7th International Workshop on
AMORPHOUS AND NANOSTRUCTURED
MAGNETIC MATERIALS
21-24 September 2015, Iaşi, ROMANIA

PROGRAMME AND ABSTRACTS
Organized jointly by:
National Institute of Research and Development for Technical Physics, Iaşi, ROMANIA

&

Institute for Materials Research, Tohoku University, Sendai, JAPAN

Sponsored by:

Ministry of Education and Scientific Research
National Authority for Scientific Research and Innovation

Funded by the Seventh Framework Programme of the European Union

Upgrading the Capacity of NIRDTP to develop Sensing Applications for Biomedicine using Magnetic Nanomaterials and Nanostructured Materials
REGPOT-CT-2013-316194-NANOSENS
Project number: 316194

Office of Naval Research Global (ONRG)
INTERNATIONAL PROGRAMME COMMITTEE

Horia CHIRIAC (CHAIRMAN)  
(National Institute of R&D for Technical Physics, Iasi, Romania)  
Akihiro MAKINO (Co-CHAIRMAN)  
(Institute for Materials Research, Tohoku University, Sendai, Japan)  
George HADJIPANAYIS  
(University of Delaware, USA)  
Ivan SKORVANEK  
(Institute of Experimental Physics, Slovak Academy of Sciences, Kosice, Slovakia)  
Alexandru STANCU  
(Faculty of Physics, “Alexandru Ioan Cuza” University, Iasi, Romania)

LOCAL ORGANIZING COMMITTEE

Horia CHIRIAC (Chairman)  
(National Institute of R&D for Technical Physics, Iasi, Romania)  
Nicoleta LUPU (Programme)  
(National Institute of R&D for Technical Physics, Iasi, Romania)  
Tibor-Adrian ÓVÁRI  
(National Institute of R&D for Technical Physics, Iasi, Romania)  
Firuţa BORZA  
(National Institute of R&D for Technical Physics, Iasi, Romania)  
Maria URSE  
(National Institute of R&D for Technical Physics, Iasi, Romania)  
Georgiana SURDU  
(National Institute of R&D for Technical Physics, Iasi, Romania)  
Cristina-Elena COJOCARU  
(National Institute of R&D for Technical Physics, Iasi, Romania)

Conference Office

ANMM’2015  
National Institute of Research and Development for Technical Physics  
47 Mangeron Blvd., RO-700050 Iasi, Romania  
Phone: +40 232 430680 / Fax: +40 232 231132 / E-mail: anmm2015@phys-iasi.ro  

Location

The 7th Edition of the International Workshop on Amorphous and Nanostructured Magnetic Materials – ANMM’2015, will be held in Iaşi, at Hotel International (5A Palat Street, Iaşi, Romania).
**Venue**

The biennial workshop on Amorphous and Nanostructured Magnetic Materials will be held on September 21-24, 2015 in Iași, Romania.

Known as The Cultural Capital of Romania, Iași is a symbol in Romanian history. Still referred to as The Moldavian Capital, Iași is the seat of Iași County and the main economic centre of the Romanian region of Moldavia.

Home to the first Romanian university and to the first engineering school, it is the second largest university centre in the country and accommodates over 75,000 students in 5 public and 7 private universities.

The social and cultural life revolves around cultural centres and festivals, an array of museums, memorial houses, religious and historical monuments.

**Aims and Objectives**

The workshop addresses to the scientific community working on amorphous and nanostructured magnetic materials research and optimization for specific applications, covering the most recent developments in the field. As a forum for novel ideas, the workshop is intended to promote contact between fundamental research and technological needs for applications.

**Scientific Programme**

The scientific programme of the Workshop includes invited lectures by exceptionally well-qualified speakers to provide a through inside-view in the key fields of the amorphous and nanostructured magnetic materials, with special emphasis on nanomaterials and nanotechnology. Contributed papers, in either oral or poster presentations, are welcomed.

There will be no parallel sessions. The language of the Workshop will be English.

Invited and oral presentations will be assisted by a PC-projector.

**Plenary talks** will be 50 minutes followed by 10 minutes of discussion, **invited talks** will be 30 minutes followed by 10 minutes discussion. **Oral presentations** will be 15 minutes talk followed by 5 minutes discussion.

**Poster presentations** will consist of visual materials about the work included within the accepted paper. The poster board will have the following available dimensions: max. width = 0.90 m, max. height = 1.10 m. The posters will be displayed during the entire conference and one of the authors is requested to be present during the poster session and answer the questions of the fellow participants.

**Topics**

Contributions are welcome on the following topics:
- Preparation and Processing
- Structural characterization
- Magnetic properties
- Applications
- Others

The list is not closed and all the scientists working in other topics related to amorphous and nanostructured materials, are encouraged to submit their contributions to the Workshop.

**NANOSENS Satellite Meeting**

A NANOSENS FP7-REGPOT-2012-2013-1 project (Contract No. 316194) Satellite Meeting will be organized within the ANMM 2015 Conference on 22nd of September 2015, covering the following topics:
- Microsensors for medical applications
- Biosensors based on nanomaterials and nanostructured materials
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<tr>
<td><strong>NANOSENS Satellite Meeting</strong></td>
<td><strong>09:00 - 10:00</strong></td>
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<td><strong>09:00 - 09:40</strong></td>
<td><strong>09:00 - 18:00</strong></td>
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<td><strong>REGISTRATION</strong></td>
<td><strong>12:30 - 18:00</strong></td>
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<tr>
<td><strong>OPENING SESSION</strong></td>
<td><strong>12:45 - 13:00</strong></td>
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<td><strong>COFFEE BREAK</strong></td>
<td><strong>13:00 - 14:00</strong></td>
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<td><strong>COFFEE BREAK</strong></td>
<td><strong>14:00 - 14:40</strong></td>
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<tr>
<td><strong>COFFEE BREAK</strong></td>
<td><strong>15:50 - 16:30</strong></td>
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<td><strong>COFFEE BREAK</strong></td>
<td><strong>16:30 - 17:30</strong></td>
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<td><strong>WELCOME PARTY</strong></td>
<td><strong>18:00 - 21:00</strong></td>
<td><strong>12:50 - 13:30</strong></td>
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<td><strong>CONFERENCE DINNER</strong></td>
<td><strong>20:00 - 22:00</strong></td>
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**Excursion (optional)**
# ANMM’ 2015

## Technical Program

### MONDAY

**September 21, 2015**

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
<th>Speaker/Authors</th>
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<tr>
<td>12:45 – 13:00</td>
<td>OPENING SESSION</td>
<td>Chair: Manuel VÁZQUEZ</td>
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| 13:00 – 14:00 | **PL.1** 2015 IEEE Magnetics Distinguished Lecturer | R.P. COWBURN  
*Department of Physics, Cavendish Laboratory, University of Cambridge, Cambridge, UK*  
**PERPENDICULAR MAGNETIC ANISOTROPY: FROM ULTRALOW POWER SPINTRONICS TO CANCER THERAPY** |
| 14:00 – 14:40 | I.1                             | S. CARDOSO, J. VALADEIRO, M. SILVA, J. AMARAL, J. GASPAR, R. FERREIRA, P.P. FREITAS  
*INESC-MN, Lisbon, Portugal*  
*Instituto Superior Técnico (IST), Lisbon, Portugal*  
*INL – International Iberian Nanotechnology Laboratory, Braga*  
**MAGNETORESISTIVE SENSORS WITH PicoTESLA SENSITIVITY FOR BIOMEDICAL APPLICATIONS** |
| 14:40 – 15:10 | COFFEE BREAK                    |                                                                                |
| 15:10 – 15:50 | I.2                             | T. STOBIECKI  
*Department of Electronics, AGH University of Science and Technology, Krakow, Poland*  
**MAGNETIC TUNNEL JUNCTIONS FOR SPINTRONICS APPLICATIONS** |
*National Institute of R&D for Technical Physics, 47 Mangeron Boulevard, Iasi, RO-700050, Romania*  
*ECE Department, University of Minnesota, Minneapolis, USA*  
**ANOMALOUS ELECTRODEPOSITION of NiFe AND CoFe NANOWIRES AND CONTROL OF COMPOSITION AND MAGNETIC PROPERTIES** |
| 16:30 – 17:30 | **PL.2** 2015 IEEE Magnetics Distinguished Lecturer | L. SCHULTZ  
*Institute of Metallic Materials, Leibniz Institute of Solid State and Materials Research (IFW) Dresden, Germany*  
*Institute of Materials Science, TU Dresden; evico GmbH Dresden, Germany*  
**INTERACTION OF FERROMAGNETIC AND SUPERCONDUCTING PERMANENT MAGNETS: SUPERCONDUCTING LEVITATION** |
| 18:00 – 21:00 | WELCOME PARTY                   |                                                                                |
### TUESDAY
September 22, 2015

**NANOSENS Satellite Meeting**

**Chair:** Hariharan SRIKANTH

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<th>Session</th>
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<th>Speaker(s)</th>
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<tr>
<td>9:00 – 10:00</td>
<td>PL.3</td>
<td>2015 IEEE MAGNETICS DISTINGUISHED LECTURER</td>
<td>B. STADLER, University of Minnesota, Associate Professor, Electrical and Computer Engineering, Minneapolis, USA</td>
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<tr>
<td></td>
<td></td>
<td>MAGNETIC NANOWIRES: REVOLUTIONIZING HARD DRIVES, RAM, AND CANCER TREATMENT</td>
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<td>10:00 – 10:40</td>
<td>I.4</td>
<td>SYNTHESIS OF SUBMICRON R-Co AND R-Fe-B PARTICLES BY THE MECHANOCHEMICAL PROCESS</td>
<td>A. GAGAY1, O. KOYLU-ALKAN1, J. M. BARANDIARAN2,3, D. SALAZAR2, G. C. HADJIPANAYIS1</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1Department of Physics and Astronomy, University of Delaware, Newark, DE, USA</td>
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<td></td>
<td>2BCMaterials, Technology Park of Biscay E-48160 Derio, Spain</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>3Dept. Electricity &amp; Electronics, Univ. Basque Country (UPV/EHU), Bilbao, Spain</td>
</tr>
<tr>
<td>10:40 – 11:20</td>
<td>I.5</td>
<td>INTEGRATION AND APPLICATIONS OF HIGH GRADIENT MAGNETIC SEPARATORS IN LAB-ON-A-CHIP DEVICES</td>
<td>L. CLIME 1, L. MALIC1, D. BRASSARD1, X. ZHANG1, N. CORNEAU2, T. VERES1</td>
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<td></td>
<td></td>
<td></td>
<td>1Life Sciences Division, National Research Council of Canada, Boucherville, QC, CANADA</td>
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<td></td>
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<td>2Bureau of Microbial Hazards, Health Canada, Ottawa, ON, CANADA</td>
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<td>11:20 – 11:50</td>
<td>COFFEE BREAK</td>
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<td>11:50 – 12:30</td>
<td>I.6</td>
<td>DEVELOPMENT OF pT RESOLUTION MAGNETOIMPEDANCE SENSOR TOWARDS MEDICAL USE</td>
<td>O. KAZAKOV A, National Physical Laboratory, Teddington, UK</td>
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<tr>
<td>12:30 – 13:10</td>
<td>I.7</td>
<td>DEVELOPMENT OF FUNCTIONAL MAGNETIC NANOPARTICLES FOR TUNABLE RF AND BIOMEDICAL APPLICATIONS</td>
<td>T. UCHIYAMA1, S. NAKAYAMA2, H. SRIKANTH, Department of Physics, University of South Florida, Tampa, Florida, USA</td>
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<td>13:10 – 15:00</td>
<td>LUNCH</td>
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<td>15:00 – 15:40</td>
<td>I.8</td>
<td>FUNCTIONAL MAGNETIC NANOPARTICLES FOR TUNABLE RF AND BIOMEDICAL APPLICATIONS</td>
<td>H. SRIKANTH, Department of Physics, University of South Florida, Tampa, Florida, USA</td>
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### BAIA

**Babes-Bolyai University, Faculty of Physic and Interdisciplinary Research Institute in Bio-Nano-Science, Cluj-Napoca, ROMANIA**  
**PLASMONIC NANOPARTICLES WITH MULTIPLE FUNCTIONALITIES - FROM BIOSENSING TO CELL IMAGING AND THERAPY**

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<th>Time</th>
<th>Session</th>
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<th>Authors</th>
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<tr>
<td>16:20 – 17:00</td>
<td><strong>I.10</strong></td>
<td>J. PARK¹, M. REDDY², E. ESTRINE², B. STADLER³, A. FLATAU¹</td>
<td>¹Department of Aerospace Engineering, University of Maryland, College Park, USA</td>
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<td>²Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, USA</td>
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<td>MAGNETOSTRICTIVE MULTILAYERED Fe-Ga/Cu NANOWIRE</td>
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<td>17:00 – 17:30</td>
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<td><strong>COFFE BREAK</strong></td>
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<td>17:30 – 18:10</td>
<td><strong>I.11</strong></td>
<td>D.A. ALLWOOD¹, J. WOOD¹, C. I. OSEGHALE², O. CESPEDES³, M. GRELL⁴</td>
<td>¹Department Materials Science and Engineering, University of Sheffield, Sheffield, UK</td>
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<td>²Department Chemical &amp; Biological Engineering, University of Sheffield, Sheffield, UK</td>
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<td>³Department of Physics &amp; Astronomy, University of Leeds, Leeds, UK</td>
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<td>⁴Department of Physics &amp; Astronomy, University of Sheffield, Sheffield, UK</td>
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<td>VOLTAGE CONTROL OF MAGNETIC PROPERTIES OF SOFT MAGNETIC FILMS</td>
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<tr>
<td>18:10 – 18:50</td>
<td><strong>I.12</strong></td>
<td>S. McVITIE, M. KRAJNAK, D. McGROUTHER</td>
<td>Scottish Universities Physics Alliance, School of Physics and Astronomy, University of Glasgow, Glasgow, UK</td>
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<td>LORENTZ MICROSCOPY OF NANOSTRUCTURED MAGNETIC MATERIALS</td>
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<td>18:50 - 20:00</td>
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<td><strong>POSTER SESSION</strong></td>
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<td>20:00 - 22:00</td>
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<td><strong>DINNER</strong></td>
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### WEDNESDAY
September 23, 2015

**Chair:** Dan ALLWOOD

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<th>Time</th>
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<tr>
<td>9:00 – 9:40</td>
<td>I.13</td>
<td>Enhanced of the Spin Seebeck Effect in Magnetic Multilayers: Role of the Fe3O4/Pt Interfaces</td>
<td>R. Ramos1,2,3, T. Kikkawa1,4, M. H. Aguirre1,5,6, I. Lucas1,7, A. Anadón1,5, T. Oyake5, K. Uchida4,9, H. Adachi5,10, J. Shiomi8, P. A. Algarabel5,11, L. Morellón1,3, S. Maekawa3,10, E. Saitoh2,3,4,10, M. R. Ibarra1,5,6</td>
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<td>11:00 – 11:30</td>
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<td>COFFEE BREAK</td>
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<td>11:30 – 12:10</td>
<td>I.16</td>
<td>Interfacial Contributions to Damping and Spin-Mixing Conductance in Magnetic/Non-Magnetic Bilayer Films</td>
<td>D. Atkinson1, M. Tokac1, A. Ganguly2, J. A. King1, S. Azzawi1, S. A. Bunyae1, G. N. Kakazev1, D. S. Schmoool4, J. Sinha2, A. Barman2, A.T. Hindmarsh1</td>
</tr>
</tbody>
</table>

1Institute of Nanoscience - Aragón, University of Zaragoza, Zaragoza, Spain
2WPI Advanced Institute for Materials Research, Tohoku University, Sendai, Japan
3Spin Quantum Rectification Project, ERATO, Japan Science and Technology Agency, Sendai, Japan
4Institute for Materials Research, Tohoku University, Sendai, Japan
5Department of Physics Condensed Matter, University of Zaragoza, Zaragoza, Spain
6Laboratory of Advanced Microscopy, University of Zaragoza, Zaragoza, Spain
7ARAID Foundation, Zaragoza, Spain
8Department of Mechanical Engineering, University of Tokyo, Tokyo, Japan
9PRESTO, Japan Science and Technology Agency, Saitama, Japan
10Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Japan
11Institute Material Science Aragón, CSIC - University Zaragoza, Zaragoza, Spain
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<th>Time</th>
<th>Speaker/Author</th>
<th>Institute/University</th>
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<tr>
<td>12:50 – 13:30</td>
<td><strong>MAGNETIZATION REVERSAL OF Co AND Co-BASED CYLINDRICAL NANOWIRES</strong></td>
<td>I.18 A. STANCU, Alexandru Ioan Cuza University, Faculty of Physics, Iasi, ROMANIA</td>
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<td>FORC DIAGRAM METHOD AS QUANTITATIVE MAGNETIC CHARACTERIZATION TOOL</td>
<td>FORC DIAGRAM METHOD AS QUANTITATIVE MAGNETIC CHARACTERIZATION TOOL</td>
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<td>13:30 – 15:00</td>
<td><strong>LUNCH</strong></td>
<td>Chair: Ivan SKORVANEK</td>
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<tr>
<td>15:00 – 15:40</td>
<td><strong>HIGH FREQUENCY MAGNETOIMPEDANCE IN Co-BASED AMORPHOUS RIBBONS</strong></td>
<td>I.19 A. TALAAT¹, M. IPATOV¹, V. ZHUKOVA¹, V.M. PRIDA², B. HERNANDO², A. ZHUKOV³, J. GONZÁLEZ³</td>
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<td>¹Department Materials Physics, University of the Basque Country, San Sebastian, SPAIN</td>
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<td>²Department Physics, Faculty of Sciences, University of Oviedo, Oviedo, SPAIN</td>
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<td>³Department Materials Physics, University of the Basque Country, San Sebastian, SPAIN and IHERBASQUE Foundation, Bilbao, SPAIN</td>
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<tr>
<td>15:40 – 16:00</td>
<td><strong>DYNAMIC FORC MEASUREMENTS IN MAGNETIC WIRES</strong></td>
<td>O.1 D. CIMPOESU, I. DUMITRU, A. STANCU</td>
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<td>Department of Physics, “Alexandru Ioan Cuza” University of Iasi, Iasi, ROMANIA</td>
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<td>16:00 – 16:40</td>
<td><strong>ENGINEERING OF MAGNETIC PROPERTIES AND GIANT MAGNETOIMPEDANCE EFFECT OF AMORPHOUS AND NANOCRYSTALLINE MICROWIRES</strong></td>
<td>I.20 A. ZHUKOV¹,²,³, M. IPATOV¹,², A. TALAAT¹,², J.M. BLANCO² M. CHURYUKANOVA⁴, J. GONZALEZ⁴, V. ZHUKOVA¹,²</td>
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<td>¹Dpto. de Fís. Mater., Basque Country University, San Sebastián, SPAIN</td>
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<td>²Dpto. de Física Aplicada, EUPDS, Basque Country University San Sebastian, SPAIN</td>
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<td>³IKERBASQUE, Basque Foundation for Science, Bilbao, SPAIN</td>
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<td>⁴National University of Science and Technology «MISIS», Moscow, RUSSIA</td>
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<td>16:40 – 17:10</td>
<td><strong>COFFEE BREAK</strong></td>
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<td>17:10 – 17:50</td>
<td><strong>APPLICATION OF BISTABLE MICROWIRES AS MICROSENSORS</strong></td>
<td>I.21 R. VARGA¹,², R. SABOL², P. KLEIN</td>
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<td>¹Inst. Phys., Fac. Sci., UPJS, Kosice, SLOVAKIA</td>
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<td>²RVmagnetics s.r.o., Kosice, SLOVAKIA</td>
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<td>17:50 – 18:30</td>
<td><strong>LOW FREQUENCY NOISE IN GIANT MAGNETOIMPEDANCE OVERVIEW &amp; PERSPECTIVES</strong></td>
<td>I.22 C. DOLABDJIAN¹, E. PORTALIER¹, B. DUFAY¹, N. TEYSSEDOU², D. SEDDAOU², A. YELON², D. MENARD²</td>
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<td>¹Normandie Univ., FRANCE; UCBN, GREYC, Caen, FRANCE; CNRS, UMR 6072, Caen, FRANCE</td>
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<td>²Department of Engineering Physics, Polytechnique Montréal, Montreal, CANADA</td>
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<td>20:00 - 23:00</td>
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10:00 – 11:00
1.25
N. NISHIYAMA, K. TAKENAKA, A. D SETYAWAN, P. SHARMA, A. MAKINO
Research and Development Center for Ultra High Efficiency Nano-crystalline Soft Magnetic Materials, Institute for Materials Research, Tohoku University, Sendai, JAPAN
ON THE CUTTING EDGE PROCESSING FOR COMMERCIALIZATION OF SOFT-MAGNETIC ALLOY “NANOMET®”

