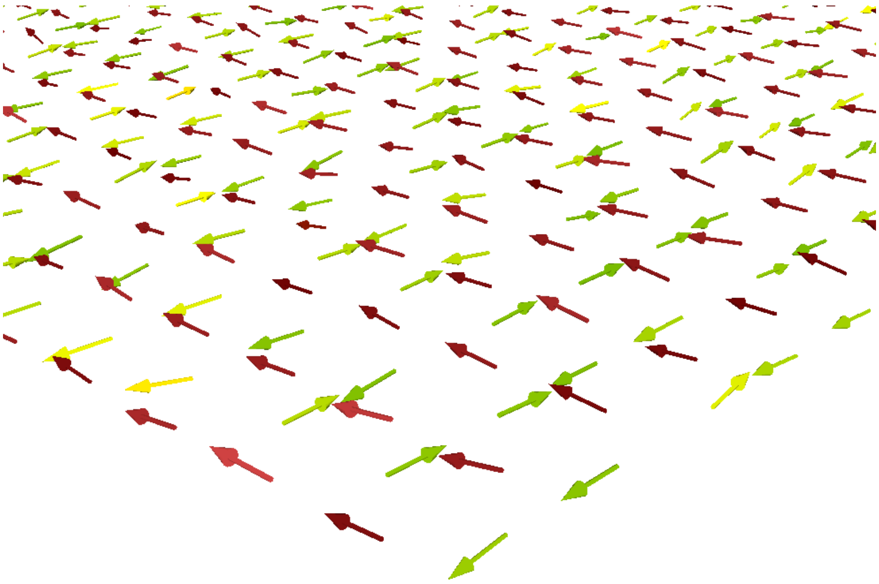

*Fig.1: Snapshot of a magnetic state during switching in a rectangular frustrated network of macrospins*

### *References*

*[1] I.D. Mayergoyz, Mathematical Models of Hysteresis and Their Applications, Elsevier, Amsterdam, 2003.*
*[2] C.R. Pike, A.P. Roberts, K.L. Verosub, Characterizing Interactions in Fine Magnetic Particle Systems Using First Order Reversal Curves, Journal of Applied Physics, 85(9), 6660-6667 (1999)*
*[3] A. Stancu, C. Pike, L. Stoleriu, P. Postolache, D. Cimpoesu, Micromagnetic and Preisach analysis of the First Order Reversal Curves (FORC) diagram. Journal of Applied Physics 93(10), 6620-6622 (2003)*
*[4] C.I. Dobrota, A. Stancu, What does a first-order reversal curve diagram really mean? A study case: Array of ferromagnetic nanowires, Journal of Applied Physics 113(4), 043928 (2013)*

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# Angular Dependent FORC Studies On FeMn/Co Exchange Bias Systems Utilizing The Magneto-Optical Kerr Effect

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First order reversal curves (FORC) are a powerful method for magnetic sample characterization, separating all magnetic states of an investigated system according to their coercivity and internal magnetic interactions. Nowadays, FORC finds multiple applications on the fields of geomagnetism, physics of thin films and also in material sciences[1,2]. A major drawback of using measurement techniques like VSM or SQUID, typically applied for FORC acquisition, is the long measurement time, limiting the resolution and the number of measurements due to time constraints. Faster techniques like MOKE result in problems regarding measurement stability over the curse of the acquisition of many minor loops, due to drift and non-absolute magnetization values. In our contribution, we will at first describe our approach using a specialized field shape providing two anchor points for applying the MOKE technique to FORC measurements[3].

The main characteristics of an exchange bias (EB) system are the horizontal shift of the magnetic hysteresis loop as well as an increase of coercivity ($H_C$), both induced by the coupling of the ferromagnetic (FM) layer to an antiferromagnetic layer (AFM). To explain the azimuthal dependence of EB and $H_C$, multiple studies based on the well-known Stoner-Wohlfarth model have been performed and can be found in literature. In these studies, different energy terms accounting for crystalline anisotropies or spin-glass like behavior at the interface were utilized to model and explain the curves resulting from the experiments. Additionally, studies investigating the magnetic reversal path via multiple anisotropy axes in EB systems have been performed, resulting in varying shapes of magnetic hysteresis loop dependent on the sample orientation towards the magnetic field as well as on the layer thickness.

As an example of the application of MOKE-FORC instead of conventional major hysteresis loops, we will present here angular dependent studies of a typical FeMn/Co exchange bias (EB) system, which was epitaxially grown on an MgO substrate. With the help of different Pt buffer layers, we managed to grow the EB system in two crystalline orientations [(100) and (111)], resulting in strong influences on the magnetic reversal behavior.

Our angular dependent FORC diagrams clearly resolve the transition towards different reversal paths in our samples and prove at the same time the feasibility of combining the powerful FORC method with the quick and precise data acquisition process available in MOKE instruments.

***References***

*[1] Pike, C. R., Roberts, A. P. & Verosub, K. L., J Appl Phys **85**, (1999).*
*[2] Dobrota, C.-I. & Stancu, A., J Appl Phys **113**, (2013).*
*[3] Graefe, J., Schmidt, M.et al., Rev Sci Instrum **85**, (2014)*

# FORC Diagram Study Of Magnetostatic Interactions In 2D Longitudinal Arrays Of Magnetic Wires

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In perpendicular nanowires arrays the essential observation regarding magnetic interactions is related to the dominance of the demagnetizing field, as revealed from FORCs (first order reversal curves). If one considers the longitudinal distribution of magnetic wires, the magnetostatic interactions between wires can have either a magnetizing but also a demagnetizing effect depending upon the values of the distances between the wires along the wire's length and on the perpendicular direction. By controlling these distances one can dramatically change the structure of interactions. To evaluate the global interaction distribution we have used the well-known technique based on the measurement/simulation of a set of first-order reversal magnetization curves (FORC). In this study we show how the FORC diagram is transforming its shape when the system is gradually changed from a 1D case towards a 2D system. The typical features observed on the FORC diagrams are correlated with the type and intensity of interactions in the nanostructured sample.

The challenge was to find for a given 2D distribution, the distances for which the two competing interactions (parallel and longitudinal) are comparable. FORC is in this case a symmetrical representation similar to the one given by Classical Preisach Model, when there are no interactions. Considering the recent investigations implying FORC histograms [1] and different types of switching, we have conducted an analysis in which we have compared the trajectories of switchings.

In this study we have simulated the switching of each wire with an Ising-Preisach model [2] (the isolated wires have an intrinsic anisotropy and a symmetrical rectangular hysteresis loop). The switching between the two states is controlled by a classical Monte-Carlo-Metropolis technique. The energy barrier between the two states is dependent on the field along the wire and on the component perpendicular to the wire.

**Acknowledgment:** This work was financially supported by the grant of the Romanian National Authority for Scientific Research, CNCS-UEFISCDI Project PN-II-ID-PCE-2011-3-0794 [IDEI-EXOTIC No. 185/25.10.2011]

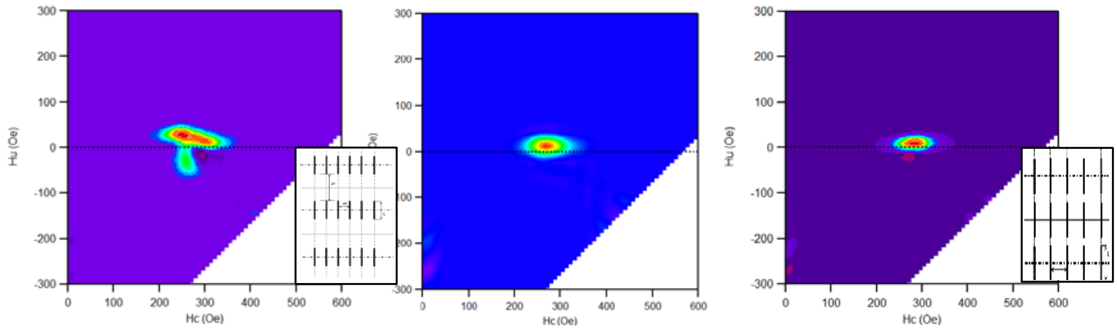


*Fig. Schematic representation of the changes in FORC diagram*

***References:***

*[1] C. I. Dobrotă, A. Stancu, Physica B, 457(2015)*
*[2] C. I. Dobrotă, A. Stancu, J. Appl. Phys. 113, 043928 (2013)*

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# FORC Diagrams: A Complementary Method For Ferroelectric Materials Characterization

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First Order Reversal Curves (FORC) formalism and the Preisach model were used for describing the switching properties of ferroics, particularly ferromagnetics, superconductors, spin glasses and recently, polarization and piezoelectric responses in ferroelectrics [1]. In addition to classical high field characterization under various types of fields (hysteresis loops and tunability), the experimental-modeling approach of the FORC diagrams is a useful tool in ferroelectric materials characterization. The FORC diagrams give additional information on the reversible/irreversible (i.e., non-switching/switching) contributions to the polarization and on the field dependence of the differential susceptibilities by using the same set of experimental data [1-3]. Furthermore, FORC diagrams are sensitive to parameters such as the crystalline orientation, defects and fatigue phenomena and to the frequency of the applied field [1,2]. Ferroelectrics materials with homogeneous composition and well-defined rectangular hysteresis loops are characterized by FORC distributions with a sharp maximum located at well-defined fields (Ec,M, Ebias,M) and with almost zero reversible (non-switching) component, while broader distributions with an important reversible component are characteristic of materials that are non-oriented, non-homogeneous, porous, with structural or charge defects. Very broad and dispersed FORC distributions were found in ferroelectrics in their fatigued state, due to the local imprint effects [1,3]. Distributions with multiple maxima were also proposed to describe ferroelectric samples with a certain degree of inhomogeneity, like unpoled solid solution ceramics [4]. Therefore, the FORC distributions can give fingerprints of the ferroelectric systems from the point of view of their local switching properties. In present work, the FORC analysis is used in order to describe the switching evolution with increasing Sn content in $BaSn_xTi_{1-x}O_3$ (BTS) solid solutions, and the influence of length scale mixing degree of soft and hard materials in PZT-based ceramic composites. For BTS ceramics a clear trend of reducing switchable (irreversible, non-zero coercivity) contribution with respect to the non-switchable (reversible) contribution to the ferroelectric polarization for increasing Sn content was observed [5]. In case of PZT-based composite ceramics, the FORC diagrams have offer valuable information about the influence of powders mixing (micro/macro mixing) and sintering methods used for samples preparation.

**Acknowledgements:** This work was supported by the Romanian UEFISCDI grant PN-II-PT-PCCA-2013-4-1119.

***References***

*[1] A. Stancu, D. Ricinschi, L. Mitoseriu, P. Postolache, M. Okuyama, Appl. Phys. Lett. 83, 3767 (2003)*
*[2] L. Stoleriu, A. Stancu, L. Mitoseriu, D. Piazza, C. Galassi, Phys. Rev. B 74, 174107 (2006)*
*[3] D. Ricinschi, L. Mitoseriu, A. Stancu, P. Postolache, M. Okuyama, Integr. Ferroelectr. 67, 103 (2004)*
*[4] C. H. Tsang and F. G. Shin, J. Appl. Phys. 93, 2861 (2003)*
*[5] M. Deluca, L. Stoleriu, L.P. Curecheriu, N. Horchidan, A.C. Ianculescu, C. Galassi, L. Mitoseriu, J.Appl.Phys. 111, 084102 (2012).*

# Magnetic Relaxation Effects On First-Order Reversal Curves

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This work is dedicated to a systematic study of the magnetic relaxation starting on magnetic states in a typical measurement of first-order reversal curves (FORC). The experiments were performed on superstructures of the form $[Ni/Pt]_6/Pt(x)/[Co/Pt]_6$ in which the coupling between the $[Co/Pt]_6$ "hard layers" and the $[Ni/Pt]_6$ ("soft layers") is adjusted by the thickness x of a Pt interlayer, prepared as presented in [1]. The FORC diagram analysis has shown that in particular cases (when the average characteristic relaxation time of the magnetic entities is in the 1-100 seconds range) the hysteresis loop shape is strongly dependent on the waiting time in each point. We also observed that some features appearing on the FORC diagram produced as described in many publications (e.g. [2]) are rapidly changing shape and some are even disappearing if one waits sufficiently in the reversal points. This fact gave us the idea for this systematic study of relaxation not only in the reversal points but also within the major hysteresis loop and we have chosen as starting point for the relaxation process points from the first-order reversal curves. One goal of this analysis is to evidence how strong the dependence on the waiting time is on the FORC diagram itself. In experiments we have observed (see figure) that even when the applied field is negative the relaxation at a certain critical field reverse tendency from a clear decrease towards an increase during relaxation, essentially due to the coupling. The second aim of this study is to present a micromagnetic model able to explain the position of the critical points on the FORCs where relaxation is negligible.

**Acknowledgment:** This work was financially supported by the grant of the Romanian National Authority for Scientific Research, CNCS-UEFISCDI Project PN-II-ID-PCE-2011-3-0794 [IDEI-EXOTIC No. 185/25.10.2011]

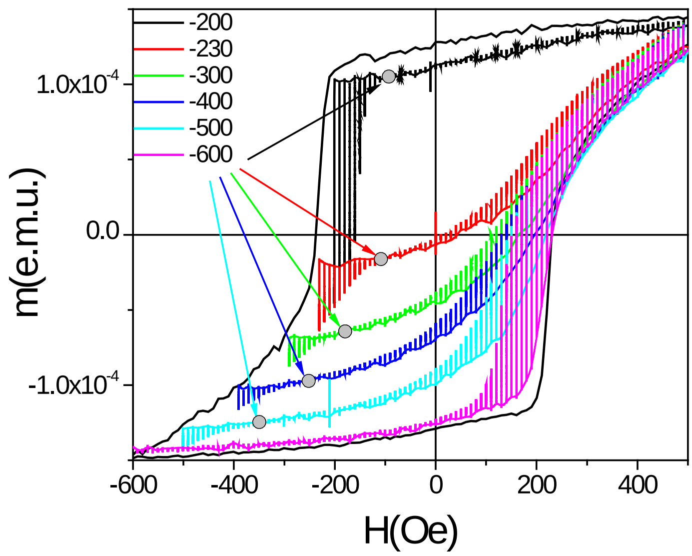


*Fig. 1: Relaxation processes measured for different FORCs*

***References***

*[1] N. Siadou et al, J. Magn. Magn. Mater., 323(12) 1671 (2011)*
*[2] A. Stancu, C. Pike, L. Stoleriu, P. Postolache, D. Cimpoesu, J. Appl. Phys. 93 6620 (2003)*

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# Magneto-Mechanical Modelling Study Of Co-Based Amorphous Micro- And Nanowires For Acoustic Sensing Medical Applications

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Throughout the last decade, hundreds of thousands of people suffering from deafness and hearing loss related diseases were benefiting from tremendous quality of life improvements provided by cochlear implantation. The working principle of a cochlear implant is based on the transduction of sound vibrations into electrical signals which are generating nerve impulses sent to the auditory system of the brain. One of the key components of the cochlear implants is represented by the acoustic sensing system. Magnetic micro- and nanowires have been presenting recently a considerable interest to the scientific community [1] for potentially being used as active elements in hairlike acoustic sensors which are mimicking the hair cells of the inner ear responsible for converting the perceived acoustic vibration into electric signals.

The effect of bending deformations and induced stresses caused by acoustic sound vibrations is leading to magnetization changes [2] and permeability variations within the wire. These induced magnetic changes could be detected by using a GMR sensor, or in the case of some special designs by a pick-up coil wrapped around the fixed-end of the wires. For a better understanding of how the microsensors act under the exposure to sound vibrations we propose a computational study, i.e. the finite element systematic study using COMSOL Multiphysics software package regarding the stress and deformation distributions during bending for different lengths and diameters of the wires. We did simulations for Co-based amorphous microwires exposed to a periodic load of 2 MPa and frequency of 10 kHz, and also constant loads of different magnitudes. Additionally, a theoretical investigation was performed in order to understand the permeability and, respectively, the magnetization changes produced by stresses within the microwires. For that, we used the model proposed by Sablik [3] for the effect of stress on magnetic hysteresis to model the first magnetization curves for the elements calculated previously. The slope at the value of the magnetic field created by excited pick-up coil is indicating the susceptibility and respectively permeability, their variation providing information about output signal changes. We are showing in this study an inverse ratio dependency between the stress distributions and the lengths of the wires and also a linear dependency law of the permeability and output signal with the bending deformations. The results are compared with Terfenol-D and Galfenol (Fe-Ga) alloys and conclusions about further improvements of Co-based microsensors are presented.

**Acknowledgement:** Financial support from the NUCLEU Programme (PN 09-43 01 01 and PN 09-43 01 02) is highly acknowledged.

***References:***

*[1] P. D. McGary, L. Tan, J. Zou, B.J. Stadler, P.R. Downey, J. Appl. Phys 99, 08B310, 2006.*
*[2] S.G.H Staples, C. Vo, D.M.J. Cowell, S. Freear, C. Ives, J. Appl. Phys. 113, 133905, 2013.*
*[3] M.J. Sablik, H. Kwun, G.L. Burkhardt, and D.C. Jiles, J. Appl. Phys. 61, 3799, 1987.*

# Hysteresis In 1D SCO Compounds Studied By Mössbauer Probes

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The design and fabrication of new spin crossover (SCO) compounds with potential applications as memories, sensors, displays, have attracted significant research interests over the last few years [1,2]. While focus was given on 1,2,4-triazole ligand molecules as suitable building blocks for crystal engineering of 1D SCO materials, study of their hysteresis behavior constitutes a challenge.

Investigation began with 4-amino-1,2,4-triazole ($NH_2$trz), that provided new 1D Fe materials that were fully characterized. We have carefully investigated the SCO behavior of a series of $Fe^{II}$ 1D $NH_2$trz coordination polymers, introducing for the first time divalent inorganic anions of different sizes to understand the variation of the transition temperature ($T_{1/2}$) vs. the volume of the inserted anion.[3] The crystal structure of the analogous $[Cu(NH_2trz)_3]^{2+}$ gave insight into the role of *supramolecular interaction* in the propagation of elastic cooperative interactions associated to SCO and *reasons for wide hysteresis loops* in these materials. Hydrostatic pressure measurements were carried out on selected 1D chain to evaluate their influence on $T_{1/2}$ and the hysteresis loop. This external pressure is different from the electrostatic pressure set up by anion-cation interactions that we have here estimated numerically, for the first time. We have also investigated First-Order Reversal Curves (FORCs), to determine the distribution of switching temperatures and interactions fields for all of the 'particles' that contribute to the hysteresis loop, an information which is not accessible in routine DC magnetic measurements.[4] A second factor studied is the role of counter anion on the SCO and hysteresis behavior. Thus, an internal anionic nuclear probe, $SnF_6^{2-}$, was successfully implanted into the crystal lattice of $[Fe(NH_2trz)_3]^{2+}$ 1D chain compound for the first time in view of sensing elastic cooperative interactions associated to their propagation in the crystal lattice.[5] We have found that the anion is able to feel the spin transition of individual chains thanks to $^{119}$Sn Mössbauer spectroscopy.