11:00 – 11:30
COFFEE BREAK

11:30 – 12:10
1.26
L. PADURARIU, L. CURECHERIU, C. CIOMAGA, L. MITOSERIU
Department of Physics, Alexandru Ioan Cuza University, Iasi, ROMANIA
TAYLORING PROPERTIES IN FERROELECTRIC-BASED COMPOSITES BY LOCAL FIELD ENGINEERING

12:10 – 12:50
1.27
I. ŠKORVÁNEK1, J. MARCIN1, L. GONZÁLEZ-LEGARRETA1, F. ANDREJKA1, M. VARGA1, I. MAŤKO2, P. ŠVEC2
1Institute of Experimental Physics, Slovak Academy of Sciences, Košice, SLOVAKIA
2Institute of Physics, Slovak Academy of Sciences, Bratislava, SLOVAKIA
AMORPHOUS AND NANOCRYSTALLINE BILAYER RIBBONS FOR MAGNETIC SENSORS

12:50 – 13:30
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P. GORRIA
Department of Physics & IUTA, EPI, University of Oviedo, Gijón, SPAIN
MAGNETO-VOLUME ANOMALIES AND INVAR EFFECT IN AMORPHOUS AND NANOCRYSTALLINE Fe-RICH ALLOYS

13:30 – 14:10
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J.A. DE TORO1, D.P. MARQUES1, P. MUÑIZ1, V. SKUMRYEV2,3, J. SORT2,3, D. GIVORD4,5,6, J. NOGUÉS3,7
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<td>N. IFTIMIE¹, D. FAKTOROVA², M. PAPEŽOVÁ², R. STEIGMANN¹, A. SAVIN¹</td>
<td>National Institute of R&amp;D for Technical Physics, Iasi, ROMANIA; Department of Measurement and Applied Electrical Engineering, University of Žilina, Žilina, SLOVAK REPUBLIC; Faculty of Physics, Alexandru Ioan Cuza University, Iasi, ROMANIA (study of ZnO thin film as metallic strip grating structure for sensitive cholesteric biosensor)</td>
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<td>Dielectrics, ferroelectrics &amp; Multiferroics Group, Dept. of Physics, “Al. I. Cuza” University, Iasi, ROMANIA; CNR-ISTEC, Faenza, ITALY (The role of pore interconnectivity on the electrical properties of PZTN porous ceramics)</td>
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<td>Faculty of Physics, Alexandru Ioan Cuza University, Iasi, ROMANIA; Andhra University, Department of Physics, INDIA (Pulsed laser deposition of Cu doped cobalt ferrite thin films)</td>
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<td>Department of Inorganic Chemistry; Faculty of Chemistry, “Al. I. Cuza” University, Iasi, ROMANIA; Department of Physics and Carpath Center, Faculty of Physics, “Al. I. Cuza” University, Iasi, ROMANIA; Department of Physical Chemistry, University of Saarland, Saarbrucken, GERMANY (Raw earth doped CO ferrite for technological applications)</td>
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Most thin magnetic films have their magnetization lying in the plane of the film because of shape anisotropy. In recent years there has been a resurgence of interest in thin magnetic films which exhibit a magnetization easy axis along the surface normal due to so-called Perpendicular Magnetic Anisotropy (PMA). PMA has its origins in the symmetry breaking which occurs at surfaces and interfaces and can be strong enough to dominate the magnetic properties of some material systems. In this talk I explain the physics of such materials and show how the magnetic properties associated with PMA are often very well suited to applications. I show three different examples of real and potential applications of PMA materials: ultralow power STT-MRAM memory devices for green computing, 3-dimensional magnetic logic structures and a novel cancer therapy.

References
INTERACTION OF FERROMAGNETIC AND SUPERCONDUCTING PERMANENT MAGNETS: SUPERCONDUCTING LEVITATION

L. Schultz*

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New means of urban transportation and logistics will become realistic with superconducting magnetic bearings using bulk high-temperature superconductors. The advantage of superconducting magnetic levitation is that it is passively stable without any electronic control, but with attracting and repelling forces to suspend a vehicle pendant or standing upright from zero to high speed. These are perfect conditions for a rail-bound, individual transport with cabins for 4 to 5 passengers, requested call by call. They will levitate without noise over a track made of rare-earth permanent magnets, saving energy and travel time. A big step forward in this vision has been made in Dresden. The world largest research and test facility for transport systems using bulk high-temperature superconductor material in the levitation and guidance system, in combination with a permanent magnet track, was put into operation. A vehicle for 2 passengers, equipped with linear drive propulsion, a noncontact energy supply, a second braking system, and various test and measurement systems is running on an 80 m long, oval driveway. In the presentation, the principle of superconducting levitation by flux pinning in high-temperature superconductors will be described and experimentally demonstrated with different model railway systems. Based on this, an overview of the SupraTrans II research facility and future directions of superconductivity-based magnetic levitation and bearing for automation technology, transportation, and medical treatment under enhanced gravity will be given.

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MAGNETIC NANOWIRES: REVOLUTIONIZING HARD DRIVES, RAM, AND CANCER TREATMENT

B. Stadler

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Magnetic nanowires can be bits, sensors, heads, artificial cilia, sensors, and nano-bots. These 7- to 200-nm diameter nanowires can easily have lengths 10,000x their diameters. They are usually layered with magnetic (Co, Fe, FeGa, FeNi, Ni) and non-magnetic metals as required by each application. This talk will reveal synthesis secrets for nm-control of layer thicknesses, which has enabled studies of magnetization reversal, magneto-elasticity, giant magnetoresistance (GMR), and spin transfer torque (STT) switching. Ten-nm diameter trilayers of \([\text{Co}(15\text{nm})/\text{Cu}(5\text{nm})/\text{Co}(10\text{nm})]\) have met or surpassed all of the criterion for the world’s smallest read heads with 30 \(\Omega\) resistance and 19% magnetoresistance. High magnetoresistance is also possible in other multilayered nanowires that exhibit excellent properties for multilevel nonvolatile random access memory (RAM). Outside their oxide templates, nanowires that are functionalized and incubated with cells are self-dispersing. Careful magnetic design of these “nano-bots” enables external steering, nano-barcode identification, and several modes of therapy.
I.1 MAGNETORESISTIVE SENSORS WITH PicoTESLA SENSITIVITY FOR BIOMEDICAL APPLICATIONS

S. Cardoso1,2*, J. Valadeiro1, M. Silva1, J. Amaral1, J. Gaspar3, R. Ferreira3 and P.P. Freitas1,3

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Measuring magnetic fields lower than the Earth field has been a source of extensive research and enormous technological progress in the past years. Many solutions have been provided so far, with SQUIDS and fluxgates reaching the lower detectivity levels in the femtoTesla range. However, these options are not competitive when portability, low cost and small size are needed. Therefore, magnetoresistive sensors are an excellent alternative, despite their lower field detectivity (typically nTesla range).

In this work, we describe several strategies developed in the past years to extend further the limits of sensitivity of magnetoresistive sensors, at room temperature. Some key aspects while designing these sensors include the size (in the micrometer range), magnetic field detectivity (limited by the noise), and compact integration or portability issues. Here we show several examples where the sensors are optimized for few picoTesla detection, through proper optimization of the materials (spinvalves and magnetic tunnel junctions), geometry (single sensors with magnetic flux concentrators, or large arrays of sensors) or tuning the operation frequency above the 1/f corner using MEMS modulators. The advantages of thin films allied to micro-nanofabrication technologies are successfully used towards full integration of sensors in flexible substrates (polyamide), or sharp microprobes. The intrinsic sensor noise is of major relevance to determine the ultimate detection level, therefore strategies to reduce noise while maintaining the signal levels are discussed. Some success cases will be presented, showing the very good performance of high sensitivity magnetoresistive sensors in biomedical applications, where biocompatible issues are additional difficulties that need to be solved.

References

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MAGNETIC TUNNEL JUNCTIONS FOR SPINTRONICS APPLICATIONS

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High density spin-polarized current flowing through magnetic tunnel junction (MTJ) nanopillars produces a torque on local magnetization via the Spin Transfer Torque (STT) effect [1]. This effect can induced precession of magnetization (microwave spin-torque-oscillator) [2] or switch the magnetization of one of the ferromagnetic layer (which is used in random access memory, STT-RAM). The STT-RAM is characterized by a low power consumption and better scalability over conventional magnetic-filed-driven RAM. Crucial issues of STT in MTJs are a reduction of the critical current density, which is possible, for example, by interfacial perpendicular anisotropy of ferromagnetic electrodes [3] and optimizing the thickness of MgO tunnel barrier [4].

In addition, the application of RF current to MTJ results in a DC voltage across the device, when the frequency is in resonance with resistance oscillations arising from the STT, this phenomena is called spin diode effect [5, 6]. Such spin-torque ferromagnetic resonance (ST-FMR) excitation in a MTJ nanopillar, as well as an inverse effect, i.e., generation of the RF signal, provide potential application in the telecommunications technology.

Finally, new solutions of the spintronics devices based on voltage-controlled magnetic anisotropy [7,8] or spin-orbit torques, will be also discussed in this presentation.

The project is supported by grants of the Polish NSC HARMONIA 2012/04/M/ST7/00799 and Swiss Contribution by NANOSPIN PSPB-045/2010.

References

ANOMALOUS ELECTRODEPOSITION OF NiFe AND CoFe NANOWIRES AND CONTROL OF COMPOSITION AND MAGNETIC PROPERTIES

O.G. Dragoș-Pînzaru¹, A. Ghemeș, H. Chiriac¹, N. Lupu¹, M. Grigoraș¹, B. Stadler² and I. Tabakovic¹,²

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The electrodeposition of NiFe and CoFe nanowires—with the length of ~3.0 μm and diameter of 35 and 200 nm—into the porous AAO templates was carried out on the sputtered Au-back electrode (300 nm) using sulfate/chloride electrolyte solution and pulsed deposition. The electrode area of Au-AAO template, determined by reversible one-electrone transfer oxidation of K₄Fe(CN)₆, used as a probe in CV, was found to be 2.4 times larger than Au-thin film electrode.

Electrodeposition of NiFe and CoFe alloys exhibits phenomenon known as anomalous codeposition, which is characterized by anomaly that less noble metal, i.e. Fe, deposits preferentially. The extent of anomalous codeposition is dependent on solution conditions (pH, additive, concentration of ions etc.) electrode material, and deposition method (controled potential, current density, or pulse deposition). The observed anomalous codeposition phenomena as a “volcano” type curve—with a maximum in Fe-content in depending on applied potential—was explained earlier [1] through the limited mass transport of Fe⁺ ions after the peak. This explanation is partially correct, but not complete. The alternative explanation through the surface concentration of H⁺ dependent adsorption/desorption of FeOH⁺ and NiOH⁺ electroactive species was proposed recently [2]. The change in NiFe or CoFe alloy composition results in change of: stress, magnetostriction, crystal structure, and grain size [3]. Thereby, the resulting compositional changes profoundly influence the magnetic behavior of NiFe and CoFe materials.

The results of pulse deposition of NiFe and CoFe nanowires with controlled composition, length, and uniformity will be presented. The process of magnetization reversal in NiFe nanowires arrays was investigated. We have found two sets of magnetic behavior of NiFe nanowires depending on composition (Ni₉₂Fe₈ and Ni₇₉Fe₂₁ vs. Ni₆₀Fe₄₀, Ni₅₆Fe₄₄, and Ni₄₅Fe₅₅). The results on electrodeposition nanowires with targeted Co₃₅Fe₆₅ composition together with their magnetic properties, will be presented.

Financial support from the European Commission FP7-REGPOT-2012-2013-1, Grant Agreement No. 316194 (NANOSENS) is highly acknowledged.

References
SYNTHESIS OF SUBMICRON R-Co AND R-Fe-B PARTICLES BY THE MECHANOCHEMICAL PROCESS

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In this presentation, we will summarize our work for the past couple of years to synthesize magnetically hard RCo₅ (R= Pr, Sm, Y) and R₂Fe₁₄B (R=Dy, Nd, Pr) particles by the mechanochemical process. The aim of this study is to prepare submicron size particles of the high anisotropy/magnetization RCo₅ and R₂Fe₁₄B compounds, study their intrinsic and hard magnetic properties as a function of particle size and then use them to make nanocomposite magnets via the core/shell method. In RCo₅, particles with a few hundred nanometers were obtained with coercivities of 20.6 kOe in YCo₅, 19.1 kOe in PrCo₅ and 41.5 kOe in SmCo₅. In the R=Nd system, a coercivity of 12 kOe was obtained in 100 nm particles, which was reduced to below 1 kOe after washing because of hydrogen absorption; upon removal of the hydrogen the coercivity increased to 3.3 kOe. The Dy₂Fe₁₄B showed a higher coercivity with a value of 26 kOe which dropped to 16 kOe after washing. High field magnetization measurements are employed to measure the magnetocrystalline anisotropy of these particles at different temperatures using the law of approach to saturation. These data are compared with the temperature dependence of coercivity to understand the origin of magnetic hardening in these particles. Also, the effect of particle size on the intrinsic and hard properties will be presented and discussed along with our most recent efforts to prepare coated particles with a core/shell structure.

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INTEGRATION AND APPLICATIONS OF HIGH GRADIENT MAGNETIC SEPARATORS IN LAB-ON-A-CHIP DEVICES

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Microfluidics and lab-on-a-chip (LOC) technologies offer tremendous opportunities for analytical chemistry and biological assays due to numerous advantages such as low reagent consumption, fast reaction time, high reaction efficiencies and large surface-to-volume ratio. Of a fundamental importance in clinical diagnostic and biological research is the initial sample preparation step, where capture and separation of target cells, cell resuspension and cell lysis are generally required.1 Among the different types of force fields of potential interest for implementing such operations, the magnetic ones play an important role since they are generally not affected by surface charges, pH, ionic concentration or temperature.2

The presentation will begin with a short review of the state-of-the-art and recent developments in microfluidics and LOC platforms along with related materials and microfabrication technologies. Then some examples of integrated micro-electromechanical systems (MEMS) such as miniature electromagnets, magnetic micro-stirrers and high gradient magnetic separators (HGMS) will be presented and discussed. A low-cost fabrication process for integrated microfluidic HGMS devices and their applications in rapid detection of foodborne pathogens such as Listeria monocytogenes is investigated both theoretically and experimentally. More specifically, arrays of magnetic micropillars are integrated in microfluidic devices and used to capture and release bacteria coated with immunomagnetic nanoparticles. Special configurations enabling efficient capture and prompt release are highlighted as well.3 The suitability of the system for food safety applications is demonstrated in terms of concentration and capture efficiency.

References
Dynamics of domain walls (DWs) in nanodevices made of soft magnetic materials has been proven to be reproducible and highly sensitive to external magnetic fields [1, 2]. Here, we apply magnetotransport measurements, magnetic imaging and micromagnetic modelling to measure, analyze and predict evolution of magnetic DWs in permalloy nanodevices, down to 75-nm wide. The complete range of magnetotransport measurements is compiled into DW magnetoresistance state space maps, which are used to identify highly reproducible transitions between domain states. The analyses allows to determine the optimal working parameters, such as the minimal field required to switch the whole device or the most appropriate angle for maximal separation of the pinning/depinning fields. It is envisaged that the complete state space maps can be used to predict evolution of nanodevices in magnetic field without a need of electrical measurements and for reliable initialization of magnetic devices into a well-specified state.

Using a well-defined state space maps, we further investigate the effect of single MB on DW dynamics. By measuring the anisotropic magnetoresistance and analysing the change in the depinning field of DWs trapped in magnetic nanodevices, it is possible to detect external small magnetic moments, e.g. originating from a MB [3, 4]. To study the sensitivity of DW nanosensors in detail, we present scanning gate microscopy studies of the interaction between a MB and DW nanosensor when the magnetoresistance of the DW nanodevice is measured with respect to the 3D position of the scanning probe with an attached MB. We demonstrate the stray-field mediated interaction between the MB and the DW, which appears as the change in the AMR signal measured in the close proximity of the probe to the DW position. Using this method, we reconstruct a 3D sensitivity map of the device, which provides a route for characterization of the device performance to non-uniform magnetic fields and promote their use as nanosensors in metrological and biomedical applications.