We have also investigated the influence of the nature of ligand on the SCO behavior. For the first time 1,2,4-triazole derivatives of α- and ß-aminoesters were designed and introduced to produce new SCO 1D coordination polymers.[6-9] A strong sensitivity of the SCO behavior was observed on increasing the carbon spacer to lead to ßAlatrz.[10,11] The two-step SCO configuration is observed for the first time in a 1:2 ratio of low-spin:high-spin states in the intermediate phase for a 1D chain. The origin of the stepwise transition was attributed to a distribution of chains of different lengths in $[Fe(ßAlatrz)_3](BF_4)_2{\cdot}2H_2O$ after FORC analyses.[12]

***References***

*[1] P. Gütlich, A.B. Gaspar, Y. Garcia, Beilstein J. Org. Chem. 9 (2013) 342.*
*[2] J. Linares, E. Codjovi, Y. Garcia, Sensors 12 (2012) 4479.*
*[3] M.M. Dirtu, A. Rotaru, D. Gillard, J. Linares, E. Codjovi, B. Tinant, Y. Garcia, Inorg. Chem. 48 (2009) 7838.*
*[4] M.M. Dirtu, C. Neuhausen, A.D. Naik, A. Rotaru, L. Spinu, Y. Garcia, Inorg. Chem. 49 (2010) 5723.*
*[5] Y. Garcia, V. Ksenofontov, S. Mentior, M.M. Dirtu, C. Gieck, A. Bhatthacharjee, P. Gutlich, Chem. Eur.J. 14 (2008) 3745.*
*[6] M.M. Dirtu, A.D. Naik, J. Marchand-Brynaert, Y. Garcia, Hyper. Interact. 217 (2010).*
*[7] A.D. Naik, M.M. Dîrtu, A.P. Railliet, J. Marchand-Brynaert, Y. Garcia, Polymers 3 (2011) 1750.*
*[8] A. Naik, M. Dîrtu, Y. Garcia, Hyper. Interact. 205 (2012) 57.*
*[9] M. Dîrtu, D. Gillard, A. Naik, A. Rotaru, Y. Garcia, Hyper. Interact. 205 (2012) 75.*
*[10] M.M. Dîrtu, F. Schmit, A.D. Naik, A. Rotaru, J. Marchand-Brynaert, Y. Garcia, Int. J. .Mol. Sci. 12 (2011) 5339.*
*[11] M. Dîrtu, F. Schmit, A. Naik, A. Rotaru, J. Marchand-Brynaert, Y. Garcia, Hyper. Interact. 205 (2012) 69.*
*[12] M.M. Dirtu, F. Schmit, A.D. Naik, A. Rotaru, I. Rusu, S. Rackwitz, J.A. Wolny, V. Schünemann, Y. Garcia, Chem. Eur. J. (2015, in press).*

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# Electromagnetic Characterization Of Current Transformer With Toroidal Core Under Sinusoidal Conditions

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Experimental setup for characterization of current transformer has been built and used in the analysis of toroidal core wounded from the electrical steel strip. This setup is based on a PC with LabVIEW software [1], also containing an AC current source, two shunt resistors and toroidal core with single-turn primary winding and two secondary windings (20 and 40 turns). AC current source generates a sinusoidal current amounting up to 20A (RMS value), at a frequency of 50Hz. This current has been used for magnetizing toroidal core over the single-turn primary winding. In series with the primary winding a shunt resistor has been connected and used in measurement of primary current. A secondary winding with 20 turns has been closed with another shunt resistor, used in measurement of secondary current. Consequently, a rated current ratio of the current transformer is 20A/1A. Electric circuit of another secondary winding with 40 turns has been left open and induced voltage has been used in the measurement of the magnetic induction in the core. A ratio error and a phase error [2] of this current transformer has been measured for different values of the excitation current.

Another experimental setup based on PC has been used in measurement of magnetic hysteresis in a previously described toroidal core [3]. The core has been excited over 40 turns winding while 20 turns winding has been used in the measurement of the induced voltage. A measured excitation current and induced voltage have been used in the calculation of the magnetic field and the magnetic induction in the core. Measurements have been performed at low values of the magnetic inductions, amounting from 0.05T to 0.6T, at a frequency of 50Hz. During such measurements both the magnetic inductions and the magnetic field are sinusoidal in time.A phase shift can be observed between these two waves. This phase shift has been calculated and represented as a function of the magnetic induction. A number of hysteresis loops (magnetization curve) and phase shifts have been recorded.

The results obtained from second experiment have been used in the calculation of the ratio and shift errors of the current transformer under sinusoidal conditions. For that purpose, a simple mathematical procedure has been introduced. This procedure takes into account the existing magnetic hysteresis by using the measured magnetization curve and phase shift function. Proposed analysis is simple since all electric and magnetic quantities are simple periodic in time. Solution of the ratio and phase errors can be obtained after several iterations, taking as an initial condition that the magnetic field inside the core is equal to zero.

Calculated ratio and shift errors have been compared to those obtained by measurements and a very good agreement has been obtained.

***References***

*[1] http://www.ni.com/*
*[2] C. Christopoulos, A. Wright: Electrical Power System Protection, Springer-Science and Business Media, 1999.*
*[3] B.M. Koprivica, A.M. Milovanovic, M.D. Djekic: Effects of Wound Toroidal Core Dimensional and Geometrical Parameters on Measured Magnetic Properties of Electrical Steel. Serbian Journal of Electrical Engineering, Vol. 10, No. 3, Oct. 2013, pp. 459 – 471.*

# Shape Anisotropy In Zero-Magnetostrictive Rapidly Solidified Amorphous Nanowires

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The magnetic behavior of rapidly solidified CoFeSiB nearly zero magnetostrictive amorphous nanowires has been recently investigated. Here we report on the micromagnetic simulations of their hysteresis loops performed using the Magpar package [1], with finite element discretization. For comparison, the experimental hysteresis loops of the amorphous nanowires have been measured using an inductive technique.

Experimental hysteresis loops and simulated ones have shown that the shape anisotropy and the demagnetizing field play important roles in the magnetization reversal process. We analyzed the details of the magnetization distribution and the magnetization reversal processes which are difficult to investigate experimentally.

We studied hysteresis loops simulated in two cases: (i) the diameter is constant and the sample length is variable and (ii) the diameter is variable and the nanowire length is constant. For instance, figure 1 shows the simulated hysteresis loops for nanowires with a fixed length and various diameters. Dynamic micromagnetic simulations reveal that magnetization reversal takes place by the nucleation of domains with reversed magnetization at the nanowire ends. Subsequently, the corresponding domain walls suffer de-pinning and propagate along the nanowire length [2].

The results are essential for understanding and controlling the magnetization processes in these novel nanowires, with important application possibilities in new miniaturized sensing devices.

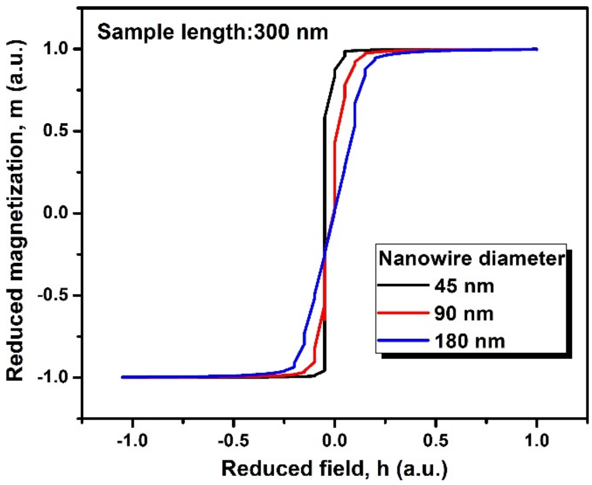


*Fig.1. Simulated hysteresis loops for $(Co_{0.94}Fe_{0.06})_{72.5}Si_{12.5}B_{15}$ amorphous nanowires with various sample diameters.*

**Acknowledgement**: Work supported by UEFISCDI through contract no. 46/2013 (project no. PN-II-ID-PCE-2012-4-0424).

***References***

*[1] W. Scholz, J. Fidler, T. Schrefl, D. Suess, R. Dittrich, H. Forster, and V. Tsiantos, Comp. Mater. Sci.* ***28****, (2003) 366.*
*[2] T.-A. Ovari, S. Corodeanu, C. Rotarescu, and H.Chiriac, IEEE Trans. Magn.* ***50*** *(2014) 2007304.*

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# Electric And Magnetic Properties Of Particulate Ferrite-Ferroelectric Composites

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Electric and magnetic properties of $x$NiFe$_2$O$_4$+$(1-x)$Pb$_{0.988}$(Zr$_{0.52}$Ti$_{0.48}$)$_{0.976}$Nb$_{0.024}$O$_3$ particulate composites ($x$NF+(1-$x$)PZTN, where $x$ = 2, 10, 20, 30, 50, 70 and 100 wt%) have been studied. The presence of a diphase composition was confirmed by X-ray diffraction while the microstructure of the composites was studied by scanning electron microscopy (SEM) revealing a good mixing of the two phases and a good densification of the bulk ceramics.

The effect of NF phase concentration on the *P-E* and *M-H* hysteresis behavior and dielectric properties of the composites was investigated. The dielectric permittivity shows usual dielectric dispersion behavior with increasing frequency due to Maxwell-Wagner interfacial polarization. AC conductivity measurements made in frequency range 1Hz-1MHz suggest that the conduction process is due to mixed polaron hopping. From ferroelectric measurements it was observed that the ferrite phase acts as an inhibitor: with increase of NF concentration in the composites we obtained flattened P-E loops with smaller values of the remanent polarization. In contrast, the magnetic properties improve with addition of ferrite phase. However the coercitive field ($H_c$) for all the composite samples is larger than that of pure NF phase. An intriguing aspect is the influence of percolation between the two phases at high NF content on dielectric, ferroelectric and magnetic properties. We demonstrated that along with interfacial polarization the percolation effect causes giant increase of permittivity at low frequencies, high dielectric losses and diffuse phase transition of the composites.

**Acknowledgements:** This work was supported by CNCSIS-UEFISCSU project PN-II-PT-PCCA-2013-4-1119.

# Study Of Left-Handed Characteristics Of Parallel Microwires Based Metastructures

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Left-handed characteristics of parallel arranged ferromagnetic microwires based metastructures were intensively studied in the last years because they induce a maximum transmission and minimum absorption window in the microwave domain [1]. In the frequency domain between NFMR (Natural Ferromagnetic Resonance) and NFMAR (Natural Ferromagnetic Anti-Resonance) a ferromagnetic microwire presents a negative magnetic behavior [2]. A specific parallel arrangement of ferromagnetic microwires induces a plasma-type behavior in the electromagnetic field and, consequently, the negative electric characteristics are obtained [3]. The simulation of the magnetic and dielectric properties of such metastructures turned out to be a useful tool in order to anticipating and engineering the left-handed frequency domain [4].

The aim of this work is to present a complex experimental and theoretical study of the ferromagnetic resonance frequencies and plasma behavior for Fe-based, CoFe-based, Co-based and FINEMETTM glass covered amorphous microwires (GCAWs), in order to obtain metastructures with tailored and enlarged left-handed frequency domain. The metastructures negative magnetic properties interval can be expanded by alternating different types of GCAWs with close NFMR-NFMAR domains, as can be seen in Fig. 1. The saturation magnetization, $M_{s1}$, and anisotropy field, $H_{k1}$, of Fe-based GCAWs are considered as reference. As one can notice, the use of Co-based and FINEMETTM GCAWs enlarges the negative behavior domain of Fe-based GCAWs towards higher frequencies, while the CoFe-based GCAWs enlarge the negative behavior domain in the lower frequency range. Fig. 2 presents the frequency domains of negative magnetic properties for Fe-based, CoFe-based, Co-based and FINEMET GCAWs, respectively, tuned in an external d.c. magnetic field, $H_{dc}$. A very good correlation was found between the simulated data and measured ferromagnetic resonance responses for different $H_{dc}$.

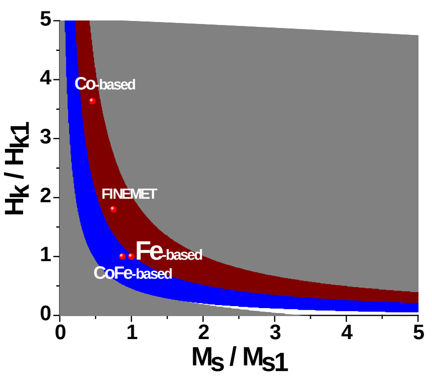


*Fig. 1. Magnetic properties of the microwires relative to the Fe-based GCAWs. The red region enlarges the negative behavior to higher frequencies, while the blue region enlarges it to lower frequencies.*

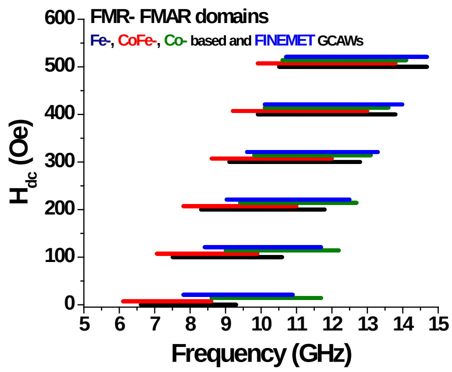


*Fig. 2. Magnetic field dependence of negative frequency domains for Fe-based, CoFe-based, Co-based and FINEMET GCAWs.*

**Acknowledgement:** Financial support from the NUCLEU Programme (PN 09-43 01 01) is highly acknowledged.

***References***

[1] F.X. Qin et al., Phys. Status Solidi C 11 (2014) 1086.
[2] C. Kittel, Phys. Rev. 73 (1948) 155.
[3] J.B. Pendry et al., J. Phys. Condens. Mater. 10 (1998) 4785.
[4] G. Ababei et al., J. Appl. Phys. (2015) in press.

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# Permanent Magnets Based On Ferromagnetic Microwires

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Magnetic materials are, without a doubt, some of the most attractive subjects of scientific research today, with a wide range of structures and forms of organization (at all levels: macro, meso, micro and nanoscopic), proving a wide variety of properties and, on the other hand, providing an almost unlimited range of applications. Such materials inevitably attracted the interest of physicists and engineers as well.

The works carry out in this paper started from the micromagnetic model of the elongated particle [1-3].

This paper presents the development of new permanent magnets based on ferromagnetic microwires, using many typo-dimensional, different alloys and different preparation methods. Experimental models are presented together with their magnetic properties related to their structural properties.

The results open a new approach for achieving low cost –permanent magnets with low content of Rare Earth (or even without) based on ferromagnetic microwires.

The expected applications of these new composite permanent magnets are in the field of MEMS.

**Acknowledgment:** The activities was carried out within the project framework 5013/2009.

***References:***

*[1] L.I. Mendelsohn, F.E. Luborsky, T.O. Paine, J. Appl. Phys. 26 (1955), R1274-R1280.*
*[2] R.B. Falk, J. Appl. Phys., 37 (1966), R1108-R1112.*
*[3] D.J. Craik, R. Lane, J. Appl. Phys., 18 (1967), R1269-R1274.*

# Multiferroic Properties Of $Sm_2NiMnO_6$ Ceramics Prepared By Spark Plasma Sintering

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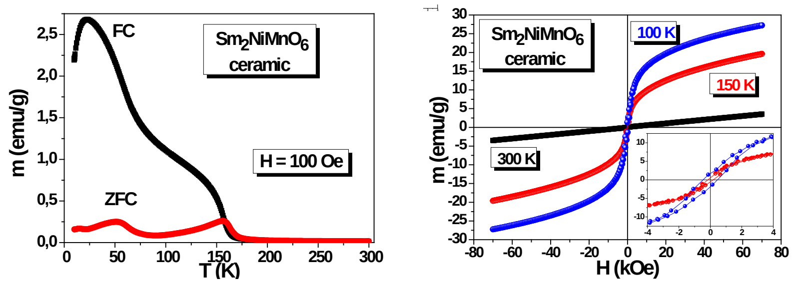
In the last years, there is a great interest in developing new multiferroic materials having simultaneously in the same phase ferromagnetic and ferroelectric order. The multiferroic materials have attracted attention due to their future application in spintronics and magnetoelectric devices [1,2].

In the present work, it was reported for the first time the new synthesis of $Sm_2NiMnO_6$ double perovskite oxides by sol-gel auto-combustion method. The Rietveld analysis of the x-ray ceramics diffraction pattern recorded at room temperature for $Sm_2NiMnO_6$ ceramics sintered at 1000°C/5min from powders obtained at 700°C/7h confirm the formation of the double perovskite with a monoclinic structure and the space group $P2_1/n$. The magnetic transitions observed in the ZFC/FC cycle indicate a change in the spin ordering at low temperatures and a weak ferromagnetic/ferrimagnetic contribution that is attributed to the possible valence states in the magnetic ordering $Ni^{2+}$-O-$Mn^{4+}$ (Fig. 1). The complex impedance investigations indicate important contribution from at least two conductivity relaxation mechanisms (given by grains and grain boundaries). The non-linear dielectric character was checked for the first time in $Sm_2NiMnO_6$ double perovskite and the results reveals a strong nonlinearity and a small hysteretic behaviour. The non-linear field-dependence ε(E) presents a tendency towards saturation for high fields (~ 30 kV/cm). In conclusion, the present structural, magnetic and dielectric data make the $Sm_2NiMnO_6$ double perovskite system for its multiferroic character a promising candidate to different applications.




*(a)* *(b)*

*Fig. 1. (a) Temperature dependence of the magnetization for $Sm_2NiMnO_6$ ceramics subjected to a ZFC/FC cycle under the magnetic field of H = 100 Oe. (b) The m(H) dependences at three different temperatures (Inset: low-field region).*

**Acknowledgements:** FG acknowledges "Alexandru Ioan Cuza" University project: code GI-2014-04 in the frame of "UAIC Grants for young researcher" competition.