References

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DEVELOPMENT OF pT RESOLUTION MAGNETOIMPEDANCE SENSOR TOWARDS MEDICAL USE

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Magnetization dynamics by pulse excitation in amorphous wire is limited in the surface layer by skin effect due to magnetic rotation. We have constituted highly sensitive linear micro magnetic field sensors utilizing Off-diagonal Magneto-Impedance (MI) effect. Recently we have succeeded in producing pico-Tesla (10^{-8}Oe) resolution MI sensors due to ultra-low intrinsic magnetic noise of amorphous wire 1).

Superconducting quantum interference device (SQUID) have ultrasensitive, which have been utilized for bio-magnetic signals. For example, magnetocardiography (MCG) is a noninvasive technology that measures the magnetic field of the heart. It was developed for general-purpose use as a noninvasive, noncontact diagnostic tool for detecting obstructive coronary artery disease (CAD), and especially for detecting cardiac ischemia. We have tried to measure MCG signal using MI gradiometer. Fig.1 shows magnetic signal along with ECG sensor at 4 cm left the pit of the stomach. The subject was a man. A distance between from sensor head to a body surface is about 3 mm. The magnetic signal shown was averaged for ten times. The magnetic wave form was confirmed that is similar to the ECG wave form. By contacting sensor head to on shirts we recorded cardiac magnetic field of premature ventricular contraction.

The SQUID has been also used to measure human brain. The application of brain signals detection was developed in various fields. In medicine area, it could be implemented in such as brain injury inspection, diagnosis of neocortical epilepsy, telemedicine or cognitive functions research. And with advances in sensing technology, neuroprosthetics applications based on brain computer interfacing (BCI) could be improved and used to restore damaged hearing, sight or movement.

Event-related potentials (ERP) is one of the important biosignals of the brain which has a wide application in examining brain activity and cognitive functions. The P300 (or P3) is one of the ERP components which normally elicited in the process of making decisions. We have recorded of the waveforms of mean P300 magnetic field in occipital region elicited by audio stimuli, for several subjects. Brainwave measurement results of MI sensor will be presented and the results will be compared to SQUID's or EEG's results.

![Figure 1](image_url)

Fig.1. Voltage from the heart and Signal on the body surface at 4cm on the left of the pit of the stomach.

References

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FUNCTIONAL MAGNETIC NANOPARTICLES FOR TUNABLE RF AND BIOMEDICAL APPLICATIONS

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Magnetic nanoparticles are considered fundamental building blocks for spintronic devices. Surface functionalization and shape anisotropy of nanoparticles are key factors that need to be precisely controlled. Dispersion of ferrite nanoparticles into a polymer matrix creates a new class of low-cost, lightweight nanocomposite materials with enhanced and tunable microwave properties for use in high-performance RF and microwave devices, such as integrated high-Q inductors, scanning antennas [1]. A challenging issue in polymer nanocomposites is particle agglomeration into non-uniform clusters during the processing stages of thick films. Our experiments have led to overcoming this limitation through surface functionalization. We have also fabricated high-aspect ratio magnetic nanotubes with excellent tunable microwave properties [2,3]. For nanomedicine and biosensing applications, a combination of these functionalized hybrid nanoparticles with giant magnetoimpedance (GMI) based sensing elements offer a promising approach for highly sensitive detection of cancer cells and biomolecules [4,5]. Strategies that go beyond simple spherical structures such as core-shell nanoparticle, nanowire, nanotube geometries can be exploited to increase saturation magnetization, anisotropy, exchange coupling and lead to enhanced heating efficiency in magnetic hyperthermia treatment of cancer cells. Overall we will present new results on functional magnetic nanostructures and their potential in emerging electromagnetic and biomedical applications.

References


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PLASMONIC NANOPLATFORMS WITH MULTIPLE FUNCTIONALITIES - FROM BIOSENSING TO CELL IMAGING AND THERAPY


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In this contribution we present our recent results in fabrication of several examples of plasmonic-based nanoplatforms endowed with biosensing, therapeutic and imaging functionalities for applications in nanomedicine. The first route of fabrication involves chemical procedures to control the size and shape (rods, prisms, stars-shaped) of gold or silver nanoparticles as well their stability by coating with various biopolymer as chitosan, poly(ethylene) glycol, pluronic, gelatine (see representative pictures in Fig. 1, first row). A second route involves self- or template-assisted assembling methods to fabricate a large variety of solid plasmonic substrates (see representative pictures in Figure 1, second row).

For instance the specific configuration of as fabricated gols nano-assemblies (Fig 1 a) allows a small population of Methylene Blue molecules to be located in very small areas between the aggregated nanoparticles (“hot spots”) to provide SERRS signal while the other population remains captured in Pluronic coating and preserves both its fluorescence signal and singlet-oxygen generation capability [1]. The applicability of chitosan-coated triangular silver nanoparticles (Fig. 1 b) is demonstrated as dual-modal sensors via surface plasmon resonance (LSPR) and surface-enhanced Raman scattering (SERS), both in solution and on solid substrate [2].

References

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Iron-gallium alloy (Galfenol, Fe$_{100-x}$Ga$_x$, 10 $\leq$ x $\leq$ 25 at. %) has been extensively investigated due to its unique combination of magnetostrictive properties (~400 ppm) and useful mechanical properties (high elastic modulus and tensile strength) [1] and thus is being considered for use in next generation sensors, actuators and even biological applications. In this research, Fe-Ga nanowires (NWs) were fabricated in alternating multilayered structures with Fe-Ga and Cu to minimize the relative contribution of shape anisotropy to magnetic domain alignment and variety of characterizations on magnetic and magnetostrictive properties were performed. Magnetic force microscopy (MFM) was used to show the magnetization process, magnetization rotation and hysteresis of individual multilayered NW. [2], [3] Recently developed characterization method showed the measurement of the dimensions of an individual NW as it buckles with induced magnetization and when 1000 Oe was applied to the NW, a magnetostriction value of ~100 ppm was estimated in the Fe-Ga segments. Lastly, we have experimentally demonstrated a proof of concept of the pressure sensing capability of the Fe-Ga/Cu NW that utilizes magneto-mechanical transduction as a sensing mechanism. The pressure sensing was performed with a vertically aligned multilayered Fe-Ga/Cu NW array in conjunction with a giant magnetoresistance (GMR) magnetic field sensor. The NW array is pressed against the GMR surface to cause the NWs deflected which induces rotation of magnetization in the NWs. The compressed NWs on the GMR sensor changed resistance value of GMR circuit and the changes increased as the NW deflection increased to the force applied to the NW-GMR system via magneto-mechanical transduction.

Fig. (Left) MFM images of magnetization rotation with external field (right) Schematic drawing of Fe-Ga/Cu nanowire based pressure sensing device.

**References**


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We have found that using an ionic liquid system to mediate applied voltage to permalloy (Ni$_{80}$Fe$_{20}$) thin films results in control of magnetic properties. Thermally evaporated permalloy films on undoped silicon substrates were gated with the ionic liquid 1-Ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide (EMITSFI). An indium-tin-oxide (ITO) coated glass slide was placed over this arrangement to allow voltages $V$ to be applied by contacting the Ni$_{80}$Fe$_{20}$ and ITO layers (Fig. 1) while performing magneto-optical Kerr effect (MOKE) magnetometry of the in-plane magnetization. The coercivity of 5 nm thick films decreases significantly as a function of applied voltage and time. The coercivity changes can be significant, with 85% decrease (3.2 Oe to 0.5 Oe) observed with a +4V potential after several minutes. A degree of recovery was possible with reversal of the voltage polarity (to -4V) allowed the coercivity to recover to 1.2 Oe. Vibrating sample magnetometry showed the saturation magnetization $M_s$ of permalloy films to reduce to less than half its initial value after application of +4V, while X-ray photoelectron spectroscopy showed an increase in oxygen content with increasing positive voltage, especially for $V > +3V$. This was in good agreement with cyclic voltammetry that showed significant oxidation events occurring at approximately $V = +3V$. These results indicate that the applied voltage leads to electrochemical oxidation and reduction of the permalloy, which results in a tuneable thickness of the remaining ferromagnetic layer. The resulting changes in shape anisotropy explain the coercivity changes we have observed. This is in contrast to the reported mechanisms in previous experiments of voltage-induced changes to ultra-thin metallic ferromagnetic layers with out-of-plane anisotropy [1–3]. These have considered surface anisotropy changes but our work indicates that effective ferromagnetic thickness may also be significant.

![Fig. 1. Experimental arrangement of optical cell.](image)

References

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LORENTZ MICROSCOPY OF NANOSTRUCTURED MAGNETIC MATERIALS

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With the introduction of aberration correction elements to transmission electron microscopes (TEM) the capability of these instruments has undergone a transformation. Furthermore specialist techniques such Lorentz microscopy has also benefitted from these developments with the differential phase contrast (DPC) mode in scanning TEM being the prime example. Lorentz microscopy covers the methods that rely on the interaction of the electron beam with electromagnetic fields, with the magnetic induction being the most exploited. In terms of resolution in Lorentz STEM a diffraction limited probe can be formed with a resolution around 0.75 nm with the JEOL Atomic Resolution Microscope (JEM-ARM200F) equipped with a CEOS (Corrected Electron Optical Systems GmbH) probe corrector for STEM imaging. An example of a system demonstrating the power of this resolution is shown in Fig. 1. This shows a cross-section of an exchange biased FM/AF multilayer. The DPC image in Fig. 1a) maps the induction along the layers with a mixed state of layers magnetised up and down. The widths of the layers are ~ 17 nm. A quantitative line trace from the area indicated in yellow is shown in Fig. 1b) in term so the magnetic deflection angle.

Whilst the improved spatial resolution is demonstrated it can also be seen in the image that strong non-magnetic contrast is present in the image as a sort of mottling. This is partly due to surface damage caused by the focused ion beam used to make the cross-section and also the polycrystalline structure of the materials than make up the film. Without the averaging shown in Fig. 1b) the signal variation can be swamped by these effects. In this presentation we will report on developments with pixelated detectors which can be used to significantly enhance the magnetic contrast. The impact on imaging of nanostructured materials will be demonstrated with examples.
ENHANCEMENT OF THE SPIN SEEBECK EFFECT IN MAGNETIC MULTILAYERS: ROLE OF THE Fe₃O₄/Pt INTERFACES

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Since the discovery of the spin Seebeck effect (SSE) [1] much attention has been devoted to the study of the interaction between heat, spin and charge in magnetic materials. The SSE refers to the generation of spin currents upon the application of a thermal gradient and detected by means of the inverse spin Hall Effect. This effect provides a conceptually new mechanism for thermoelectric energy conversion based on magnetic materials that may be used for waste heat recovery and temperature control, however the magnitude of the effect is small and routes for enhancement are currently being explored. We will report an unexpected enhancement of the SSE voltage in multilayer structures based on Fe₃O₄/Pt thin films at room temperature. This is the result of the variation of the conditions for propagation of spin current in the multilayer systems, which result in an enhancement of the overall spin current [2]. We explained our results considering the pumping effect of magnon and electron spin currents at the ferromagnetic/metal and their inter conversion interfaces. Our findings open the possibility to design thin film heterostructures that may boost the application of thermal spin currents in spintronic and thermoelectricity.

References
ON PROCESSING CONDITION FOR METALLIC GLASS WITH LOW VISCOUS WORKABILITY

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Metallic glass is non-crystalline alloy which transforms into the supercooled liquid above the glass transition temperature upon heating. Viscous flow of the supercooled liquid allows us to process metallic glass into various shapes. Viscous workability of the alloy strongly depends on fragility and thermal stability of the supercooled liquid. The former is defined as temperature dependence of viscosity around $T_g$, and viscosity of the supercooled liquid with higher fragility becomes lower. The latter is time until the crystallization of the supercooled liquid. Although soft magnetic Fe-based metallic glasses are expected to be processed into various shapes, such as magnetic core, they tend to suffer from lower viscous workability. In this paper, processing condition for metallic glass with relatively low viscous workability will be discussed with a similar case, i.e. imprinting Gd-based metallic glass grating at the supercooled liquid state.

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In the field of itinerant-electron magnetism, magnetic transitions between antiferromagnetic and ferromagnetic states are of substantial interest, as their study provides information on the strength of the magnetic interactions. Furthermore, it is well known that reducing the dimensionality of magnetic material leads to modifications in their physical properties. The magnetic phase diagram of intermetallic compounds, presenting itinerant and correlated electrons, has been explained by Moriya and Usami theory of magnetic phase transition for itinerant electron systems [1]. According to this theory, the competition between ferromagnetic and antiferromagnetic correlations would lead to phase transitions induced by both magnetic field and temperature.

In order to systematically study the influence of dimensionality on the magnetic properties of nanostructured intermetallic compounds, a new technique to produce simultaneously both bulk crystalline and nanowires of intermetallic compounds was developed. This new production method is based on the combination of two known methods (patent pending): the metallic flux method for growing crystals and the aluminum anodization method to obtain Al2O3 nano porous template.

Concerning the results, from the constructed magnetic phase diagram for the bulk and nanowires, the role of dimensionality on the magnetic phase transitions of FeGa and MnSn compounds, possible precursors of important Heusler materials, will be shown.

References
INTERFACIAL CONTRIBUTIONS TO DAMPING AND SPIN-MIXING CONDUCTANCE IN MAGNETIC/NON-MAGNETIC BILAYER FILMS

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Magnetization dynamics in the picosecond regime are largely determined by damped precessional behaviour. Damping has thus received significant research effort both in terms of understanding the underlying physics and for technological applications. Damping has also been used to study interfacial spin transport, where spin-current, generated by ferromagnetic precession, flows into an adjacent non-magnetic layer and is dissipated under the influence of the spin-orbit interaction, resulting in enhanced damping in the ferromagnetic layer. Here experimental results and analysis are presented to show the influence of different nonmagnetic (NM) capping layers on ferromagnetic (FM) layers on the magnetization damping. The interpretation of the damping mechanisms includes discussion of spin-pumping and the spin-mixing conductance across the FM-NM interface. Dynamic magnetization measurements were made on bi-layered and multi-layered FM/NM structures, produced by sputtering or thermal evaporation, using either time-resolved MOKE or VNA-FMR. The ferromagnetic metal was either Ni80Fe20 or Co and the NM layers included Cr, Cu, Ir and Au. The influence of non-magnetic capping layers of light and heavy of ferromagnetic layers are discussed and show clear effects for increased mass capping layers in the thin-film limit with contributions to both intrinsic and extrinsic damping mechanisms. The effect of the interfacial structure in FM/NM bilayers upon magnetization [1] and damping [2] are presented for Cr and Au capping layers of NiFe ferromagnetic thin-films where the influence of interfacial intermixing is demonstrated and interpreted in light of detailed structural analysis [3]. Damping measurements with current were used to find the spin Hall angle [4]. More recently, the effect of the NM layer thickness in FM/NM layer systems upon the damping behaviour has been determined as a function of the capping layer thickness in the ultra-thin limit to further understand the onset of damping associated with NM layers [5]. Finally, new results are presented for multi-layered thin films where the dominant crystal phase was controlled in a ferromagnetic cobalt film as a function of the Co thickness to introduce either a non-equilibrium fcc (111) texture or a bulk-like hcp (0001) phase with increasing film thickness. Measurements on Co layers with different over-layers show the atomic scale structure in the vicinity of the interface plays a key role in the transmission of pure-spin currents, creating significant differences in the enhancement of damping [6].

References

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MAGNETIZATION REVERSAL OF Co AND Co-BASED CYLINDRICAL NANOWIRES

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The recent interest on the magnetization reversal process of novel families of nanowires originates in the need to have full information about their magnetic properties for different functionalization and technological applications [1]. The electrochemical route to fabricate nanowires is attracting much interest owing to their low-cost and reliability to fabricate tailored magnetic nanowires and nanotubes. This technique enables the synthesis of nanowires with cylindrical symmetry in opposition to nanostripes prepared by lithography techniques. Arrays of such nanowires can be grown with diameter of 15 to 200 nm, and length from 100 nm up to tens of microns. Cylindrical nanowires can be also grown with compositional multisegmented character and with controlled modulation in diameter intended to play a similar role as notches in lithography nanostripes. The particular study of Co-based nanowires is relevant since their magnetocrystalline anisotropy, in opposition to Py nanowires, plays an important role to determine the magnetization reversal mechanism by vortex or transverse domain walls and spin rotation modes [2].

Most recent results in our laboratory will be overviewed specially focusing on the spin reversal process in Co and CoFe individual nanowires after their release from porous templates. Knowledge of the fine crystalline structure, through high resolution transmission electron microscopy and other advanced techniques, is essential to determine the magnetocrystalline anisotropy and the spin reversal process. Two main magnetization reversal mechanisms are identified by micromagnetic simulations. In fcc or bcc cubic phase CoFe wires, a vortex-like structure nucleates at the end followed by its propagation along the nanowire. In hcp-Co nanowires, the c axis orientation is determined by the synthesis parameters and typically exhibits a significant perpendicular anisotropy component, and micromagnetic simulations reveal that reversal takes place by spin rotation near the surface and the propagation of a Bloch-point like at the very core. The spin configuration has been imaged by magnetic force microscopy under variable applied field, where vortex and pinned walls at specific transition regions along modulated nanowires are confirmed. MFM images are correlated to hysteresis loops of individual nanowires obtained by magnetooptic Kerr effect. In addition, XMCD-PEEM imaging, usually used on 2D samples, has allowed us to unveil additional magnetic information of spin distribution below the surface due to the mean free path of the secondary electrons. Finally, electron holography and Lorentz microscopy has enabled to visualize and analyze the magnetic flux distribution and infer the stability of the vortex spin configuration in Co nanowires in arrays.