***References***

*[1] G.Catalan and J. F. Scott, Advanced Materials, vol. 21, no. 24, pp. 2463–2485 (2009).*
*[2] C. A. F. Vaz, J. Hoffman, C. H. Ahn and R. Ramesh, Advanced Materials, 22, 2900–2918 (2010).*

# Magnetic Properties Of (1-X)$BiFeO_{3-x}BaTiO_3$ Multiferroic Solid Solutions

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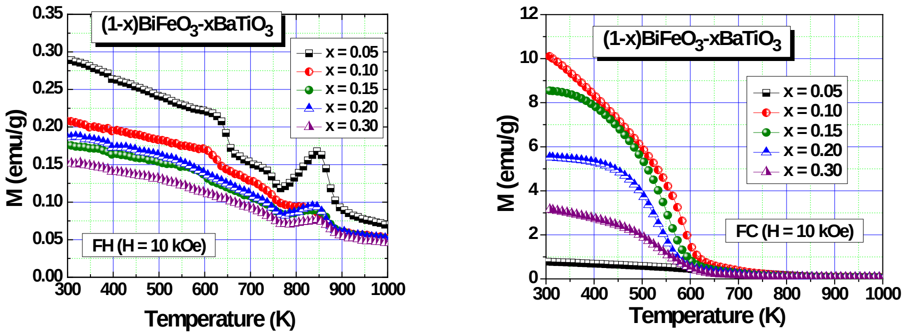
In the present work, the magnetic properties of (1-x)$BiFeO_3$-x$BaTiO_3$ ($0 \leq x \leq 0.30$) solid solutions ceramics are investigated in details. To induce ferromagnetism at room temperature the strategy of forming solid solutions with $BaTiO_3$ was adopted. Although $BaTiO_3$ is not a magnetically ordered material, its influence in distorting the spinoidal antiferromagnetism towards a ferromagnetic state by structural factors was also expected in the solid solution at room temperature.

Pure phase of (1-x)$BiFeO_{3-x}BaTiO_3$ ceramics was prepared by a two-step solid state reaction procedure [1]. The magnetic hysteresis loops for the as-prepared (1-x)$BiFeO_3$-x$BaTiO_3$ solid solutions at room temperature show that the expected antiferromagnetic behaviour typical for $BiFeO_3$ (with linear M(H) dependence) is turned into a weak ferromagnetic state by the addition of $BaTiO_3$. The variation of their magnetisation against temperature M(T) shows the presence of a temperature-dependent magnetic order, with magnetic moments (under the excitation field H = 10 kOe) which monotonously decrease with the temperature increase. The thermomagnetic FH/FC cycle (Fig. 1) acts not only in producing spin re-arrangements, but also induces irreversible compositional changes due to the $BiFeO_3$ chemical instability at high temperatures and variations of the oxygen stoichiometry associated with $Fe^{3+}/Fe^{2+}$ transitions. For the most homogeneous ceramic with composition x = 0.30, a magnetoimpedance characterization (the evolution of the real and imaginary part of the impedance under dc magnetic field and at few selected temperatures) was also performed. The results show that both components of the complex impedances are sensitive to the magnetic field at any temperature, with a stronger variation in the range of fields of (0, 20 kOe) and a tendency to saturation at higher fields.




*(a)* *(b)*

*Fig. 1. Thermomagnetic data M(T) of the (1-x)$BiFeO_3$- x$BaTiO_3$ ceramics at H = 1T during: (a) Field heating (FH) process; (b) Field cooling (FC) process.*

**Acknowledgements:** The financial support of the CNCS-UEFISCDI project PN-II-PT-PCCA-2013-4-1119 is highly acknowledged.

***References***

*[1] A. Ianculescu et al., J Optoel&Adv. Mater. 10, 1805 (2008).*

# Hysteresis Modeling And Micromagnetics To Characterize Cultural Heritage: The Case Of Cucuteni Painted Pottery From Eastern Romania

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In the last decades the interest of the scientific community in characterizing, monitoring and conserving objects belonging to Cultural Heritage has continuously expanded. In fact there is a growing interest in understanding the ancient techniques and materials used for producing the artworks which is of help, also, in preventing the artefacts degradation.

The Cucuteni-Trypillia civilization is perhaps one of the most intriguing subjects when analysing South-Eastern European prehistory during the 5-4th millennia BC. Although its importance is not limited to spectacular excavated artefacts, it is famous worldwide for its anthropomorphic and zoomorphic figures, and sophisticates polychrome pottery which have significantly enhanced our knowledge of daily life and artistic handicraft of Old European civilizations.

In order to understand the technology used for manufacturing the Cucuteni pottery artworks we have conducted an interdisciplinary study on a significant number of pottery samples selected from a wide geographical area covering the present-day Eastern Romania. Magnetic measurements, including a first-order reversal curve are the main physical techniques used for investigating the technological parameters of the Cucuteni pottery.

The magnetic properties investigation of pottery was typically used by previous studies for dating inferences, yet the magnetic properties of ancient ceramics can also be convenient for their characterisation, to evaluate the technological conditions applied for their production (temperature, atmosphere, and duration of firing), as well as to distinguish groups of sherds having different provenance.

The analysis of magnetic properties provides new information which help understanding the mineralogical transformations due to the firing process. The magnetic measurement's results seem to be influenced by the soaking time, the modality of cooling, and by the clay composition and homogeneity. In terms of pottery technology, the magnetic measurements confirm the mineralogical transformations detected by XRD analysis and suggest a certain degree of standardization in the Cucuteni pottery production.

**Acknowledgment:** This work was financially supported by the grant of the Romanian National Authority for Scientific Research, CNCS-UEFISCDI Project PN-II-ID-PCE-2011-3-0794 [IDEI-EXOTIC No. 185/25.10.2011]

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# Synthesis And Magnetic Properties Of Iron Oxide Nanoparticles With Narrow Size Distribution

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Nanosized magnetic materials, in particular iron oxides nanoparticles have attracted increasing attention due to unique magnetic properties which made them interesting from both theoretical and technological points of view [1]. Various synthesis routes have been developed for obtain iron oxide nanoparticles such sol–gel process, forced hydrolysis and precipitation, hydrothermal technique and sonochemical technique [2]. Usually, it is difficult to obtain iron oxide nanoparticles with small size and narrow size distribution through the conventional synthetic routes due to the complexity in control of nucleation and particle growth process [3].

In this paper, we report the ultrasonic assisted synthesis and magnetic properties of iron oxide nanoparticles. The iron oxide nanoparticles were synthesized ultrasonically assisted, using as iron oxide precursor iron chloride and sodium hydroxide as sources of oxygen. The ultrasonically assisted reaction was continued for 30 min at different temperatures, and the precipitated were filtered and washed thoroughly with ethanol and deionized water. The samples were dried in air at room temperature and then treated at 300°C for 2 h to obtain crystalline iron oxide nanoparticles. The resulting material was characterized by powder X-ray diffraction (XRD), scanning electron microscopy (SEM) and vibrating sample magnetometer (VSM). The XRD pattern of samples, revealed the presence of hematite. The SEM micrography of iron oxide nanoparticles shows the spherical morphology and narrow size distribution of iron oxide particles. Magnetic hysteresis loops were measured at room temperatures on iron oxide nanoparticles using a vibrating sample magnetometer (VSM) Princeton Instruments Micromag TM 3600. The analysis of the hysteretic properties was made using first-order reversal curves (FORC) diagram. In order to obtain more information concerning the interactions between the particles FORC diagrams at low temperature were also measured. We also discuss the relation between the FORC distributions at different temperatures.

**Acknowledgment:** This work was financially supported by the grant of the Romanian National Authority for Scientific Research, CNCS-UEFISCDI Project PN-II-ID-PCE-2011-3-0794 [IDEI-EXOTIC No. 185/25.10.2011].

***References***

*[1] Ursachi, I.; Vasile, A.; Chiriac, H.; Postolache, P.; Stancu, A. Materials Research Bulletin: 46, 2468-2473, 2011;*
*[2] Hassanjani-Roshan, A.; Reza Vaezi M.; Shokuhfar A.; Rajabali Z.; Particuology: 9, 95–99, 2011;*
*[3] Cui H.; Liu Y.; Ren W.; Advanced Powder Technology; 24 93–97, 2013.*

# Modeling The Size Effects On The Dielectric And Switching Properties In Nanostructured Ferroelectric Ceramics

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The role of grain size on the tunability (electric field dependence of the dielectric constant) in nanostructured BaTiO3 ceramics was studied by an experimental-modeling approach. When reducing grain size in ceramics down to 100 nm, the permittivity diminishes below 1000 and a tendency towards linearization of the permittivity vs. field dependence and lack of saturation is observed [1]. To explain the observed experimental features, the highly inhomogeneous nature of the nanostructured ceramic was considered. The ceramic was described as a composite formed by grains with ferroelectric core and low-permittivity linear dielectric grain boundary. The role and contribution of the grain boundaries increases when reducing grain size at nanoscale. A complex model for describing the grain size influence on the tunability response in dense nanostructured ceramics was developed. Virtual ceramic microstructures with progressive reduction of grain size were generated and the local electric fields have been computed by finite element approach at various external voltages.

The effective permittivity-field responses $\varepsilon_{eff}(E)$ have been computed by taking into consideration the specific local field distribution with Finite Element Method (FEM) [2]. A remarkable agreement between the experimental tunability features and model calculations was obtained in describing the reduction of permittivity and tunability and tendency of linearization of the $\varepsilon_{eff}(E)$ when reducing the ceramic grain size.