References
FORC DIAGRAM METHOD AS QUANTITATIVE MAGNETIC CHARACTERIZATION TOOL

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The first-order reversal curve (FORC) diagram technique is now method of choice for the study of many hysteretic physical processes. This use is not limited to ferromagnetic and ferroelectric materials but also in more exotic forms of hysteretic processes like the ones observed in spin transition materials [1-4] and even in the study of hysteresis observed in molecular magnets at very low temperature. Designed as an identification technique only for the systems correctly described by the Classical Preisach Model (Mayergoyz, 1985) the use of the FORC diagram method was proposed as a purely experimental qualitative characterization tool by Pike and collaborators in 1999. Essentially, the FORC diagram was seen for many years as a tool to find a kind of fingerprint of a magnetic material or a magnetization process. Some experimentalists however continued to interpret the FORC distribution as a Preisach distribution of coercive and interaction fields. The physical interpretation of these coercivities and interactions is still a matter of debate. Is the coercivity observed on the FORC diagram the intrinsic coercivity of some elements inside the sample? Can we expect a biunivocal correspondence between the physical entities (particles, domains, etc.) and a contribution in the FORC diagram? These questions and others similar didn’t have yet a clear answer and some confusion arose from this ambiguity in many publications. For several years now we have engaged in a systematic study of the FORC distributions with the aim to reveal the possibility to use FORC diagrams as quantitative tools. To address this problem we have used a perfect network of magnetic wires with the diameter in the range of tens of nanometers and lengths in the micrometer range. As each isolated wire has a rather well established simple hysteretic behavior which is described by a rectangular symmetrical loop we could argue that this is the closest physical sample to an ideal Preisach system. However, the studies performed on various systems of wires arrays, in perpendicular [5-6] or longitudinal [7] geometry, the results show that in all the cases the biunivocal association of one wire with a singular contribution on the FORC distribution is not possible. Each wire is giving multiple images on the FORC diagram. In this presentation we shall elaborate on this idea and show the limits of the quantitative interpretation of the FORC distribution. We also shall provide recommendations concerning the good practice in discussing the experimental FORC diagrams.

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References

HIGH FREQUENCY MAGNETOIMPEDANCE IN Co-BASED AMORPHOUS RIBBONS

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Magnetic properties of amorphous alloy ribbons have been extensively studied for nearly a quarter of a century since their first production. Much interest in these materials has been stimulated by their remarkable magnetomechanical and magnetotransport properties. Thus, magnetostriction of some tens of parts per million (ppm) combined with coercivities of less than 10 Am\textsuperscript{-1} and magnetic anisotropy constants of less than 100 J m\textsuperscript{-3} give rise to many potential applications as field, stress and strain sensors, and as mechanical actuators. Similarly, nearly-zero magnetostrictive amorphous alloys exhibit giant magnetoimpedance ratio (GMI) values as large as 600\%, that is the external applied magnetic-field dependence of the electrical impedance $Z$ of an amorphous and/or nanocrystalline ferromagnetic material (ribbon or wire).

This talk deals with the GMI response of near-zero magnetostriction Co-based amorphous ribbons in as-cast (with four different wide dimension) state, and exhibiting a macroscopic uniaxial magnetic anisotropy induced by stress-annealing treatment (300 MPa applied tensile stress at different temperature i.e., 340, 360, and 400 °C, respectively, during 1 h) is investigated in the frequency range from 10 MHz up to 1000 MHz. Comparison among MI effect of as-cast state and stress-annealed ribbons is discussed. It is remarkable that a more spectacular and defined MI effect is observed in the stress-annealed ribbons owing to the presence of a macroscopic uniaxial transverse magnetic anisotropy developed with the stress-annealing treatment that enhances the transverse component of the magnetic susceptibility. The influence of a preceding stress relief before the stress-annealing process on the MI effect is also analyzed.
Amorphous thin ferromagnetic microwires (typically of 1-30 µm in diameter) have attracted growing attention in the last few years owing to excellent magnetic properties, such as Giant Magnetoimpedance, GMI, effect, fast magnetization switching and domain wall dynamics [1]. The main advantages of glass-coated microwires are the excellent magnetic softness, inexpensive fabrication method allowing preparation of long and continuous microwires and thinnest dimensions among the cast magnetic wires. Thus, magnetically soft thin wires exhibiting GMI effect are already successfully employed for magnetic sensors applications [2].

Generally soft magnetic properties of amorphous glass-coated microwires are affected by the magnetoelastic energy related to the presence of glass coating. Spontaneous magnetic bistability and fast domain walls, DW, propagation are reported for microwires with positive magnetostriction constant exhibiting rectangular hysteresis loops. GMI effect and best soft magnetic properties are usually reported in amorphous microwires with vanishing magnetostriction constant [1].

We present an overview of the factors affecting soft magnetic properties and giant magnetoimpedance (GMI) effect in thin amorphous wires. Low coercivity and high Gaint magnetoimpedance (GMI) effect have been observed in as-prepared Co-rich microwires. One of the problems affecting the performance of magnetic sensors utilizing GMI effect is the GMI hysteresis [3,4]. We showed that the GMI hysteresis can be related to either deviation of the helical magnetic anisotropy or to interaction of the inner axially magnetized core with the outer domain shell with circular magnetization.

We showed that the magnetoelastic anisotropy is one of the most important parameters that determine magnetic softness and GMI effect of glass-coated microwires and annealing can be very effective for manipulation the magnetic properties of amorphous ferromagnetic glass-coated microwires.

After annealing of Co-rich we can observe transformation of inclined hysteresis loops to rectangular and coexistence of fast magnetization switching and GMI effect in the same sample. We demonstrated that the switching field value of microwires can be tailored by annealing in the range from 4 to 200 A/m.

References

APPLICATION OF BISTABLE MICROWIRES AS MICROSENSORS

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Amorphous glass-coated microwires are composite materials that consist of metallic nucleus (diameter of \(\sim 0.1-50\ \mu m\)) that is covered by glass-coating (thickness \(\sim 2-20\mu m\)) that are produced by drawing and quenching of molten master alloy. As a result of production process, it is a magnetoelastic anisotropy that determines their magnetic properties. Having positive magnetostriction, the amorphous glass-coating microwires are characterized by magnetic bistability (magnetization has only two values \(+M_s\) or \(-M_s\)). The switching between the two values of magnetization appears at the so-called switching field by the single Barkhausen jump.

The switching field is sensitive to various external parameters (magnetic field, temperature, mechanical stress, etc [1]), which gives us possibility to employ the microwires in construction of microsensors. Their dimensions allow their application inside various composite materials [2]. Glass-coating increases their resistance against chemically aggressive environment [3] as well as provide their biocompatibility [4].

In the given contribution, the various examples of possible applications of bistable microwires will be present. The possibility of health and stress monitoring of various composite materials, applications of microwires in medicine as well as different sensors utilization of microwires in construction and magnetometry will be shown.

References


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LOW FREQUENCY NOISE IN GIANT MAGNETOIMPEDANCE OVERVIEW & PERSPECTIVES

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The numerous magnetometers exploiting ferromagnetism as a sensing mechanism are ultimately limited, in theory, by their thermal magnetic noise. Over the last 15 years, have studies been carried out, in order to evaluate and to reduce Giant Magneto-Impedance equivalent magnetic noise in a wide range of frequency. Recently, the origins of \(1/f\) and white noise have been clarified, taking account of the sensor’s intrinsic time-dependent fluctuators (based upon a phenomenological description given by the fluctuation dissipation theorem) [1,2] and of the conditioning electronics [3]. At present, this noise modeling may be summarized by the equation

\[
\frac{b_{\vartheta}^2(f)}{b_{\vartheta}^2(f)} \approx \left( \frac{3 \mu_0 k_B T H_k^2}{\pi \vartheta M_s^2} \right) X'(f) + \frac{\partial Z_{ij0}(f)}{\partial B} R_1 + e_{n_{preamp}}^2 + e_{n_{Rx}}^2 + R_1^2 e_{n_{preamp}}^2
\]

where \(J \vartheta\) is the effective volume of the wire, \(\mu_0\) the permeability of free space, \(k_BT\) the thermal energy, \(H_k\) is the anisotropy field, \(M_s\) is the saturation magnetization, and \(x'(f)\) is the imaginary part of the GMI wire susceptibility. The term \(k_{DS}\) is a correction factor depending upon the detector type. The \(e_{n_{dc}}(\omega)\) terms are the equivalent conditioning voltage noises of the two port network, \(Z_{ij0}\) is the GMI impedance at the bias field, the \(\partial Z_{ij}(B)/\partial B\) are the intrinsic sensitivities of the corresponding impedance components, \(R_1\) the bias resistance and \(I_{ac}\) the ac bias current of frequency, \(f_0\). The first term in the equation represents the sensor noise; the second, that of the conditioning electronics.

To validate the hypothesis which yields this equation, experiments have been performed to confirm that the low frequency noise sources are primarily intrinsic to the sensor. In addition, numerous extrinsic noise sources can impact the equivalent magnetic noise of the sensor. In order to identify the relevant parameters and the principal noise source contributions, analyses based on correlation measurements were carried out. We have also investigated impedance variation versus frequency at low frequencies, where \(1/f\) noise dominates. This allows us to evaluate the frequency dependence of the imaginary part of the susceptibility, and to refine the model. Combining the results of these two investigations, an approach to material optimization can be established. The objective of this presentation is to provide an overview on the state of art of GMI noise performance and to present a perspective of material and sensor improvements.

References


Among metallic soft magnetic materials, amorphous and nanocrystalline alloys are the most promising candidates for high frequency applications. These relatively new materials developed during the last decades are meanwhile successfully applied in high grade magnetic cores for inductors. We will survey characteristic features of amorphous and nanocrystalline alloys particularly relevant for inductor applications at higher frequencies. In particular we will discuss the optimization of the high frequency properties of inductances made of these materials by applying new annealing and processing technologies.

Interesting applications, for example, are DC/DC converters for small power range, shielding materials for wireless charging systems, or sensor application requiring high anisotropies. The challenges for future electronic circuits, thus, generate new requirements on the magnetic materials involved.

As an example, we will discuss nanocrystallin materials with huge anisotropy. Tape wound cores were produced using this nanocrystalline ribbons with linear hysteresis loops and particularly low DC permeability down to $\mu_{DC} = 100$ which ultimately allows accomplishing high circuit frequencies up to 50 MHz. The huge anisotropy was achieved by continuous annealing under tensile stress along the ribbon axis [1].

On the other hand, we will discuss inductances made of planar sheets used in inductive wireless power transmission systems. Nanocrystalline soft-magnetic shielding material is used to avoid lossy eddy currents being induced in electrically conducting components like batteries or ground layers of electronic circuits. For designing inductive wireless power systems e.g. at variable frequency, detailed loss information are of interest. The product of the coupling factor $k$ and the geometric average of the coil’s quality factors $Q$ [2], is proposed to qualify materials concerning both a) shielding against conducting components on the backside of the receiving coil and b) establishing a high mutual inductance of the transformer coils, resulting in higher system efficiencies.

References
RECENT PROGRESS IN BASIC SCIENCE OF HIGH \( B_s \) AND LOW CORE LOSS NANOMET® ALLOYS

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Almost two decades after the discovery of popular nano-crystalline soft magnetic alloys (FINEMET and NANOPERM alloys), a series of nanocrystalline alloys based on Fe-Si-B-P-Cu, named as NANOMET® were developed in our group [1. New nanocrystalline alloys show marginal amorphous-forming ability due to high content of Fe. We gained a thorough understanding of crystallization process, formation of phases and their magnetic properties along with the magnetic interactions between different phases present in the alloy. Effects of thermal treatment (annealing temperature, heating rate etc.) on nano-structure and magnetic properties were understood. All of this led us to the development of NANOMET® alloys, which not only have the high \( B_s \) (> 1.8 T) comparable to silicon steel but also exhibit much lower core loss, simultaneously. Nano-crystallization process of NANOMET® is very fast and the crystallization heat is large due to high density of \( \alpha \)-Fe grains. Two step annealing process, which control the growth of pre-existing nuclei, nucleation density and crystallization heat is developed. The basic understanding also led us to the development of these alloys in wide ribbon form (~ 120 mm). In this talk, I will present the recent progress that we have made in the basic understanding of NANOMET® alloys.

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ON THE CUTTING EDGE PROCESSING FOR COMMERCIALIZATION OF SOFT-MAGNETIC ALLOY “NANOMET®”

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A series of Fe-Si-B-P-Cu amorphous alloys, NANOMET® exhibit high saturation magnetic flux density ($B_s > 1.8$ T), low coercivity ($H_c < 10$ A/m) and low core loss ($W_{1.7/50} \sim 0.4$ W/kg) [1]. These excellent magnetic properties are attributed to the higher Fe content (~ 85 at. %) than that of conventional Fe-based amorphous alloy. By utilizing its excellent properties, several prototype products such as transformers or motors have been produced for evaluating their performance. As a result, it is revealed that magnetic cores composed of stacked or wound NANOMET® ribbon exhibited the core loss of less than half to quarter as compared to those of laminated commercial Si-steel strip [2]. Consequently, NANOMET® is promising soft magnetic materials to contribute energy saving. However, there are several remaining issues that should be solved such as wider ribbon production, nano-structural controlling by annealing, degrading ductility of annealed ribbon or so on. In this talk, details of processing development for NANOMET® alloys for commercialization will be presented. In addition, solutions for predictable difficulties in mass production will also be discussed.

This work was supported by “Tohoku Innovative Materials Technology Initiatives for Reconstruction (TIMT)” funded by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Reconstruction Agency, Japan. A part of research was carried out in collaboration with Production Engineering Development Center, Panasonic Corporation.

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TAYLORING PROPERTIES IN FERROELECTRIC-BASED COMPOSITES BY LOCAL FIELD ENGINEERING

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The paper demonstrates the possibility of tuning the dielectric and ferroelectric properties in composites by local field engineering via microstructural control. The interfaces between regions with contrasting permittivities in composites modify the local field distribution. The effective macroscopic properties of composites are a result of this local field inhomogeneity and therefore, the properties of ferroelectric-based composites can be tailored by controlling the microstructure characteristics (local field engineering) or by adequate choice of the phase constituents and phase interconnectivity. This approach can be applied to design ferroelectric-magnetic composites with specific dielectric/ferromagnetic properties. Since the local field inhomogeneity increases when the difference in permittivities of the constituent phases is higher, porous ferroelectric structures ensuring a maximum permittivity contrast have a great potential in order to reach desired ferro/dielectric properties, although porosity is usually considered detrimental in electroceramics.

Based on this idea, 3D FEM models have been developed to compute local field distributions in realistic microstructures in order to explore the possibility to maximize their ferroelectric (switching) or non-linear dielectric responses (tunability). The role of nanostructuring and of porosity on the macroscopic properties (effective permittivity, tunability, P(E) hysteresis loops) were studied theoretically and validated for BaTiO3 nanostructured ceramics, for a few types of PZT ceramics with various porosities, including anisotropic, for PbTiO3 films with vertical nanoporosity and ferroelectric-ferrite magnetoelectric composites [1-4]. As a first step, different realistic 3D microstructures were generated. Local field distributions were computed by 3D FEM calculation and used as inputs in switching (Preisach) or tunability (Johnson) models, in order to derive the ferro/dielectric and tunability responses. If properly engineered in well-controlled microstructures, interfaces in composites may be used as an elegant factor to enhance functionalities as result of the field concentration in some specific regions.

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AMORPHOUS AND NANOCRYSTALLINE BILAYER RIBBONS FOR MAGNETIC SENSORS

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Rapidly solidified amorphous and/or nanocrystalline bilayer ribbons are interesting for their intrinsically graded properties, which can lead to specific sensor or actuator principles. A double-nozzle planar flow casting technique offers the possibility of simultaneous formation of two mechanically solid connected homogeneous layers with different composition and uniform thickness of tenths of microns along the ribbon length, which makes possible combining unlike alloys with selected properties and unique overall behavior. In order to optimize the magnetic performance of these systems for selected applications it is important to deepen knowledge about various post-preparation processing techniques that can be used to tailor their properties. One possible technique, often employed for this purpose, is thermal treatment under presence of external magnetic field. This work is devoted to study of the effects of field-annealing in order to tailor the soft magnetic properties in series of FeCuNbSiB, FeCo- and FeNi-based amorphous and nanocrystalline bilayer ribbons. We show that besides the effects of field-annealing, the magnetic reversal process in such bilayers is strongly influenced by interlayer stresses, which are induced in material due to different thermal expansion of two mechanically coupled individual layers. This can lead to very large induced magnetic anisotropy. Examples of our recent work on soft magnetic amorphous and nanocrystalline bilayer ribbons for sensor applications will be briefly highlighted.

This work has been supported by the Slovak Agency for the Research and Development (projects APVV-0492-11 and APVV-0147-11) and by VEGA 2/0192/13.
Today, we know that there exist many Fe-based alloys exhibiting magneto-volume anomalies in the physical properties. The most renowned is the INVAR effect, which was discovered by Guillaume from investigations on ferromagnetic fcc FeNi alloys at concentrations around Fe$_{65}$Ni$_{35}$. These alloys show almost constant ‘invariant’- thermal expansion as a function of temperature in a wide range around room temperature. Although this discovery took place more than hundred years ago (1897), there is still today an intense research activity in this topic, which is at the crossover between Solid State and Materials Sciences [1-3]. Ferromagnetic INVAR alloys exhibit low thermal expansion (LTE) below the magnetic ordering temperature, thus making them very attractive as functional materials. Those technological applications requiring temperature-independent size and shape, such as precision sensors for aerospace technology or high-resolution screens, are the primary target for these LTE compounds. Therefore, the search for new INVAR materials or the investigation on new processing methods to be applied to the already known INVAR alloys in order to enlarge the temperature range for LTE above room temperature is nowadays a challenging issue [4-6].

In this talk we will present a great variety of experimental results showing the magneto-volume anomalies exhibited by different Fe-based alloys such as FeZrB metallic glasses, Fe-Cu mechanically alloyed binary alloys, ball milled FeNi Invar alloys or polycrystalline R$_2$Fe$_{17}$ (R = rare earth) alloys among others, including nanostructured ones. The combination of magnetometry-based experimental techniques (in order to get information about the temperature and applied magnetic field dependencies of the magnetization), neutron and x-ray diffraction under extreme conditions (temperature and hydrostatic pressure) or x-ray absorption techniques allows a detailed characterization of the alloys. Therefore, a deeper insight into the strong magneto-volume coupling, governed by the Fe-Fe interatomic distances, can be attained.