The macroscopic P(E) hysteresis loops were also described a combined Monte Carlo - FEM model. The Monte Carlo model was employed to describe the ferroelectric domain structures for various grain sizes and the P(E) dependence was computed taking into account the local field inhomogeneity as described by FEM calculations. This model successfully explained the modifications of hysteresis loops induced by the reduction of grain size to nanoscale: the transition from a more rectangular hysteresis loop to a narrow, tilted and hardly saturated one [1].

**Acknowledgements:** the support of CNCS-UEFISCDI Project No. PNII-RU-TE-2012-3-0150 is highly acknowledged.

***References:***

*[1] L. Curecheriu, S.B. Balmus, M.T. Buscaglia, V. Buscaglia, A. Ianculescu, L. Mitoseriu, J. Am. Ceram. Soc. 95, 3912-3921 (2012)*

*[2] Leontin Padurariu, Lavinia Curecheriu, Vincenzo Buscaglia, Liliana Mitoseriu, Phys. Rev. B 85, 224111 (2012)*

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# Synthesis And Properties Of 1-D Nickel Oxide Structures Produced By Using Natural Fibers As Bio-Templates

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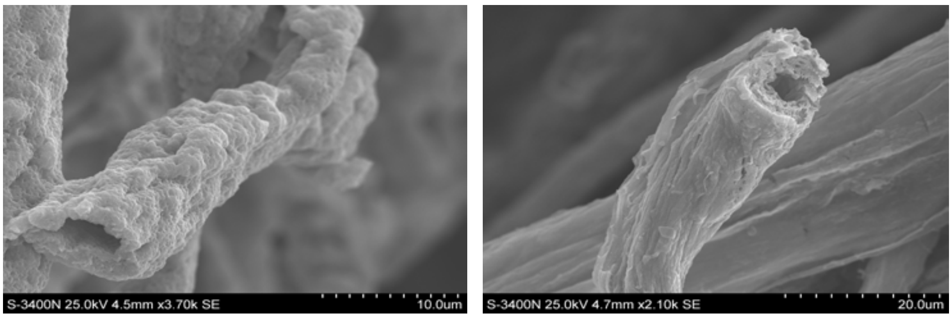
Nature has provided numerous examples of exceptionally building materials. Therefore, a variety of bio-inspired morphology synthesis strategies have been explored. The process of in situ modification with bio-templates has attracted considerable attention because of the structural and compositional hierarchical order and its unique performance regarding the use of templates, different from man-made materials. Nickel oxide (NiO) is an important semiconductor and antiferromagnetic material, widely used in electrochemical, optical and magnetic applications. The valuable functionality greatly depends on its nano- and microscale structure and therefore, many efforts were made in attempting to prepare nanostructured NiO with different morphologies. Biomorphic nickel oxide is expected to show enhanced ferromagnetic behavior, photocatalytic and antimicrobial activities, due to its special nano/microstructural arrangement. The aim of this work was to prepare biomorphic 1-D NiO microtubes by using as bio-template different natural fibers and to study the effects of the synthesis parameters (temperature, precursor concentration) on their microstructure and functional properties.

Pure phase of biomorphic NiO microtubes (Fig. 1) with nanoporous structure were successfully prepared using cotton (Gossypium), hemp (Cannabis sativa) and flax (Linum usitatissimum) as 1-D biotemplates.

The final products were obtained by infiltration of nickel nitrate ($Ni(NO_3)_2\cdot 6H_2O$) solution with different concentration into biotemplates, followed by calcination at different temperatures, in air, for 1h. The phase formation and morphologies have been investigated by using X-ray diffraction (XRD) and scanning electron microscopy (SEM) (Fig. 1). The influence of the synthesis parameters and templates on the functional characteristics of the 1-D NiO samples was determined and interpreted in terms of their nano/microstructural properties.

**Acknowledgements:** The financial support of the CNCS-UEFISCDI Project No. PN-II-ID-PCE-2011-3-0745 is highly acknowledged.




*(a)* *(b)*

*Fig.1. SEM image of biomorphic NiO produced by using as biotemplate: a) cotton; b) flax.*

# Investigation Of Magnetic Materials Used In Electromagnetic Shielding At Low Frequency Field Disturbances

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Low frequency magnetic fields (LFMF) of 50/ 60 Hz generated by power supply systems represent the mostly common low frequency disturbances, which have a strong influence on sensible electrical and electronic equipment (EEE) operation, such as medical and IT equipment, and on human body.

Although the LFMF disturbances levels are regulated by international bodies (EN, IEC, IEEE, SR EN, ICNIRP), the time-quantifiable impact on these EEE is not fully understood and currently shielding protection is still not efficient. A solution to assure the immunity of highly sensible EEE represents the passive and active magnetic shields based on high efficient magnetic materials.

The mechanism to cancel the magnetic field action implies comprehensive knowledges on the complexity of the processes which occur in the magnetic screens and accurate mathematical modelling of the operating regime of these magnetic materials which have hysteretic and non-linear characteristics. Further on, a higher screen efficiency requires an adequate design for every shielding magnetic material, concerning the material properties matrix and material geometry.

The paper proposes a detailed study on magnetic properties of FeSi and Ni based soft magnetic materials used in construction of passive and active high performance magnetic screens at low frequency disturbances fields. A comparative analysis of experimental data and numerical modeling and simulations are done. The results concern in new specifications for shielding magnetic materials and a better understanding of the highly sensible EEE operation under LFMF influence.

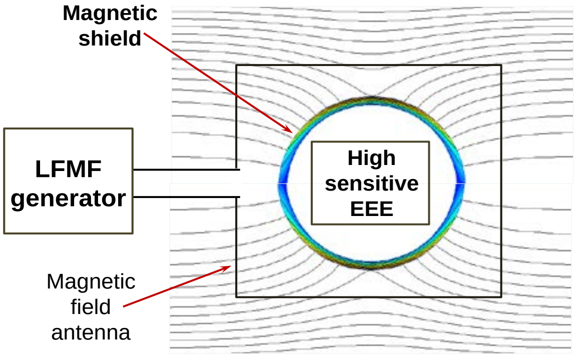


*Fig. 1. Test stand for magnetic shield effectiveness investigation under LFMF action*

***References***

*[1] Augello, A., Della Chiara, s.a., Immunity tests of implantable cardiac pacemaker against CW and pulsed ELF fields: Experimental and numerical results, IEEE Transactions on Electromagnetic Compatibility, Volume: 48, Issue 3, 2006, pp. 502 - 515.*
*[2] Kobayashi K., Kon A., Yoshizawa M., s.a., Active Magnetic Shielding Using Symmetric Magnetic Field Sensor Method, IEEE Trans. on Magn., Vol. 48, No. 11, November 2012, pp. 4554 - 4557.*
*[3] Hoburg, J.F., Bain, J.A., Silva, J.M., Susceptibility of magnetic information storage to power frequency magnetic fields, IEEE Electromagnetic Compatibility Magazine, Vol.2, No.2, 2013, pp.59-67.*
*[4] Sang-Yun L., Yun-Seog L., In-Hyuk C., s.a., Effective combination of soft magnetic materials for magnetic shielding, IEEE Transactions on Magnetics, Vol. 48, No. 11, November 2012, pp. 4550-4553.*

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# Hysteresis Characterization And Modeling Of Novel Thick-Film Pzt Microactuators

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Micromanipulation and microassembly tasks are increasingly required in different applications. For instance, they are often used to produce complex microsystems, or to characterize micro-objects (biological ones or artificial ones). In order to increase the success of the micromanipulation and microassembly tasks, miniaturized robotics structures (microrobots) have been being used since more than a decade. They permit to work in confined environments, consume less power, and can provide the required positioning resolution, generally in the order of tens of nanometers. Among the well known microactuators employed in these microrobotic structures are piezoelectric microactuators. They offer large bandwidth, high resolution and an ease of powering (electrical). Furthermore, they can be exploited as sensors also.

We have developed a new kind of piezoelectric microactuators recently (Fig.1.a). Based on the thinning of PZT (lead, zirconate, titanate) ceramics bonded on silicon, and called thick-film microactuators, the proposed devices possess dimensions in a scale lower than the existing ones, making them well adapted to more miniaturized structures. Furthermore, their small thickness (down to few tens of micrometers) make them require low driving voltages for larger output displacements. Finally, the developed microactuators exhibit a bandwidth larger than the existing ones. Such microactuators are very promising for the development of MEMS structures with actuation and sensing purpose.

This paper reports the characterization of the new kind of piezoelectric microactuators which shown highly nonlinear behavior, such as hysteresis and creep. In this paper we will focus on the characterization and modeling of the hysteresis of such actuators. It is shown that the gain of these thick-film microactuators exceeds 4µm/V and the related hysteresis is of 16% (Fig.1.b). A generalized Bouc-Wen model is afterwards employed to track the hysteresis. Thanks to this model, an open-loop compensation of the hysteretic behavior of the cantilever was efficiently performed.