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HIGH TEMPERATURE MAGNETIC STABILIZATION OF COBALT NANOPARTICLES BY AN ANTIFERROMAGNETIC PROXIMITY EFFECT

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Thermal activation tends to destroy the magnetic stability of small magnetic nanoparticles, with crucial implications in ultra-high density recording among other applications. It has been demonstrated that ferromagnetic-antiferromagnetic (FM-AFM) interfacial exchange-coupling is an effective method to increase the effective anisotropy of FM nanoparticles to enhance their blocking temperature, \( T_B \) [1]. However, a \( T_B \) enhancement beyond room temperature using this approach has been rarely reported. Here we demonstrate that low blocking temperature ferromagnetic (FM) Co nanoparticles (\( T_B < 70 \) K) become magnetically stable above 400 K when embedded in a high Néel temperature antiferromagnetic (AFM) NiO matrix. [2] The origin of this remarkable \( T_B \) enhancement is due to a magnetic proximity effect between a thin CoO shell (with low Néel temperature, \( T_N \); and high anisotropy, \( K_{AFM} \)) surrounding the Co nanoparticles and the NiO matrix (with high \( T_N \) but low \( K_{AFM} \)). This proximity effect yields an effective AFM with an apparent \( T_N \) beyond that of bulk CoO, and an enhanced anisotropy compared to NiO. In turn, the Co core FM moment is stabilized against thermal fluctuations via core-shell exchange-bias coupling, leading to the observed \( T_B \) increase. Mean-field calculations provide a semi-quantitative understanding of this magnetic-proximity stabilization mechanism.

References

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DYNAMIC FORC MEASUREMENTS IN MAGNETIC WIRES

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Recently large attention has been paid to the fabrication and investigation of magnetic properties of ferromagnetic wires due to the possibilities of their technological applications. The performance of the devices using magnetic wires relies on their switching characteristics. The magnetization switching is typically experimentally studied using the first-order reversal curve (FORC) method [1]. The FORC technique is used to evidence the intensity of interactions between the switching physical entities in ferromagnetic samples, and also the distribution of coercive field. Majority of the experimental studies are assuming to be time independent. However the kinetic effects may affect quite dramatically the results. In order to acquire the dynamic FORC, an ac magnetometer based on the induction coil principle [2] was constructed. 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 switching of domains and grains in soft magnetic materials are influenced by the field rate. The Fig. 1 shows the dynamic FORC curved and the corresponding FORC diagram obtained for a magnetic steel wire at a specific field sweep rate.

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STUDY OF ZnO THIN FILM AS METALLIC STRIP GRATING STRUCTURE FOR SENSITIVE CHOLESTEROL BIOSENSOR

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Nanostructures made of zinc oxide (ZnO) are easy and reliable to produce in a wide manner of different forms and structures [1]. ZnO is very versatile and due to its high coupling coefficient, many applications exist, like SAW devices [2], bulk acoustic wave devices, gas sensors [3], infrared detectors, tactile sensor arrays [4] and enzyme biosensors [5]. Biosensors offer the opportunity to sense biological material providing valuable information for medical diagnostics and monitoring of pathogens in the environment. Thus the development of high sensitivity, cost effective, real-time and portable biosensing is of primary importance. This paper presents the characterization of ZnO thin film as biosensing material by metallic strip grating structure, for the real-time detection. Also, the interest in surface waves appeared due to evanescent waves in the metallic strip grating in subwavelength regime. The experimental test is making with the transducer with metamaterials lens [6] in the subwavelength regime, and a simulation of the evanescent wave’s formation has been performed at the edge of Ag strips, with thicknesses in the range of micrometers. In this work, high quality ZnO films were grown on ITO/glass substrates by vacuum thermal evaporation method is characterized by X-ray diffraction the film crystalline quality and by scanning electron microscopy (SEM) the film morphology.

Keywords
Thin films ZnO, characterization, metallic strip grating, subwavelength regime, biosensing applications.

References
THE ROLE OF PORE INTERCONNECTIVITY ON THE ELECTRICAL PROPERTIES OF PZTN POROUS CERAMICS

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Pb0.988(Zr0.52Ti0.48)0.976Nb0.024O3 ceramics (denoted as PZTN) are interesting for their piezoelectric properties, which are the best known in the PZT family so far. Graded porosity is highly necessary in order to adapt the acoustic impedance from ceramic solid to water [1]. Therefore, understanding the role of porosity to the functional properties is essential. Even for the same porosity, the properties can be completely different according to the microstructural characteristics (phase interconnectivity). The aim of the present work is to investigate the role of the pore interconnectivity on the properties of porous PZTN ceramics (45 vol.% porosity). Ceramics with the same porosity and different pore interconnectivity induced by: (i) the addition of pore former or by (ii) starch consolidation were investigated by comparison with dense material. The XRD patterns show pure phase for all the ceramics. Following the different sintering processes according to the use of pore formers, the connectivity as resulted from SEM are: 0-3 interconnectivity for starch consolidation method and 3-3 interconnectivity in the other case.

The dielectric properties determined at room temperature by Impedance Spectroscopy method show a reducing permittivity when increasing frequency with a normal relaxation dispersion. A higher permittivity for (0-3) connectivity by comparison with (3-3) is found for all the investigated frequencies. High field tunability at room temperature shows typical non-linear behavior with larger hysteresis and slightly higher tunability for (0-3) connectivity. Moreover, the sample with 0-3 connectivity has almost the same tunability as the dense material, while for the other porous sample a decrease of the tunability was observed. The tunability was discussed by considering the role of phase connectivity in the frame using effective medium approximations (Bruggman and Maxwell-Garnett approaches) [2, 3].

The present results show that the electrical properties of porous PZTN ceramics are strongly dependent on the phase interconnectivity. High tunability with lower permittivity than the dense ceramic can be reached in samples with (0-3) connectivity.

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Cobalt ferrite thin films are used in magnetic data storage, sensors, actuators, wave guides applications due to their interesting magnetic properties (e. g.: moderate saturation magnetization, high coercive field, large magnetostrictive coefficient and high magneto-crystalline anisotropy generated by the strong L-S coupling of the predominantly B-sited coordinated Co$^{2+}$ ions). Copper substitutions in various typed of ferrites was reported to enhance the magnetic properties, increase the cell parameter and decrease the Curie point.

The aim of this study was to investigate the structural and magnetic properties of the Cu doped cobalt ferrite films obtained by pulsed laser deposition (PLD) [1, 2]. In this purpose, various targets with chemical formula Co$_{1-x}$Cu$_x$Fe$_2$O$_4$ ($x=0-0.5, 0.1$ step) were synthesized using standard powder ceramic technique. The Fe$_2$O$_3$, Co$_3$O$_4$ and Cu$_2$O$_3$ oxide powders were mixed in the suitable proportions, ball milled for 5 h and calcined in air at 950 °C for 5 h. The final sintering step was done at 1250 °C for 2 h. The other experimental parameters such as target-substrate distance (4 cm), deposition time (60 min), pressure (~10$^{-5}$ Torr) and substrate temperature (400 °C) were maintained constant. The structural and chemical properties of the obtained films were studied by profilometry, X-ray diffraction, scanning electron microscopy/energy dispersive X-Ray spectroscopy and Raman spectroscopy while the magnetic response was investigated using a vibrating sample magnetometer.

The XRD patterns presented in Figure 1 revealed the presence of residual phases as the Cu addition increases. The study revealed the influence of copper doping level on the properties of cobalt ferrite thin films deposited by PLD techniques.

References
SYNTHESIS AND CHARACTERIZATION OF MnFe(P$_{1-x}$As$_x$) ALLOYS WITH NEAR ROOM TEMPERATURE MAGNETOCALORIC EFFECT

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The magnetocaloric effect (MCE) is defined as the thermal response of a magnetic material to an applied magnetic field and is apparent as a change in its temperature. The nature of the MCE in a solid is the result of the entropy variation due to the coupling of the magnetic spin system with the magnetic field. When a material is magnetized, the entropy associated with the magnetic degrees of freedom, magnetic entropy $\Delta S_m$, is changed due to a change in the magnetic order of the material. In adiabatic conditions, $\Delta S_m$ is compensated by the entropy associated with the lattice, resulting in a change of material temperature, $\Delta T_{ad}$.

The magnetocaloric materials with near room temperature applications are Gd and some from its alloys. Gd is considered the reference refrigerant material for magnetic cooling. Gd and its alloy Gd$_3$(Si,Ge)$_4$ are the best materials available today for magnetic refrigeration near RT. Advanced magnetocaloric materials exist in other solid systems where structural changes are coupled with ferromagnetic ordering, and therefore, can be triggered by a magnetic field.

The MnFeP$_{1-x}$As$_x$ alloys system that we presented in this work is the most promising substitute for Gd and its alloys. Polycrystalline specimens with suitable chemical composition ($x = 0.45; 0.50; 0.55$) were prepared by arc melting in argon atmosphere, using high-purity elements. The arc melted buttons were annealed at the temperatures about 800°C for tens of hours under vacuum and slowly cooled down to RT in the furnace. Systematic investigations of the structural and magnetic properties of the synthesized compounds were performed by optical microscopy, X-ray diffraction and neutron diffraction. The obtained structure and the remanent stresses, mosaic blocks and atomic position were evaluated by using FullProf and GSAS procedures. Magneto-thermical properties (variation of $\Delta S_m$ and $\Delta T_{ad}$ vs magnetic field intensity) were performed using a home-made facility, specially built for this purpose, by using a Foner electromagnet that produces a magnetic field of maximum 2.5 T. $\Delta T_{ad}$ was determined by direct measurement and $\Delta S_m$ was determined by calculation. Large MCE was observed in the compound MnFeP$_{0.45}$As$_{0.55}$ at RT. It was found that at about 300 K, the magnetic entropy change value is 14.2 J/kgK for field change of 2 T (Figure 1). We appreciate that in field variation of 5 T, the magnetic-entropy variation can double.

Fig. 1. Magnetic-entropy changes of MnFeP$_{0.45}$As$_{0.55}$ compound for magnetic field variation of 2 T

The origin of the large magnetic-entropy change should be attributed to the comparatively high 3d moments and the rapid change in the magnetization in the field-induced magnetic phase transition.

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References
Magnetic hyperthermia with low Curie temperature particles is a very promising approach in the therapy of cancer. This novel healing method offered to the scientific community convincing reasons for experimental and theoretical studies [1, 2]. The Fe-Cr-Nb-B magnetic particles (MPs) with low Curie temperature (Tc) in range of 42-44 °C have special magnetic and thermal properties for their use in magnetic hyperthermia [3, 4]. This paper analyzes the temperature field induced by the heating of the magnetic particles with low Tc in an ac magnetic field. The particles have a spatial distribution after their injection within the tumor as a result of diffusion and convection. Their spatial distribution near the injection sites (IS) was computed as a solution of the general convection-diffusion equation in a porous tissue. The ferrofluid flow within the tissue was modeled using the continuity and Darcy’s equations. The ferrofluid injection rate during the injection process influences significantly the spatial distribution of the particles and temperature field within tumor. Higher values of the ferrofluid flow rate determine a strong convection of the particles to the tumor center. The FeCrNbB system determines an automatic control of tumor heating. The temperature field increases from 37°C to the Curie temperature of the particles which becomes the maximum temperature within tumor. The heating of tumor can be managed by controlling the Curie temperature of the MPs. Small quantities of ferrofluid 0.1 - 0.3 cm³ and implicitly a small dosage of Fe-Cr-Nb-B particles per unit gram of tumor determine a temperature rise in the therapeutic temperature range in a tumor. The ferrofluid injection rate influences significantly the spatial distribution of the particles within tumor. The FeCrNbB systems open new borders in the application of the magnetic hyperthermia with low Curie particles in the cancer therapy.

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References

SYNTHESIS AND PROPERTIES OF ONE DIMENSIONAL BIOTEMPLATED NiO MICROSTRUCTURES

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Natural evolution has provided numerous examples of exceptional building materials. Therefore, a variety of bio-inspired morphology synthesis strategies are being explored through processes of in situ modification with bio-templates because of their structural and compositional hierarchical order. Nickel oxide is an important semiconductor and antiferromagnetic material, widely used in electrochemical, optical and magnetic applications and its functionality greatly depends on its nano-/microscale characteristics [1]. 1-D structures are receiving significant attention because of their potential applications in energy conversion, separation science, environmental protection and chemical sensors [2]. The aim of this work was to prepare by inexpensive wet methods pure phase biomorphic 1-D NiO microtubes by using natural fibers as bio-templates and to study the effects of the synthesis parameters (bio-template, precursor concentration) on their microstructures and functional properties.

The final products were obtained by infiltration of various biotemplates (Cotton – Gossypium, Hemp – Cannabis sativa and Flax – Linum usitatissimum, Fig. 1) with nickel nitrate solution (Ni(NO3)2·6H2O) at different concentrations, followed by calcination in open atmosphere. The phase formation and morphologies have been investigated by using X-ray diffraction (XRD) and scanning electron microscopy (SEM). The influence and effects of the synthesis parameters on the functional characteristics and sensing properties of the 1-D NiO microstructures were determined and interpreted in correlation with their nano/microstructural properties.

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Spinel ferrites doped with rare earth metals are a versatile class of materials with numerous applications in medicine [1], wastewater treatment [2] and electronics [3], that can be obtained using cheap and efficient methods which offer a good control over their size, morphology and composition and therefore on their properties.

We hereby report the synthesis of CoFe$_{2-x}$RE$_x$O$_4$ (where RE: Gd, Dy or Yb and x= 0; 0.01; 0.03; 0.05; 0.1; 0.2 and 0.3) through the coprecipitation method using carboxymethylcellulose sodium salt (CMC) as surfactant and capping agent [4] and the correlation between the composition and morphology of the obtained nanoparticles and their magnetic properties.

The obtained phases were identified through X-ray (fig. 1) diffraction and infrared spectroscopy, their composition was determined by means of energy dispersive spectroscopy and their size and morphology were obtained from the XRD spectra and transmission electron micrographs. The magnetic properties were measured by vibrating sample magnetometry.

The obtained nanoparticles have an average size of 20 nm with variations according to their composition. Large dopant concentrations with large ionic radii metals can lead to phase separations but most of the samples were of high purity with no phase separations even at 0.3 doping. The ionic radii of the doping metals and their electronic structure directly influence the lattice parameter, crystallite size and magnetic properties of the nanoparticles.

References
MECHANOSYNTHESIS OF OLEIC ACID COATED Fe₃O₄ NANOPARTICLES. STRUCTURAL, THERMAL AND MAGNETIC CHARACTERISTICS

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Oleic acid coated magnetite nanoparticles (Fe₃O₄) have been obtained by a new combined route, ceramic method and subsequent wet mechanical milling. A stoichiometric mixture of the easily accessible Fe and Fe₂O₃ precursors was used. The synthesis procedure involved two steps. In the first step, well crystallised magnetite was obtained by heat treatment of precursor’s mixture. The second step consists in the wet milling of the as obtained magnetite powder in a high energy planetary ball mill using oleic acid as process control agent. Similar conditions of milling were applied in order to obtain magnetite samples by dry mechanical milling. The samples have been characterized by X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), magnetic measurements M=f(H), scanning electron microscopy (SEM) and differential scanning calorimetry (DSC). Two different processing mechanisms are observed for dry and wet milling modes according to XRD analysis. The mean crystallite size of magnetite is at about 19 nm after 240 minutes of wet mechanical milling according to XRD. The High Resolution SEM confirmed that the milled powder consists in nanoparticles that have particles with the size up to 30 nm. The bond of the oleic acid to the magnetite nanoparticles has been observed by FTIR and DSC investigations. The presence of free and bonded oleic acid is revealed and the free oleic acid can be removed controlled by heat treatment. The magnetisation of the milled samples is lower as compared to the magnetisation of the un-milled sample due to several causes such as disordered structure, finite size effect and powder contamination. A powder contamination with iron occurs during milling and this leads to the formation of a wüstite-FeO phase for the dry milled samples. In the case of the wet milled samples, due to an oleic acid layer the FeO phase formation is prevented.

References
Fe$_3$O$_4$/Ni$_3$Fe NANOCOMPOSITE POWDER OBTAINED BY MECHANOSYNTHESIS-ANNEALING ROUTE

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Fe$_3$O$_4$/Ni$_3$Fe composite-nanocomposite powder has been obtained, starting from Fe, Ni and Fe$_2$O$_3$ powders via mechanosynthesis and subsequent annealing. The incipient formation of magnetite phase is noticed for the sample milled for 2 hours. The complete formation of Ni$_3$Fe and Fe$_3$O$_4$ is not achieved even after 10 hours of milling. The presence of a small amount of unreacted Fe$_2$O$_3$ was found. Subsequent annealing led to the complete reaction between the precursors and also to the increase of the crystallite size of both nanocomposite component phases. Even for the un-milled homogenized mixture of precursors, a partial formation of Ni$_3$Fe and Fe$_3$O$_4$ was noticed after annealing. In the case of the milled and annealed samples, the complete formation of the Fe$_3$O$_4$/Ni$_3$Fe composite occurs after 6 hours of mechanical milling. The DSC analyses and the XRD patterns of the samples subjected to DSC revealed the formation of a FeO - wüstite phase for the starting sample and also in the case of the samples milled short times (up to 1 h). A diminution of the temperature required for the magnetite phase complete formation is observed upon increasing milling time. The first magnetization curves reveal a two-stage evolution in the case of the milled samples. For the milling times up to 3 hours, where the Fe$_2$O$_3$ phase is still substantial, a tendency of the magnetization to decrease is remarked. As a consequence of the progressive formation of Fe$_3$O$_4$ and Ni$_3$Fe, the value of magnetization increases for the samples milled for longer durations. An increase of the magnetisation in the case of the samples milled and subsequent annealed is noticed as compared to the magnetization value of the as-milled samples.

References


AMORPHISATION OF Fe-BASED ALLOY VIA WET MECHANICAL ALLOYING ASSISTED BY PCA DECOMPOSITION

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Amorphisation of Fe75Si20B5 (at. %) alloy has been attempted both by wet and dry mechanical alloying starting from a mixture of elemental powders. Powder amorphisation was not achieved even after 140 de hours of dry mechanical alloying. Using the same milling parameters, when wet mechanical alloying was used, the powder amorphisation was achieved after 40 hours of milling. Our assumption regarding the powder amorphisation capability enhancement by contamination with carbon was proved by X-ray Photoelectron Spectroscopy (XPS) measurements which revealed the presence of carbon in the chemical composition of the wet mechanically alloyed sample. Using shorter milling times and several process control agents (PCA) (ethanol, oleic acid and benzene) with different carbon content it was proved that the milling duration required for powder amorphisation is linked to the carbon content of the PCA. Differential Scanning Calorimetry (DSC), thermomagnetic and X-ray Diffraction (XRD) measurements performed to the heated samples revealed the fact that, the crystallization occurs at 488°C, thus leading to the formation of Fe3Si and Fe2B. Thermogravimetry measurements (TG) performed under H2 atmosphere, showed the same amount of contamination with C, which is about 2.3 wt. %, for the amorphous samples regardless of the type of PCA. Saturation magnetisation of the wet milled samples decreases upon increasing milling time. In the case of the amorphous samples wet milled with benzene up to 20 h and with oleic acid up to 30 h, the saturation magnetisation has roughly the same value, indicating the same degree of contamination. The XRD performed on the samples milled using the same parameters, revealed that powder amorphisation can be achieved even via dry milling, just by adding the equivalent amount of elemental C calculated from the TG plots. This proves that in this system by considering the atomic species which can contaminate the powder, they can be used as microalloying elements which could provide the required extra amount of metalloids.