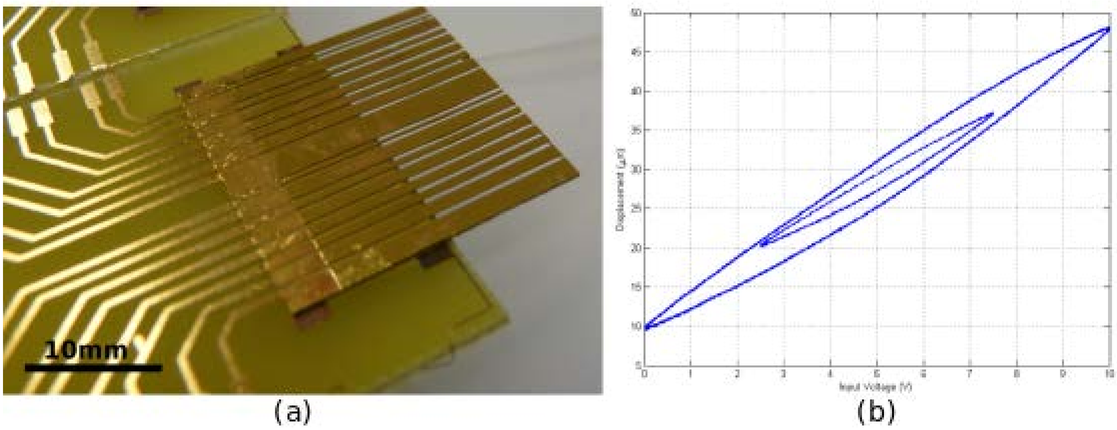


*Fig. 1: (a): the new thick-film piezoelectric microactuators. (b): input-output map characteristics of the microactuator.*

# Magnetic Properties Of Aligned Composite Nanofibers Produced By Electrospinning Method

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During the last decade magnetic composite nanofibers have attracted a special attention not only for their magnetic properties but also for their potential applications. Ultra -fine fibres with controlled and uniform diameters in the micrometer to nanometer range have been successfully produced by electrospinning. In our previous studies we focused on the production of PVC matrix - ferromagnetic particles composite nanofibers and their application as absorbent material in high frequency electromagnetic fields [1, 2]. Considering these studies, we asked what changes appear in the magnetic behavior of such structures if the composite nanofibers would be alienated in a thread form. In this paper, we report the production of one fiber consist from alignment composite nanofibers. The composite fiber (Fig.1) has been successfully obtained using a device that combines electrospinning and mechanical alignment techniques. The chemical reagents used in this work were: tetrahydrofuran (THF), N,N-dymethilformamide (DMF), poly(vinyl chloride) (PVC) and α-Fe2O3 nanoparticles.

The obtained fiber was characterized by X-ray diffraction (XRD), scanning electron microscopy (SEM) and vibrating sample magnetometer (VSM). The magnetic hysteresis loops measured at room temperatures on α-Fe2O3 nanoparticles and composite fiber shows discrepancy between the coercive fields. In order to attain a detailed characterization, the first-order reversal curves (FORC) [3-4] where measured at room temperature. The FORC analysis was used to compare the interaction field distribution in the powder sample and the interactions between the particles included in the composite fiber.

**Acknowledgment:** this work was financially supported by PN-II-RU-TE-2012-3-0449 No. 26/26.04.2013

*Fig.1. SEM image of obtained fiber consisting from aligned composite nanofibers.*

***References:***

[1] O. Chiscan, I. Dumitru, P. Postolache, V. Tura and A. Stancu, Mater. Lett. 68, 251 (2012)
[2] O. Chiscan, I. Dumitru, V. Tura, H. Chiriac and A. Stancu, IEEE Trans. Magn. 47, 4511 (2011)
[3] A. Stancu, C. Pike, L. Stoleriu, P. Postolache, D. Cimpoesu, J. Appl. Phys. 93 6620 (2003)
[4] C. I. Dobrotă, A. Stancu, J. Appl. Phys 113, 043928 (2013).

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# Influence Of Shape And Area Hysteresis Loops On Heating Process Of Magnetic Nanoparticles For Hyperthermia Applications

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In the last two decades magnetic hyperthermia (MHT) used as therapeutic method attracted a lot of interest. The magnetic nanoparticles (MNPs) subjected to an alternating magnetic field generate a specific amount of heat and raise the tumor temperature tumor to maximum 46°C at which certain mechanisms of cell damage are activated [1,2]. The generated heat is quantitatively related to the specific absorption rate (SAR) of nanoparticles which is due to the specific loss per cycle of hysteresis loop and Neel or Brown magnetization relaxation processes. In many situation is more productive for comprehension and optimization of MHT to make appeal to simulation. Comsol MultiPhysics is a friendly software allowing the study and analysis of general or specific temperature distributions in different treatment situations. In this study starting from experimental data referring to the influence of MNPs size and shape on saturation magnetization and coercive field, implicitly on hysteresis loop shape and losses [3], were simulated diverse situations. The temperature profile in tumor tissues were plotted for different MNPs diameters and consequently different specific absorption rates. Finally the influence of temperature distribution on hysteresis losses and tissue heating process was studied for MNPs with Curie temperature close to temperature the cell apoptosis.

**Acknowledgement:** the authors acknowledge the support given by Romanian CNCS - UEFISCDI project number PN-II-RU-TE-2012-3-0449.

***References:***

*[1] Kumar CSSR, Mohammad F: Magnetic nanomaterials for hyperthermia-based therapy and controlled drug delivery Adv Drug Deliver Rev2011, 63:789–808.*

*[2] Wang YM, Cao X, Liu GH, Hong RY, Chen YM, Chen XF, Li HZ, Xu B, Wei DG: Synthesis of Fe3O4magnetic fluid used for magnetic resonance imaging and hyperthermia J MagnMagn Mater2011, 323:2953–2959.*

*[3] J. Carrey, B. Mehdaoui, and M. Respaud Simple models for dynamic hysteresis loop calculations of magnetic single-domain nanoparticles: Application to magnetic hyperthermia optimization. JOURNAL OF APPLIED PHYSICS109, 083921 (2011)*

# High Sensitive Magnetic Field Sensor Based On Patterned Magnonic Crystals

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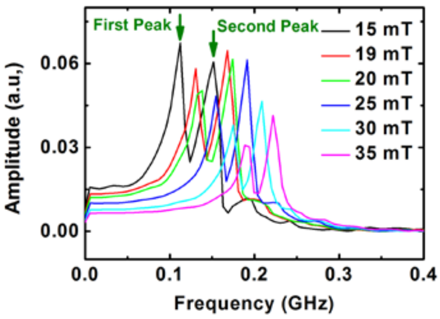
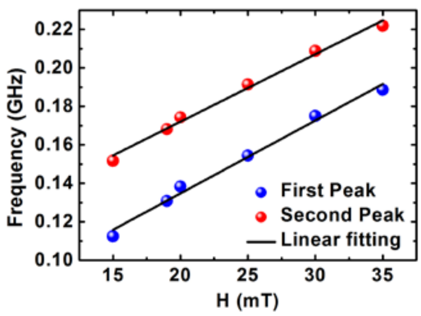
Patterned magnonic crystals have been attracting much attention due to its possible applications such as spintronic devices and microwave communications. Numerous studies have been focused on understanding of the single or collective spin wave modes in various patterned magnonic crystals [1]. Recently, utilizing an artificial one-dimensional magnetic crystal as an extremely sensitive magnetic field sensor was experimentally demonstrated at room temperature [2]. The reported magnetic field sensor can achieve a high sensitivity about 104 %/Oe using a propagation effect of magnetostatic surface wave mode in the YIG material. However, very few have been known for the detailed propagation behaviour of magnetostatic surface wave mode and the effect of magnetic field response on the two-dimensional (2D) artificial magnonic crystals.

In this work, we explore further details of the magnetostatic surface wave mode in magnetic nanoelement arrays as 2D magnonic crystals by means of micromagnetic simulations. Material parameters of Permalloy (Py) are used for the saturation magnetization and the exchange stiffness. The Py is considered to have zero magneto-crystalline anisotropy so that the Py system becomes an ideal playground in examining the propagation dynamics of magnetostatic surface wave mode. Nanoelement in the present study has been defined to have an ellipsoidal shape with various dimensions and intervals of ferromagnetic nanoelements as lattice structures of the magnonic crystal. By changing the bias magnetic fields, the magnetostatic surface wave modes are intensively investigated under a pulsed magnetic driven field. The observed dynamic behaviour of the magnetostatic surface wave is analysed by the Fourier analysis. We have found that the dynamic behaviour of the magnetostatic surface wave strongly depends on the bias magnetic field, such as two magnetic resonance frequency picks can be shifted with several tens of about megahertz by changing the bias magnetic field of 1 mT, as shown in Fig. 1(a).