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We have synthesized the La_{0.54}Ho_{0.11}Sr_{0.35}Mn_{1-x}Cr_{x}O_{3} manganites by sol-gel method and performed structure investigations by neutron diffraction by using the HFRD neutron diffractometer at IBR-2 reactor, Frank laboratory of neutron physics, Dubna, Russia. The variation of the molar magnetization and of the resistance with temperature and intensity of the applied magnetic field were determined by using a Foner type magnetometer and, respectively, the four probes method at NIRDTP Iasi, Romania and JINR, Dubna, Russia between 77 and 400 K, at $H_{\text{max}} = 1$ T.

SAXS and SANS measurements were performed in the temperature range from 258 to 353K ($H=0$). SAXS experiments were carried out on a Rigaku X-ray instrument with high-speed Cu rotating anode (SMAXS 3000 Point SAXS system, at MIPT, Dolgoprudniy, Russia) using a standard transmission configuration, by using CuK$_\alpha$ radiation. SANS experiments were performed at the time-of-flight YuMO spectrometer situated at high flux pulse IBR-2 reactor, JINR, Dubna, Russia. The measured neutron scattering spectra were handled by using SAS software.

A monotonous decrease of the lattice constants and of the unit cell volume with the increase of the Cr concentration were observed. The variation with temperature of molar magnetization at relatively low magnetic fields presents a dependence on the thermal history of the samples, attributed to the transformation from the ferromagnetic to spin glass state. A large variation of the resistance with the magnetic field intensity was observed around room temperature for all investigated manganites.

For samples with $x=0.05, 0.10, 0.15$ and $0.20$ at temperature range from 258K to 353K the SANS data allows us to obtain the volume fraction of the magnetic phase using the Porod invariant. An interesting behavior can be observed for $x = 0.15$ sample, where we obtain the scattering exponent $\alpha \approx 2$ already for $T = 293$ K, which indicates the formation of 2D disk-like structures. We found that for $x = 0.00, 0.05$ and $0.20$ at $T = 343$ K, we have $\alpha = 1$ and showed that the magnetic nanodomains have a 1D rod-like shape with the radius $R$ in the range $2.5 - 5\,\text{Å}$ and the height $H$ in the range $40 - 60\,\text{Å}$. For these concentrations the general characteristic is that a decreasing of temperature determines a slight increasing of the scattering exponent $\alpha$, which indicates that the rod-like magnetic structures expand to form wormlike structures.
Cobalt-based perovskites, also called cobaltites were discovered in early 1950's but their specific magnetic ordering was recognized only in 1960's. In the recent years rare earth perovskite cobaltites are increasingly accepted as materials of great importance due to rich physics and chemistry in their ordered-disordered structure for the same composition. The evolution of the physical properties as a function of hole doping in cobaltites has similarities to those observed in perovskite manganites and has been studied extensively. This new work shows that we studied the structure and composition influence on the transport and magnetic properties for a class of perovskite-based cobaltites. In terms of theoretical research the fast development of theoretical methods based on congruity of computer simulation enabled us a refined interpretation of experimental data. The new theoretical aspects studied in perovskites for the last few years [1], linked to the new research on the simulation activity [2], allowed us to progress in the improvement of the design on cobaltites with controlled magnetic properties. Performance parallel computers [3], and a variety of visualization techniques are utilized to make direct comparison with experiments. In many cases, these allow us the capability to predict materials with enhanced or new magnetic properties. Some of our valuable simulating tool employs highly sophisticated symbolic computation techniques that could model glassy magnetic behaviour for some complex cobaltites. Similar to manganites, cobaltites exhibit also a great ability to form mixed valent perovskites, involving the Co$^{3+}$ and Co$^{4+}$ species. However, it must be emphasized that differently from manganites the cobaltites may, in many cases, exhibit a large oxygen deficiency. So far, magnetic and magneto-transport properties for a class of oxygen deficient perovskites, LaCo$_{1-x}$M$_x$O$_{3-δ}$ with $M = $ Nb and Ru, were by simulation investigated. Experimental steps have been driven: (1) the synthesis of some cobaltites materials type; (2) XRD and ND analysis on synthetized samples; (3) electric charge transport and magnetic properties investigations on this cobaltites materials. The results cover a comprehensive investigation of the magnetization, and magneto-transport properties of the cobaltites glassy magnetic behaviour.

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SYNTHESIS AND CHARACTERIZATION OF MULTIFERROIC MN DOPED BiFeO$_3$

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Multiferroic BiFeO$_3$ and Bi$_{0.95}$Mn$_{0.05}$FeO$_3$ nanoparticles were prepared by sol-gel autocombustion method to estimate the influence of Mn on the structural, ferroelectric and magnetic properties of BiFeO$_3$ material. In the synthesis process, solutions of the metal nitrate salts and citric acid in desired proportions were prepared separately by using minimum amounts of deionized water and then mixed in 1:1 molar ratio to form an aqueous solution. The pH of the mixed solution was adjusted to 7 using ammonia. The solution was then heated up to 80°C to transform it into dried gel. At this stage, the temperature of the container was further increased to 110 °C only to be ignited at any point of time. Upon ignition, the dried gel burns in a self propagating combustion manner until all gels were completely burnt out to form ash like flakes. These flakes were then neatly collected and collapsed into fluffy loose powder by using a glass rod or spatula. X-ray diffraction studies on the samples reveal R3c distorted single phase perovskite structures in both the cases. Crystallite sizes were estimated using Scherrer formula to obtain the values of 45 and 39 nm for undoped and Mn doped BiFeO$_3$ samples, respectively. Fourier transform infrared spectroscopy studies on the samples display the presence of only the metal-oxygen bonds of the compounds and thus confirms the formation of perovskite structures. Room temperature polarization-electric field hysteresis loops on the samples at different frequencies and excitation field amplitudes show the behaviour of spontaneous electric polarizations. The obtained remnant polarization values of BiFeO$_3$ and Bi$_{0.95}$Mn$_{0.05}$FeO$_3$ nanoparticles at 50Hz and 50 V amplitude are 0.38 $\mu$C/mm$^2$ and 0.62 $\mu$C/mm$^2$, respectively. Room temperature magnetic hysteresis loop measurements on the samples indicate that the doping of Mn in bismuth sites in the BiFeO$_3$ has produced a considerable improvement in the magnetization from 0.53 emu/g to 2.53 emu/g. Thus, it can be inferred from the above that the Mn doping in BiFeO$_3$ multiferroic nanoparticles is capable of enhancing both the ferroelectric and ferromagnetic properties. The interpretations of the obtained results are made in light of the structural contributions for ferroelectricity, antiferromagnetic spin spiral cycloid structure around the FeO$_6$ octahedra, weak ferromagnetic exchange interactions between the cations located at A- and B-sites and the possible magnetoelectric coupling between the ferroelectric and ferromagnetic orders.
EFFECT OF THE BUFFER LAYER AND INTERLAYER ON THE PERPENDICULAR MAGNETIC ANISOTROPY OF Nd-Fe-B SINGLE AND MULTILAYER FILMS

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Thin film permanent magnets with perpendicular magnetic anisotropy are of high interest for applications in magnetic micro-electro-mechanical systems (MEMS), and microstructured magnetic sensors [1]. The hard magnetic properties and mechanical adhesion of Nd-Fe-B films highly depend on the nature and thickness of buffer layer. In this paper the influence of buffer layer and interlayer on the perpendicular magnetic anisotropy and mechanical properties (adhesion to substrate) of Nd-Fe-B films is reported. We obtained good hard magnetic properties by inserting a Mo layer having a suitable thickness \( t \) (about 40 nm) between the Nd-Fe-B magnetic layer and the silicium (Si) substrate. Large out-of-plane coercivity \( (H_{c,\perp} = 1220 \text{ kA/m}) \) and remanent ratio (remanent magnetization/saturation magnetization) \( H_{r,\perp} = 0.99 \) are also obtained by the stratification of the Nd-Fe-B magnetic film with a total thickness of about 540 nm in three NdFeB(180nm)/Mo(5nm) bilayer sequences using Mo as interlayer. Nd-Fe-B thick films deposited on large areas have the tendency to peel off from substrate during annealing [2]. Using a Ni film with a thickness of about 8 nm alongside with a Mo film of 40 nm as buffer layer improves the adhesion to substrate and keeps the anisotropic hard magnetic performances of the Nd-Fe-B films unchanged. By increasing the total thickness of the Nd-Fe-B magnetic layer from 540 nm to 1620 nm and their stratification in nine NdFeB(180nm)/Mo(5nm) sequences the coercivity increases from 1220 kA/m to 1640 kA/m (Figure 1).

The coercivity increase can be ascribed to a stronger pinning effect as a result of the increased number of NdFeB/Mo interfaces.

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EFFECT OF SOFT CONTENT ON MAGNETIC PROPERTIES OF MnBi-BASED HARD/SOFT COMPOSITE MAGNETS

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The low-temperature phase (LTP) of MnBi promises to be a competitive candidate as magnetic material for rare earth-free permanent magnets, because of the large magnetocrystalline anisotropy and positive temperature coefficient of coercivity [1]. Moreover, its use as hard magnetic phase in exchange-coupled magnets, when combined with soft magnetic phases, gives rise to further enhancement of \((BH)_{\text{max}}\). In this regards, there have been many efforts to obtain the pure LTP-MnBi phase [2].

In this paper, we report the effect of the Fe content on magnetic properties of MnBi/α-Fe permanent magnets prepared by spark plasma sintering (SPS) consolidation of the low-energy ball-milled powders obtained from annealed Mn_{50}Bi_{50} melt-spun ribbons and commercial Fe micropowders. The powders have been mixed in different ratios. The size of the MnBi powders was varied between 20 and 100 µm, depending on the milling time, while the size of the commercial Fe powders was up to 10 µm. Different processing parameters of SPS technique, such as sintering temperature, time and pressure were found to have great effect on the magnetic properties of the as-prepared magnets. A systematic work has been accomplished to investigate the evolution of the microstructure and magnetic properties of the milled powders and corresponding compacted samples by using XRD, SEM, DSC, and VSM. Single-phase MnBi bulk magnets with a maximum energy product \((BH)_{\text{max}}\) of 6.3 MGOe at room temperature have been produced. The soft magnetic phase has a strong effect on the magnetic properties of MnBi/α-Fe SPS-compacted magnets, namely the addition of soft magnetic phase enhances the magnetization of the composite. Nevertheless, a kink was still observed on the demagnetization curves and the coercivity decreases when the soft magnetic phase content is larger than 10 wt.%, due to the decrease of the exchange coupling between the magnetic phases. The coercivity decreases with the increase of the angle between the easy axis and the applied field direction, indicating that a coherent rotation of magnetization occurs in MnBi/α-Fe SPS-compacted magnets, according to the classical Stoner–Wohlfarth model [3]. The highest values of \((BH)_{\text{max}} \sim 8.7 \text{ MGOe} \) was obtained at room temperature in Mn_{50}Bi_{50}/10% α-Fe SPS-compacted magnets.

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MAGNETOSTRICTION OF NANOCRYSTALLINE
Fe$_{81.2}$Co$_4$Si$_{0.5}$B$_{9.5}$P$_4$Cu$_{0.8}$

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Nanocrystalline Fe-Co-Si-B-P-Cu alloys have recently attracted much attention due to their high magnetic saturation polarization $J_s$ above 1.8 T combined with good soft magnetic properties. One prominent example is Fe$_{81.2}$Co$_4$Si$_{0.5}$B$_{9.5}$P$_4$Cu$_{0.8}$ [1] which is also the subject of the present investigations. Amorphous ribbons of this composition have been produced by rapid solidification in 25 mm width and 22 µm thickness. The material was annealed for about 6 seconds (cf. [2]) between temperatures of about 380°C and 540°C. A nanocrystalline bcc structure was achieved after annealing between about 400°C and 530°C. Annealing at higher temperatures lead to the precipitation of borides accompanied by a degradation of the soft magnetic properties. Optimally annealed samples show a coercivity of $H_c = 5$ A/m and a high saturation polarization of $J_s =1.83$ T. These values are in excellent agreement with the results reported by Setyawan et al [1]. In addition to previous work however, we have also studied the saturation magnetostriction by using the SAMR technique [3]. Thus, the magnetostriction in the nanocrystalline state was found to be $\lambda_s \approx 19$ ppm which is about 50% of the value in the amorphous as cast state. Figure 1 summarizes the results.

**Fig. 1.** Coercivity $H_c$, magnetic saturation polarization $J_s$ and saturation magnetostriction $\lambda_s$ of Fe$_{81.2}$Co$_4$Si$_{0.5}$B$_{9.5}$P$_4$Cu$_{0.8}$ after annealing 6 seconds at $T_a$.

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THE STUDY OF THE CHELATING/COMBUSTION AGENT INFLUENCE ON THE FUNCTIONAL PROPERTIES OF COBALT FERRITES

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Ferrites with cubic spinel structure represent one of the most important classes of magnetic materials with multiple applications in different areas such as magnetic high-density information storage, magnetically controlled transport of anti-cancer drugs, magnetic resonance imaging (MRI) enhancement, sensors and pigments, etc [1]. Among ferrites, cobalt ferrite (CoFe2O4) has gained a particular attention in the last years due to its high coercivity, moderate magnetization, strong anisotropy and great physical and chemical stability [2].

The large number of applications of ferrites with small particles has promoted the development of various chemical methods for their synthesis. It is well known that the synthesis protocol determines the structural and microstructural characteristics of materials, which in turn, influence their magnetic and electrical properties.

In this paper we present a study of the different chelating/combustion agents influence on the functional properties of the cobalt ferrites prepared by using a technique that combines the chemical sol-gel process with the combustion process. This method is used mainly in oxide materials synthesis because it presents a series of advantages such as: simple equipment, inexpensive precursors and low temperatures for synthesis. In order to prepare cobalt ferrites we have used metal nitrates as cation sources and four different chelating/combustion agents. The formation of single phase with cubic spinel structure and free of impurities for all samples was confirmed by IR, XRD and SEM analysis.

Also, the dielectric and magnetic properties at room temperature were investigated and we can conclude that in this kind of synthesis the nature of chelating/combustion agents influenced the functional properties of cobalt ferrite.

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PSEUDO CORE-SHELL POWDERS LIKE PERMALLOY/RHOMETAL TYPE

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Nanocrystalline Permalloy (Ni₃Fe) powders were prepared by mechanical alloying starting from elemental Ni and Fe powders. A mixture of the Permalloy and carbonyl Fe mixture were pressed at 600 MPa and then subjected to annealing at different temperatures (ranging from 400 up to 900 °C) in argon atmosphere in order to obtain core-shell like particles by micro-alloying [1]. The large Permalloy particles are surrounded by very small particles of carbonyl Fe. At the Permalloy-iron interface a non-uniform layer of Rhometal composition is evidenced to be formed by micro-alloying [1, 2]. During the annealing, independent on annealing temperature, the Permalloy conserves its nanocrystalline state previously obtained by mechanical alloying. The samples have been investigated by X-ray diffraction, scanning electron microscopy, energy dispersive X-ray spectrometry, magnetic M(H) and electrical resistivity measurements. The spontaneous magnetization of the core-shell powders vs Ni₃Fe content shows a drop for the Ni₃Fe amount larger than 76 wt%, due to the formation of the Rhometal layer (which has a magnetisation smaller than the magnetization of Ni₃Fe). The electrical resistivity measured on the sintered compacts obtained by the core-shell Permalloy/Rhometal powders is of 4.8•10⁻³ Ωm, 3 times larger than the electrical resistivity of the iron sintered compacts.

The core-shell like particles of Permalloy/Rhometal composition could lead to a new type of magnetic cores with specific characteristics.

References
SPIN CROSSOVER MATERIALS FOR NANOELECTRONIC AND SPINTRONIC DEVICES

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Spin crossover (SCO) materials have been studied for almost a century for their intriguing physical properties. The change of the magnetic state of such a molecule from a diamagnetic low spin (LS) state to paramagnetic high spin (HS) state upon the application of several external stimuli like temperature, pressure, light irradiation, magnetic field [1] etc. has fascinated researchers and in the last couple of decades these materials have been proposed in numerous applications. These applications vary from capacitive memories, sensors, displays, photonic devices, nanoelectronics/spintronic and NEMS [2]. However, in this field there is a severe lack of studies regarding the behavior of SCO materials in electronic devices. Here we show the different electrical properties of [Fe(Htrz)₂(trz)](BF₄) SCO complex ranging from powder towards a microelectronic device. We show the AC and DC properties of the mentioned complex as well as the fabrication technique of the device[3]. We show for the first time the possibility of modulating the electrical conductivity by doping our complex and keeping the hysteretic behavior of the complex in all material dependent electrical parameters[4,5]. Also the current of the fabricated microelectronic device can be modulated by light [6], and the same device can be switched from one state to another using an electric field both in the hysteretic region. The observed effects are robust and may serve as a viable route for future nanoelectronic and spintronic applications.

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SYNTHESIS AND CHARACTERIZATION OF Co NANODOTS ARRAYS

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In the recent years, it turned out that magnetic nanodots arrays could behave extremely different, with very useful implications for various applications (e.g., ultrahigh-density magnetic storage media).

In this work, uniform and large area Co nanodots arrays have been electrodeposited on silicon substrates. The nanoholes have been produced by using a contact mask fabricated by E-beam lithography (EBL). Prior to the electrodeposition, a thin Au layer was deposited by thermal evaporation on the Si substrate, which served as working electrode during the electrochemical deposition. In order to prepare the contact mask, after a standard spin coating process, a layer of 950K PMMA resist of 400 nm thick was deposited on the Si substrate, baked 1 h at 150°C and exposed to an electron beam in an e-Line plus EBL system from Raith. After the development of the e-resist, good circular nanoholes with the diameter of about 200 nm were obtained. The nanoholes were designed at different distances: 300 nm, 500 nm and 700 nm, respectively. The electrodeposition was performed by applying pulses of - 1.1 V for 230 ms, alternating with relaxation periods at 0 V for 100 ms, using an aqueous solution of CoSO4 (40 g/L) and H3BO3 (40 g/L) at two different pH values (4 and 6). Scanning electron microscopy (SEM), magnetic force microscopy (MFM) and Nano-MOKE have been used to characterize the Co nanodots arrays. Fig. 1a shows the SEM image of the Co nanodots obtained at pH = 4, with the inter-dots distance of 300 nm.

Fig. 1. (a) SEM image of Co nanodots obtained at pH = 4. The inter-dots distance is 300 nm. (b) Magnetic hysteresis loops of Co nanodots obtained at 2 different pH values.

The magnetic hysteresis loops measured by magneto-optical Kerr effect indicate a different behavior of the Co nanodots arrays, depending on the pH of the electrodeposition bath (Fig. 1b). One can observe also the coercive field evolution, which is independent of the distance between the nanodots, but depends on the Co nanodots structure (cubic for pH = 4 and hexagonal for pH = 6). The method presented in this paper allows the preparation of large arrays of Co metallic nanodots and the control of their structure by tailoring the electrodeposition conditions.

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ELECTRODEPOSITION OF DIAMETER CONTROLLED CoFe NANO WIRES INTO PATTERNED ALUMINA TEMPLATES

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In the last decade, the role of nanostructured materials in addressing the challenges of modern society became widely recognized. Among many other nanomaterials, nanowires – and in particular magnetic nanowires – found their way as a technical solution in key areas like electronics, recording media, sensors or nanomedicine, to name just a few. Magnetic nanowires can be synthesized by various methods, but electrodeposition from aqueous solutions is preferred because of its low cost, high yield and purity of the obtained nanowires [1,2]. Usually, a porous membrane with regular arrangement of nanopores is used to obtain nanowires of the same diameter over the entire area of the template [3]. For sensing applications of the magnetic nanowires, it will be of great interest if one can have so called “bunches” of nanowires with controlled diameter as shown in Figure 1.

In order to obtain a patterned alumina membrane, we started with high purity aluminum sheet with a thickness of 0.25 mm which was first annealed in Ar for 4 hours at 500 °C. The substrate was then washed with acetone and 3 M NaOH solution, then electropolished for 5 min at 18 V in a mixture of HClO₄:C₂H₅OH in order to obtain a smooth surface. We used a two-step anodization process [4] and by successive anodizations we obtained two different regions with pores of 25 nm using sulfuric acid (H₂SO₄) solution as electrolyte and 50 nm using oxalic acid (H₂C₂O₄). The anodizing time was adjusted according to the experimentally determined anodizing rate in order to obtain a 60 µm thick membrane. The area between the two patterns was anodized for 24 hours in oxalic acid. The remaining aluminum metal at the bottom was chemically etched in saturated HgCl₂ and barrier layer was removed in 5 % H₃PO₄ in order to get a free standing Al₂O₃ membrane. A Ti/Au electrode was sputtered on the backside of the membrane and CoFe nanowires were electrodeposited into the template. Evidence of the electrodeposited nanowires will be presented at the conference.

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Magnetic ferrites represent an attractive class of materials because of their properties and are widely used in technical applications. The removal of the dyes from waste waters using magnetic nanoparticles is an effective way, allowing recovering both the adsorbents and the dyes. We tested zinc ferrite to remove the acid RED-G azo-dye from the solution resulted from dyeing and finishing in textile industry. The magnetic nanoparticles were prepared by two methods: co-precipitation and synthesis in the microwave field, respectively. The last one ensures a homogenous heating of reaction medium and allows a considerable decrease of preparation time. The synthesis was performed at 105°C for 30 min., using zinc nitrate, ferric or ferrous salts, in the presence of NaOH solution. The polyvinyl-pyrrolidone was used as dispersing agent. The average size of the obtained particles ranged from 50 to 100 nm. The saturated magnetization of ferrite nanoparticles depends on the preparation method. Zinc ferrite-1 was obtained by co-precipitation and Zinc ferrite-2 in microwave field (Fig. 1).

To be able to be used for the dye retention, ferrite nanoparticles have been functionalized with a cationic surfactant, 1-hexadecylpyridinium chloride monohydrate, in alcoholic medium. Fixing of reagent on the ferrite particle's surface has been proven by analysis of FT/IR spectra. The dye adsorption was done by mixing zinc ferrite-2 in the solution of Acid RED-G at pH in the range of 4-9. Adsorption capacity increases with the amount of adsorbent, but does not vary significantly with the pH of the solution. Immobilization of the cationic surfactant on nanoparticles surface is very important, because the dye uptake is done mainly through formation of ion pairs.

References
FOCUSED ION BEAM MILLING STRATEGIES FOR MICROWIRES ANALYSIS AND MICRO-FABRICATION

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The focused ion beam (FIB) microscope has gained widespread use in fundamental materials studies and technological applications over the last several years because it offers both high-resolution imaging and flexible micromachining in a single platform. A focused ion beam system produces and directs a stream of high-energy ionized atoms of a relatively massive element, focusing them onto the sample both for the purpose of etching or milling the surface and as a method of imaging. The ions’ greater mass allows them to easily expel surface atoms from their positions and produce secondary electrons from the surface, allowing the ion beam to image the sample before, during and after the lithography process. The system utilizes a liquid-metal ion source to produce Ga⁺ ions. The ion beam has other uses as well, including the deposition of materials from a gaseous layer sprayed above the sample by means of a Gas Injection System – the ions in the beam strike atoms down onto the surface of the sample where intermolecular attraction fix them. The FIB system has four basic functions: milling, deposition, implantation and imaging. When combined with milling, FIB deposition can create almost any microstructure.

One can make use of FIB weather for analysis purposes and, usually, in this case sections into materials are made to gain insight of its structure, composition, etc. or for creating nano/micro-structures that are further used or analyzed in other devices.

In order to tailor a sample for a specific purpose its orientation relative to the ion beam is essential. For this, a suitable combination of stage tilt, sample holder shape and sample positioning on the sample holder has to be used.

We are presenting here our work with the FIB on microwires, either glass-coated or uncoated, along with the strategy used for their processing (Fig. 1, Fig. 2).

![Fig. 1. Cross-section made by FIB into a glass-coated microwire with a metallic deposition on the surface for thickness measurements.](image1)

![Fig. 2. A notch made into a glass-coated microwire used in measurements of domain wall movement.](image2)

Financial support from NUCLEU PN 09-43 01 02 and the European Commission FP7-REGPOT-2012-2013-1, Grant Agreement No. 316194 (NANOSENS) is highly acknowledged.
EFFECT OF HIGH-ENERGY BALL MILLING ON THE STRUCTURE AND MAGNETIC PROPERTIES OF Fe-Nb-Cr-B GLASSY SUBMICRON POWDERS

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Amorphous and nanostructured magnetic materials have attracted increased attention in the last decades due to their novel magnetic properties and potential applications in high performance electronic devices, health care and magnetic recording technology [1-3]. In this context, it is extremely important to understand how their reduced dimensionality is influencing the structural and magnetic behavior in order to make them useful for applications. Among other magnetic powders useful in medical and engineering applications, Fe-Cr-Nb-B submicron powders with low Curie temperature proved to be very appropriate for self-regulating magnetic hyperthermia [4].

In this paper we report our most recent results on the structure evolution and magnetic properties of Fe\(_{79.7-x}\)Nb\(_{0.3}\)Cr\(_x\)B\(_{20}\) (x = 11.5÷13 at. %) submicron powders produced by high energy ball milling (Retsch PM 200), in dry and wet atmosphere, from glassy melt-spun ribbons precursors. The effect of post-milling heat treatment on the magnetic properties of the powders is also presented. The structure evolution was investigated after each step of the milling process, enabling to determine the effect of different milling conditions on the production of submicron powders with suitable properties. The dry milling results in a rapid decrease of the powders size, but leads also to the rapid increase of T\(_C\) to about 180\(^{0}\)C. The wet milling in water leads to a more rapid decrease of the powders size, but they still remain in the 1–3 \(\mu\)m range even after 10 h of milling. The wet milling in surfactant, such as oleic acid, seems to give better results and the powders are in the submicron range after 24 h of milling, whilst their magnetic properties are following pretty well the ones of the glassy melt-spun ribbons precursors. Following the structural and magnetic characterization we have developed a protocol for wet/dry mechanical milling of Fe\(_{79.7-x}\)Nb\(_{0.3}\)Cr\(_x\)B\(_{20}\) (x = 11.5÷13 at. %) glassy melt-spun ribbons, which allows us to tailor the magnetic properties of the obtained submicron magnetic powders in the range of 10÷25 nm, and mainly the Curie temperature around 40-45\(^{0}\)C.

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References
VISUALIZATION OF INTERACTIONS BETWEEN Fe-Cr-Nb-B MAGNETIC NANOPARTICLES AND CANCER CELLS BY UHR-SEM

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Fe-Cr-Nb-B magnetic nanoparticles (MNPs) are interesting for self-controlled hyperthermia because of their low Curie temperature [1]. The effect of heating on the cancer cells is mainly determined by the interactions between MNPs and cancer cells. The main purpose of this study was to investigate the interactions between Fe-Cr-Nb-B MNPs and the human osteosarcoma cells (MG-63) and to study the changes of the cells morphology by using a ultra-high resolution scanning electron microscopy (UHR-SEM). To this end, we tried to modify the surface of the simple silicon chips and make them suitable for cells growth. The first approach was carried out by functionalizing the surface with a biocompatible layer of carboxymethyl chitosan. For another experiment we tried to make silicon chips surface more adherent by plasma etching. The protocol used to fix the cells was very simple and economic, involving only two reagents, glutaraldehyde and ethanol. UHR-SEM images indicate a tight connection between cells and MNPs after 4 h of exposure, making obvious that MNPs tend to adhere better on the surface of the cells. This stage may represent the beginning of the MNPs internalization. We observed also that MNPs are attracted by the cells surface, evidencing a clear tendency to penetrate the membrane of the cancer cells. This is probably due to the affinity of the cells for the Fe in MNPs. Moreover, we noticed almost no differences on cells shape and morphology.


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ON THE TEMPERATURE DISTRIBUTION IN TISSUE PHANTOM TUMOR IN THE PRESENCE OF Fe-Cr-Nb-B MAGNETIC NANOPARTICLES FOR SELF-REGULATED HYPERThERMIA APPLICATIONS

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Hyperthermia treatment involves the heating of a tumor up to 47°C by using magnetic nanoparticles in an applied alternating magnetic field, for different periods of time [1]. Consequently, it is extremely important to have the magnetic nanoparticles randomly dispersed on the surface and in the volume of the tumor, but also to have to evaluate correctly the temperature distribution in the different regions of the tumor, when an alternating magnetic field is applied.

In this work, we investigated the heat distribution in two types of phantom tissue by means of a magnetic fluid in an alternating magnetic field. For the first experiment, as phantom tissue we used a fine grained polyester cylinder of 2 cm in length and 1 cm in width, whereas for the second one a 3 cm\textsuperscript{3} of pork liver was used. Like magnetic material we used three different concentrations of low Curie temperature Fe-Cr-Nb-B magnetic nanoparticles dispersed in water. Our previous studies indicated that by changing the Cr content we can control rigorously the equilibrium temperature, which is strongly related to the Curie temperature of the magnetic particles [2]. We examined the temperature distribution as a function of the magnetic nanoparticles concentration. The phantoms with magnetic nanoparticles inside were exposed to an alternating magnetic field and the temperature measurements were carried out by using three fiber optic temperature sensors positioned on specific location. A detailed map of the temperature distribution on the phantom tumor was realized.

The obtained results showed that the increase of the temperature depends on the nanoparticles concentration. Moreover, the magnetic nanoparticles accumulation in the area of interest is highly dependent on the rate of injection thereof. The obtained data are extremely useful to establish the density of magnetic nanoparticles which can be used for optimum effects on the tumor, depending on their size and the tumor consistency, but also to consider the best method to introduce the particles in the tumor.

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PREPARATION AND CHARACTERIZATION OF A FERROFLUID BASED ON LOW CURIE Fe-Cr-Nb-B MAGNETIC PARTICLES

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The ferrofluids are colloidal suspensions of magnetic particles (MPs) that have been lately investigated for different biomedical applications such as contrast agents for MRI, magnetic cell separation, magnetically guided embolization and magnetic hyperthermia [1]. In this work, we prepared a biocompatible ferrofluid based on Fe-Cr-Nb-B particles with low Curie temperature [2] and potential use in magnetic hyperthermia. To this end, magnetic particles were prepared by high energy ball milling using a Retsch200 planetary ball mill. Two approaches were chosen for preparing the ferrofluid. In one experiment, the particles were dispersed in sodium oleate solution for 30 min. at 80°C. Although the obtained suspension was stable in an applied magnetic field, the ferrofluid based on sodium oleate as surfactant, displayed a relatively low value of the magnetization along with the invariance of the viscosity with the applied magnetic field. We assumed that the results are due to the reduced size of the particles (approx. 10 nm) and the sodium oleate bilayer coating the particle. Another possible explanation would be the oxidation of the particles during the washing procedure which could reduce the magnetic core of the particles. The second approach used calcium gluconate as a dispersion medium for MPs, and the obtained ferrofluid showed higher saturation magnetization and an increase in viscosity with the applied magnetic field. The use of calcium gluconate helped to avoid the drawbacks involved in the first approach such as oxidation, keeping the biocompatibility characteristic. We obtained a magnetization of the ferrofluid of 1.5 emu/cm³ and a detectable variation of the viscosity with the magnetic field. By applying an alternating magnetic field the temperature of the ferrofluid increases up to 47°C, in agreement with the Curie temperature of the magnetic particles. Thus, the calcium-gluconate-based ferrofluid is a good solution for successful use in self-controlled magnetic hyperthermia.

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MICROFLUIDIC DEVICE FOR THE DETECTION OF Fe-Cr-Nb-B NANOPARTICLES USED IN HYPERTERMIA APPLICATIONS

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Hyperthermia is one of the various clinical protocols that are nowadays used as auxiliary therapy in cancer treatment [1]. Magnetic hyperthermia uses a combination of alternating magnetic fields and magnetic nanoparticles as heating agents. Recently, it has been demonstrated that Fe-Cr-Nb-B nanoparticles have suitable magnetic properties for self-regulating hyperthermia application such as low Curie temperature [2]. One of the most important aspects in hyperthermia cancer treatment is to precisely know the amount of magnetic nanoparticle, dispersed in a biocompatible liquid carrier, and injected in tumor tissue. Also it is important to detect and to quantify the amount of nanoparticles eliminated by the affected body. In this work, we fabricated a magnetoresistive device capable to detect Fe-Cr-Nb-B magnetic nanoparticles used in hyperthermia cancer therapy. The device consists of magnetoresistive sensors and microfluidic channels that are used to guide the nanoparticles on the sensors area. The magnetoresistive sensors were microfabricated by using the conventional patterning techniques and the microfluidic channels were fabricated by PDMS by using a mr-DWL negative photoresist mold. After sensor microfabrication, the PDMS microfluidic channels were bonded to the magnetoresistive sensor chip. The FeCrNbB nanoparticles were dispersed in a liquid carrier by ultrasonication. The nanoparticle solutions were injected through the microchannels and the output voltage of the sensor was recorded. In order to build a sensor calibration curve, solutions with different nanoparticle concentrations were used in the detection experiments.

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TOWARDS SIMPLE SMALL-THROUGH-BIG IMMUNOASSAY: POLYMER MICROBEADS AS TAGS FOR OPTICAL DETECTION IN VISIBLE SPECTRUM

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The current immunoassay methods are becoming ever more sophisticated in terms of sensing capabilities, types of sensors, detection procedures, and dedicated electronics and software. However, there is a permanent need for an immunoassay approach that could get rid, to some extent, of intrinsically-arisen drawbacks of the tags and their associated reading equipments. Taken into account that microbead technology turned out to have increased potential for versatile bioassays [1], we sought to a new approach to address the tags-related shortcomings by using magnetic nanoparticles and polymeric beads into an inverse approach as compared to conventional magnetic-microbeads-related assays. Explicitly, in this particular approach, the target antigens are caught from solution by using magnetic (nano)particles, whereas non-magnetic polymeric beads, functionalized with antibodies against the targets, are used as tags for simple optical observation/confirmation of the binding event.

Based on this inverse solution, this work is a proof-of-concept of a sandwich immunoassay relying on magnetic (nano)particles, used as carriers for capture antibodies and targets, and polymeric non-magnetic beads exploited at this point as tags/reporters in an easy-to-use and cheap bioassay based on optical detection.

By using polystyrene beads with sizes of 2 or 5 µm in diameter (Fig. 1) and magnetic nanoparticles (20 nm in diameter), both coated with goat immunoglobulin G (IgG), we have managed to detect anti-goat IgG for concentration less than 20 pg/mL.

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Reference

Fig. 1. Optical and SEM images of the polymeric beads and magnetic nanoparticles.

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MICROMAGNETIC SIMULATIONS OF CYLINDRICAL MAGNETIC NANOWIRES WITH ZERO MAGNETOSTRICTION

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In this paper we have performed a complex study of the magnetic behavior of rapidly solidified CoFeSiB nearly zero magnetostrictive amorphous nanowires using experimental and theoretical techniques. We accomplished the theoretical part with the Magpar package [1, 2]. The experimental hysteresis loops of the amorphous nanowires which have been measured using an inductive technique are presented and correlated with finite element micromagnetic simulations. Experimental and calculated data have shown that both shape anisotropy and the demagnetizing field play important roles in the magnetization reversal of these novel nanomaterials. 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 [3].

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

Fig. 1. Typical hysteresis loops simulated for nanowires in which the magnetic behavior is determined by the shape anisotropy

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References
INVESTIGATION OF THE METAL-GLASS INTERFACE IN GLASS-COATED MICROWIRES BY UHR-TEM

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Soft magnetic glass-coated amorphous and nanocrystalline microwires are nowadays used in many applications, such as multifunctional materials for structural health monitoring, electronics and magnetic sensors devices. The magnetic behavior of the microwires is dependent on the metallic nucleus composition, the induced mechanical stresses during the manufacturing process, but also on the metal-glass interface quality. In this paper, we present our latest results on the microstructural investigation of the metal-glass interface in the glass-coated microwires, by means of the high resolution transmission electron microscopy.