*(a)*




*(b)*

*Fig.1 (a) Spectral analysis of the magnetostatic surface wave mode by Fast Fourier Transform. (b) Magnetic resonance frequency shifting depending on the bias field.*

***References***

*[1] V. V. Kruglyak, et al., Phys. Rev. Lett. 104, 027201 (2010).*
*[2] M. Inoue, et al., Appl. Phys. Lett. 98, 132511 (2011).*

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# Universal Behavior Of Magnetocaloric Effect In A Layered Perovskite $La_{1.2}Sr_{1.8}Mn_2O_7$ Single Crystal

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In this paper, we present a detailed analysis on temperature and magnetic field dependences of the magnetic entropy change, $\Delta S_m(T,H)$, near the ferromagnetic (FM)-paramagnetic (PM) phase transition of a $La_{1.2}Sr_{1.8}Mn_2O_7$ single crystal. The sample was prepared by the floating-zone method. Magnetic measurements versus temperature (5-300 K) and magnetic field (0-50 kOe), M(H,T), were performed on a superconducting quantum interference device (SQUID) magnetometer. Experimental results reveal the material exhibiting a single FM-PM phase transition at TC = 85 K, which belongs to a second-order phase transition (SOPT). As a result, $|\Delta S_m|$ reaches the maximum value (|ΔSmax|) around TC, and increases with increasing H. Depending on H, the $|\Delta S_m|$ values are found to be 0.93, 1.73, 2.38, 2.91, and 3.33 J·kg-1·K-1 under the applied magnetic field change H = 10, 20, 30, 40, and 50 kOe, respectively. However, the peak position of the $-\Delta S_m(T)$ curves is effectively tuned to higher temperature when H increases. Further, all the $\Delta S_m(T)$ curves measured at different H values do not collapse into a universal curve when they were normalized to their respective $\Delta S_{max}$ value, and rescaled the temperature axis with $\theta_1 = (T - T_C)/(T_r - T_C)$ for a reference temperature $T_r > T_C$ or $T_r < T_C$. Nevertheless, all the $\Delta S_m(T,H)$ data can be collapsed into a unique curve in the whole temperature range if using two separated reference temperatures, $T_{r1}$ and $T_{r2}$, to construct the universal curve with $\theta_2 = -(T - T_C)/(T_{r1} - T_C)$ for $T \leq T_C$ and $\theta_2 = (T - T_C)/(T_{r2} - T_C)$ for $T > T_C$. This nature of this phenomenon is discussed thoroughly by means of the crystal structure and magnetic anisotropy of the material.

# Torque-Induced Magnetization Response Of NiFe Cylindrical Films

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Existing magnetostrictive torque sensor designs typically measure the rotation of the saturation magnetization under an applied torque and their theoretical treatment revolves around the minimization of the free energy equation adapted according to the assumptions considered valid in each design. In the torque measurement design discussed in this paper, Ni-rich NiFe films have been electrodeposited on cylindrical austenitic steel rods. Contrary to existing designs, the excitation field is applied along the axial direction and is low enough to ensure that the resulting magnetization along the same direction remains in the linear region of the M(H) characteristic. Assuming homogeneous magnetization, negligible hysteresis and demagnetizing fields, and positive magnetostriction constant $\lambda$, torque T may be expressed in terms of an effective uniaxial anisotropy constant Ku around 45o to the axial direction:

$$K_u = \frac{3}{2}\lambda\sigma = \frac{48}{\pi d^3}\frac{G_{Nife}}{G_{steel}}\lambda T \qquad (1)$$

where d is the rod's diameter, GNiFe is the modulus of rigidity of the NiFe ribbon glued on the shaft and Gsteel is the modulus of rigidity of the steel substrate.

It is shown, that when the applied field energy EH is counterbalanced by a torque induced anisotopy term EK: (i) the resulting M is the linear superposition of the effect of a torque-induced effective field HT and the excitation field H (ii) H accounts for the vertical offset of the magnetization response (iii) T increases the slope of the M(H) characteristic. Theoretical results are compared against quasi-static constant torque and constant field measurements shown below:

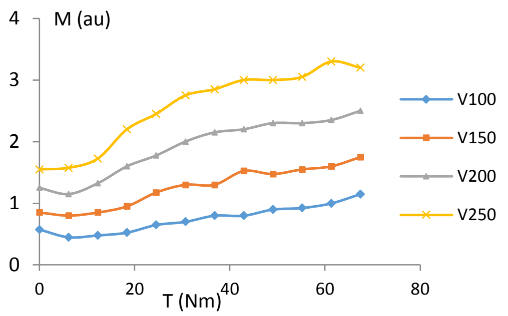


*Fig. 1 – Magnetization response vs applied torque T at various applied fields*

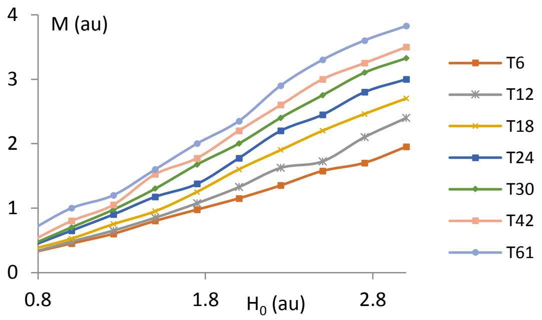


*Fig.2– Magnetization response vs applied field H0 at various torque levels*

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# Evaluation Of The Effects Of Aging In Synthetic Saliva Solution Of Commercial And Silanized Nd-Fe-B  Magnets For Dental Application

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The main reason limiting long-term clinical application of neodymium-iron-boron (Nd-Fe-B) magnets in dental field is their marked corrosion tendency in middle aggressive media containing chloride such as saliva.

This is due both to the high intrinsic porosity of Nd-Fe-B alloys and to the inhomogeneity of the magnetic surfaces that leads to uncoated areas.

The defects in the coating are the seeds for preferential pitting corrosion that implies the mechanical deterioration, the modification of the magnetic properties, and, nonetheless, the release of cytotoxic agents.

Thereby it becomes necessary to overcome the corrosion resistance lack of Nd-Fe-B magnets with new wear resistant encapsulating materials osurface coatings.

We propose a multi-layered organic-inorganic structure able to supply specific functional properties to the whole assembly (i.e. anticorrosion resistance, wear resistance and durability).

For this reason, we evaluated the influence on the magnetic force of commercial nickel plated Nd-Fe-B during aging time in synthetic Fusayama saliva solution at pH 5.5. Furthermore we evaluated the protective action of a new hybrid silane coating dipped on nickel plated Nd-Fe-B magnets. We also performed simulations to study how the dimension of the defect can alter the magnetic field/force generated by the Nd-Fe-B.

Our key result underlines that the hybrid coating does not affect the magnetic force of Nd-Fe-B magnets preventing corrosion degradation in aggressive solution.

Thus the limiting aspects avoiding the use of Nd-Fe-B magnets for orthodontic and prosthodontic applications can be overcome by using silane agents as surface coating.

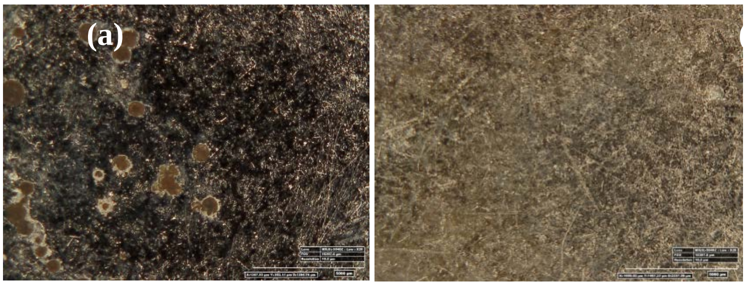


*Fig.1. Morphological evaluation, with Hirox KH8700 3D Digital Microscope, of aging in Fusayama synthetic saliva solution after 3 days: (a) Commercial Nd-Fe-B nickel plated magnet sample with formation of large portions of pits; (b) Nd-Fe-B magnet sample with new hybrid organic-inorganic coating resistant to corrosion.*

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# Charging Effect On Li-Ion Batteries. Aging And Hysteresis Phenomena

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Li-Ion batteries are known in literature like no-memory systems and without hysteresis effect.

Those particularities could represent great advantages in practical applications, the leak of memory effect and hysteresis phenomena would make easier the process used to obtain the state of charge for a certain battery in any moment of use, unfortunately in usual applications those effects exists.

This paper aims at investigating the conditions which make de Li-Ion batteries to show this features and also to study the hysteresis effect obtained.

The measurements had been carried out at 23 Celsius degree, using single cells Li-Ion batteries, with nominal tension 3.7V and capacity of 1200mAh. The charging and discharging sequences were composed from repeated steps of 30 minutes open circuit voltage (OCV) followed by 10 minutes constant current (charge or discharge), until the exit condition is reached.

From the experiments can easily observe that charging method has a significant effect over Li-Ion cells [1], even if the charging current is the same, and recharging steps are identical in all the cycles, an incomplete charging process affects rate of capacity and make the system to exhibit a hysteretic character.

Having a pronounced hysteresis makes difficult to estimate an accurate value of battery SOC using only voltage measurements, a solution for this can be a theoretic model which can provide useful information [2].

From all the experiments, it can be concluded that the charging procedure has a big influence on battery performances and state of health [3]. Using those results and taking in consideration also the effect of relaxation time, battery models can be improved in order to obtain better results.

**Acknowledgment:** This work was supported by the strategic grant POSDRU/159/1.5/S/137750, Project “Doctoral and Postdoctoral programs support for increased competitiveness in Exact Sciences research” cofinanced by the European Social Found within the Sectorial Operational Program Human Resources Development 2007 – 2013

***References:***

*[1] Qiu, S. Q., Chen, Z. H., Masrur, M. A., Murphey, Y. L., Battery Hysteresis Modeling for State of Charge Estimation Based on Extended Kalman Filter, 2011 6th IEEE Conference on Industrial Electronics and Applications (Iciea), 148-149*

*[2] Vasebi, A. Partovibakhsh, M. Bathaee, S. M. T. , A novel combined battery model for state-of-charge estimation in lead-acid batteries based on extended Kalman filter for hybrid electric vehicle applications, Journal of Power Sources, Vol. 174, 30-40*

*[3] Eichi, H. R., Chow, M. Y., Modeling and Analysis of Battery Hysteresis Effects, 2012 IEEE Energy Conversion Congress and Exposition (Ecce), 4479-448*