The as-cast Co₆₈.₁₅Fe₄.₃₅Si₁₂.₅B₁₅ and Fe₇₃.₅Si₁₃.₅B₉Nb₃Cu₁ glass-coated amorphous microwires (GCAWs) were fabricated by the glass-coated melt spinning method. GCAWs with the amorphous metallic nucleus of 20 µm in diameter and 10 µm thickness of the glass wall were obtained. The nanocrystalline structure in the glass coated nano-crystalline wires (GCNWs) was induced by thermal treatments at 550°C for 1 h, in vacuum. The investigated samples were prepared in lamella shapes from GCWs by focus ion beam technique (FIB) using a SEM/FIB Crossbeam Neon 40EsB microscope. UHR-TEM investigations of the metal-glass interface were carried out using the UHR-TEM Libra 200MC microscope from Zeiss, equipped with S-TEM (scanning electron microscopy), selected area electron diffraction (SAED), EELS (Electron Energy Loss Spectroscopy) and X-Flash 5030 EDX detector energy dispersion X-ray) modules.

![Fig. 1. EELS spectra of the atom diffusion length at the metal-glass interface for CoFe-based GCNWs.](image)

EDX and EELS analyses indicate that the cobalt and iron atoms diffusion length at the metal-glass interface increases from about 20 nm for GCAWs to about 45 nm for CoFe-based GCNWs, as shown in Fig.1. The oxygen diffusion increases from 30 nm for GCAWs to about 110 nm for GCNWs.

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A new type of sensor with high capability for arterial pulse wave detection is proposed in this work. As sensing active element we selected different magnetic microwires prepared by in-rotating water cooling technique, with the nominal composition Fe$_{73.5}$Nb$_3$Cu$_1$Si$_{13.5}$B$_9$ and 110μm in diameter, subsequently cold drawn successively up to 10 μm. Our studies indicate that the 30 μm cold drawn microwire annealed at 550°C exhibits the optimum nanocrystalline structure that produces a high relative magnetic permeability up to 5x10$^6$ and a high sensitivity at stress, bending or torque. The change in relative magnetic permeability is about 80% for a 1000 MPa applied stress.

The sensor consists of a single coil, 10 mm long, with 150 turns wound directly on the nanocrystalline magnetic microwire, the environmental magnetic fields being compensated. The sine a.c. current passing through the coil induces a strong variation of the magnetic permeability of the nanocrystalline microwire, resulting in significant impedance variation proportional with the sensor bending due to the direct contact with the pulsating blood vessel. An electronic circuit transforms the impedance variation into an electrical signal, which is subsequently filtered and amplified (Fig. 1). In the given configuration, the achieved sensor sensitivity for pulse detection is of 5.138 mV/bending degree. The collected electrical signal provides important and vital information about the shape of the pulse wave, the rigidity of the blood vessels in the monitored region, the number of the heart beats or the irregularities of the heart rate, such as extrasystoles. The new pulse wave detection sensor has a simple architecture, small size, being suitable for the detection and recording of the pulse waves of patients with cardiovascular diseases or for the monitoring of the elderly.

![Pulse wave recorded at wrist with the proposed magnetoelastic sensor based on nanocrystalline microwires.](image)

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CURRENT CONTROLLED DOMAIN WALL VELOCITY IN AMORPHOUS MICROWIRES

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The dynamics of magnetic domain walls is an important area of interest both for understanding the underlying processes and for developing new technological applications. Usually, the domain wall displacement is controlled by magnetic field or by spin-polarized electrical current [1]. Until now, the current driven domain wall motion was studied in Permalloy planar nanowires prepared by means of electron beam lithography. It has been shown that the nucleation and propagation of magnetic domain walls can be controlled with a spin-polarized dc current [2, 3]. In contrast, large values of the wall velocity and enhanced wall mobility values have been recently emphasized in cylindrical amorphous and nanocrystalline microwires and submicron wires prepared by rapid solidification. In these novel materials, it has been observed that the wall velocity depends on the applied field, on the wire defects, and that it can be significantly increased by means of annealing in the presence of a transverse field, by applying a current during annealing, or simply by applying an orthogonal field during measurements.

Here we study the effect of a dc current which passes through cylindrical Fe$_{77.5}$Si$_{7.5}$B$_{15}$ amorphous microwires on the domain wall velocity.

![Graph showing field dependence of domain wall velocity](image)

The observed behavior is a consequence of two contributions: (i) the effect of the circular field created by the current on the magnetic moments from the wire’s outer shell, which enhances the mobility and velocity of the head-to-head domain walls within the inner core; and (ii) a direct contribution of the spin-polarized current on the magnetic domain wall.

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References
FINEMET microwires exhibit interesting magnetic properties and structural characteristics, which recommends them for various sensors applications and not only. By cold drawing their properties are enhanced significantly, not only because of the induced stresses during the drawing process but also due to the evolution of the nanocrystalline structure with the annealing [1]. Both volume (magnetic permeability, coercive field) and surface (giant magnetoimpedance or GMI response) magnetization processes affect strongly the macroscopic behavior of the microwires. All these effects are related to the magnetic induced anisotropies evolving in the FINEMET microwires.

In this paper, we studied the magnetic and magnetoelastic properties of FINEMET nanocrystalline wires with diameters ranging from 40 μm down to 10 μm, obtained by cold drawing FINEMET amorphous wires of 105 μm in diameter prepared by in-rotating-water spinning. Their unique magnetic properties are discussed considering the stresses induced during preparation and cold drawing, the stresses relief following annealing, the annealing-induced structural transformations (e.g., nanocrystallization) and the corresponding changes in the magnetic anisotropy. The different magnetic behavior observed after conventional annealing at 500°C and, respectively, 550°C, with the permeability reaching the maximum after annealing at 500°C and the giant magnetoimpedance (GMI) response being maximum after annealing at 550°C, can be ascribed to the different evolution of the nanocrystallization process in the center of the wire and on the surface, as confirmed by UHR-TEM studies. Furthermore, the cold drawn wires were annealed by Joule heating using a.c. currents of different frequencies (1÷10 MHz) to control the area of the cross section of the wire in which the nanocrystalline structure appears. The longitudinal magnetic permeability measurements corroborated with the GMI response and the surface measurements by magneto-optical Kerr magnetometry shown that, in the case of current annealing a well-defined circumferential or even oblique anisotropy is induced. The TEM studies emphasized also smaller nanograins on the surface compared with the inner core of the wires subjected to a.c. current annealing. Using different frequencies for the a.c. currents it was possible to control the magnitude of the longitudinal magnetic permeability and GMI response, accordingly with the requirements for different sensing applications.

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References
INVESTIGATION OF DOMAIN WALLS NUCLEATION AND MOTION IN SUBMICRON AMORPHOUS WIRES

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The controlled nucleation and motion of domain walls in magnetic nanowires is of recent interest for applications in domain wall logic devices and in miniature magnetic sensors [1, 2]. Ultrathin amorphous glass-coated wires with metallic nucleus diameters of the order of hundreds of nanometers have been recently prepared by rapid quenching from the melt [3]. Their axial magnetization process occurs through the displacement of a single 180° domain wall along the entire sample length.

Here we studied the approaches to control the domain wall nucleation and displacement in cylindrical Fe_{77.5}Si_{7.5}B_{15} amorphous glass-coated submicron wires using a combination of nucleation coils and notches. A small nucleation coil is located at one of the sample ends in order to apply field pulses aimed to enhance the nucleation of reverse domains. Conical notches with various depths up to a few tens of nanometers were made in the glass coating and in the metallic nucleus using a focused ion beam (FIB) system. Magneto-optical Kerr effect (MOKE) surface hysteresis loop measurements have been performed on wire samples with diameters between 100 and 750 nm in order to study the influence of the FIB-made notches and of the nucleation coils on coercivity and on the overall characteristics of the domain wall propagation.

In summary, the simultaneous use of nucleation coils and notches is one of the most efficient techniques of controlling the domain wall motion in cylindrical magnetic amorphous wires. Their effect on coercivity and on the characteristics of the domain wall motion depends on wire diameter, notch depth and position on the wire length, and characteristics of the applied nucleation pulse.

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References
Arrays of ferromagnetic wires have been proposed recently as a possible key component within enhanced acoustic sensing devices [1]. One feasible application is the use of magnetic nanowires within cochlear implants in order to transduce the sound vibrations into electric signals that are sent as nerve impulses to the auditory system of the brain. We are proposing in this work a magneto-mechanical modeling study of a new acoustic sensing design based on a pick-up coil wrapped around a Co-based wire [2]. The bending deformations produced by sound pressure are inducing internal stresses within the wires which are causing a variation of the magnetic permeability that is sensed by the pick-up coil. We are first performing a theoretical investigation of the internal stresses distribution within the samples when exposed to loads with different intensities, using the Structural Mechanics module of the COMSOL Multiphysics software. Using a micromagnetic study based on the model proposed by Sablik et al. [3] we developed a new technique for obtaining the stress – magnetic permeability variation. The analysis of the magnetic permeability variation in the wires was performed based on the stress distributions calculated previously. A significant permeability change was detected at the bottom fixed-end of the wires.

We also simulated the magnetic permeability changes of several samples that were placed within an air-filled chamber with an acoustic sound source. The sound pressure distribution throughout the chamber was calculated with the COMSOL Multiphysics package, as were the deformation and stress distributions caused by the sound pressure on the magnetic wire. Based on the stress-magnetization relationship we are showing the distributions of magnetization and permeability changes within the wire. We have found that, for the modeled configuration, the changes in magnetic permeability have values of the order of $10^{-5}$ to $10^{-4}$ H/m, with the maximum values around the fixed-end of the wire, where the highest stress variation was found.

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The deposition of soft or hard magnetic materials on the glass-coated amorphous wires leads to changes in the magnetic behaviour of these materials due to the contribution of the nature of the deposited material and to the supplementary stresses induced by the deposited material [1]. The soft or hard magnetic materials deposited on the glass-coated microwires determine changes in the magnetic behaviour of these materials due to the contribution of the nature of the deposited material, its structure, and of the induced external stresses [2].

The aim of this paper is to present results on the stress induced effect of deposited Co and CoPtRh layers and applied external stresses on the magnetic and magneto-transport properties of nearly zero magnetostrictive CoFeSiB glass-coated microwires. Considering the importance of the role of stresses and of temperature it is expected that the combination of both will strongly affect the magnetic behaviour of the composite magnetic multilayer microwires.

Amorphous Co$_{68.5}$Fe$_{4.5}$Si$_{12.5}$B$_{15}$ glass-coated microwires with diameters of 23 µm and the thickness of the glass cover of 14.5 µm have been coated with Co and CoPtRh layers with the thickness of 900 nm. The Co and CoPtRh layers affect both the longitudinal and transverse anisotropy, affecting the axial magnetization process as well as the circumferential magnetization process involved in the phenomenon of magnetoimpedance (MI). Isothermal annealing at 300°C have been performed in vacuum atmosphere for 1 h. The CoFeSiB/Co and CoFeSiB/CoPtRh composite multilayer microwires present bi-phase magnetic behaviour as a result of the coupling between the ultra-soft magnetic phase of the amorphous CoFeSiB microwire and of the magnetic harder layer. After the thermal treatment all samples present bistability, the coercive filed decreasing for the samples with Co and CoPtRh layer. While in the case of the as-cast multilayer microwires the most sensitive MI effect was found in the CoFeSiB sample without deposited layer, in the case of annealed samples the strongest effect can be found in the CoFeSiB/Co sample. For the as-cast wires, the application of longitudinal tensile stresses of up to 323 MPa determines the inclination of hysteresis loop resulting in an ultra-soft magnetic behaviour. The tensile stresses applied to the CoFeSiB/Co multilayer microwires leads to a magnetic behaviour similar to the high magnetostrictive microwires, i.e. a rectangular hysteresis loop.

In conclusion, through the composition and annealing parameters and the parameters of the magneto-transport properties we can control the magnitude and sensitivity of the MI effect that allows us to design and develop magnetic sensors using the composite multilayer microwires as sensing elements which will operate in various ranges of magnetic field and sensitivity in function of the required specifications.

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INFLUENCE OF THE INTERWIRE DISTANCE ON LEFT-HANDED PROPERTIES OF Fe-BASED MICROWIRE METASTRUCTURES

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Nowadays, the microwave properties of artificial structures based on parallel arranged glass-coated amorphous microwires (GCAWs) are intensively investigated in order to develop metastructures with controllable left-handed properties. The properties of such metastructures are dependent on their geometrical parameters and also on the intrinsic properties of the microwires, offering flexibility for achieving different engineering requirements [1-4].

In this work we report some experimental and theoretical results on the left-handed properties versus the interwire distance for three new proposed Fe$_{77.5}$Si$_{7.5}$B$_{15}$ GCAWs-based microwires metastructures. The main aim is to obtain low reflection and high transmission values of the incident electromagnetic field in the microwave frequency domain.

The proposed metastructures were developed by parallel arrangement of Fe-based microwires with the metallic nucleus diameter $D_m = 6 \, \mu\text{m}$, the glass coating thickness $t_g = 8 \, \mu\text{m}$ and length $L = 8 \, \text{mm}$, on a commercial Teflon sheet holder, at different interwire distances, $d$, of 1 mm, 2 mm, and 3 mm, respectively. The left-handed characteristics of the metastructures were examined by measuring the reflection, $S_{11}(\text{dB})$, and the transmission, $S_{21}(\text{dB})$, coefficients using a X-band microwave-guide in the frequency range $8 - 12 \, \text{GHz}$, in an external d.c. magnetic field, $H$, ranging from 0 to 32 kA/m [4]. The Nicolson-Ross-Weir (NRW) and Landau–Lifshitz–Gilbert (LLG) models were used to calculate the complex dielectric permittivity and magnetic permeability of the studied metastructures.

The experimental results indicate that the metastructures present a decreasing of the relative reflection with 30% at $H = 0 \, \text{kA/m}$ from 45% at $H = 32 \, \text{kA/m}$, while the relative transmission increases from 75% at $H = 0 \, \text{kA/m}$ to 100% at $H = 32 \, \text{kA/m}$ by decreasing the interwire distance between GCAWs from 3 mm to 1 mm. The dielectric losses increase with 100% for $H = 0 \, \text{kA/m}$, respectively 50% for $H = 32 \, \text{kA/m}$, while the magnetic losses increase with 50% for $H = 0 \, \text{kA/m}$, respectively 20% for $H = 32 \, \text{kA/m}$, with the decreasing of the interwire distance due to the increasing of the high frequency interaction between GCAWs. The calculated results using the NRW and LLG models confirm the left-handed behavior of the proposed metastructures. The variation of the interwire distance proves to be a useful tool to obtain metastructures with controlled left-handed characteristics.

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THE EFFECT OF BALL MILLING PROCESS ON MAGNETIC AND STRUCTURAL PROPERTIES OF Fe$_{73.5}$Cu$_1$Nb$_3$Si$_{15.5}$B$_7$ POWDERS

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FeCuNbSiB magnetic alloys (ribbons, wires, thin films, powders) have been extensively studied due to their remarkable soft magnetic properties [1-3]. The interest in such systems displaying soft magnetic behaviour has been raised by their potential applications in a large variety of magnetic devices [1].

The aim of this work was to investigate the ball milling time influence on the morphology, structural and magnetic properties of Fe$_{73.5}$Cu$_1$Nb$_3$Si$_{15.5}$B$_7$ powders. Ribbons with the nominal composition Fe$_{73.5}$Cu$_1$Nb$_3$Si$_{15.5}$B$_7$ composition, from Vacuumshmelze GmbH & Co. KG, isothermally annealed in a vacuum furnace (10$^{-6}$ Torr) for 1 hour at 450°C, were milled using a planetary ball mill (SPEX Sample Prep 8000-series) for 10 min. to 60 min., in Ar atmosphere.

Morphological, structural and magnetic analyses of the powders were carried out. Scanning electron microscopy (SEM), X-ray diffractometry (XRD), and vibrating sample magnetometry (VSM) were used to analyze the shape and surface morphology, the structural evolution, and the magnetic behaviour of powders. The Curie and crystallization temperatures were determined from the thermomagnetic curves. Fe$_{73.5}$Cu$_1$Nb$_3$Si$_{15.5}$B$_7$ powders with powder average size from about 110 µm to 30 µm were obtained after milling times of 10 min. and 60 min., respectively. Increasing the milling time, mechanically induced crystallization of the powders was observed. The crystallization state during the ball milling process, indicated by the thermomagnetic curves, was confirmed by the existence of specific diffraction peak located at about 20=45°, corresponding to the (110) reflection of α-Fe(Si) phase from XRD analysis of powders. The milling process leads to the decrease of the saturation magnetization and the increase of the coercive magnetic field. The increase of the coercive magnetic field becomes significant for powders' average size smaller than about 40 µm.

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CoFe-based microparticles with low coercivity, high permeability and saturation magnetization properties were studied in the last couple of years because of their potential use in electromagnetic interference shielding, radar systems and high-energy storage systems. Ball milling method is a common way to fabricate micron-size particles by tailoring the size and structure of bulk metallic precursors.

In this paper, we report our experimental results on the structural and high frequency magnetic properties of ball milled CoFe-based particles for applications as filler element of microwave shielding materials.

Amorphous high-pressure gas-water-atomized Co$_{68.15}$Fe$_{4.35}$Si$_{12.5}$B$_{15}$ particles (AGA) with preponderant spherical shape and micrometric size ranging between 20 µm and 100 µm were used as precursors in our study. The SPEX Sample Prep 8000M MIXER/MILL device was used to further reduce the gas-atomized particle dimensions by grinding them for 10 and 20 hours in air. The ball to material ratio (BPR) was 5:1.

The size, shape and surface morphology of ball-milled (BM) particles were examined by scanning electron microscopy (SEM) using a Jeol JSM-6390A microscope. The evolution of the nanocrystalline phases during ball milling was investigated by XRD analysis in Bragg-Brentano configuration using a Bruker D8 Advance diffractometer. The quasi-static magnetic properties were measured using a vibrating sample magnetometer (VSM) in a maximum applied field of 0.8 T, at room temperature. The microwave absorption properties of CoFe-based BM particles were investigated using the 7 mm coaxial cell method in microwave domain from 2 to 12 GHz. The cell was connected to the emission/reception port of a PNAL-5230A vector network analyzer after a short-open-through calibration. The BM particle were mixed with epoxy resin in ~ 15 wt.% ratio and then pressed into toroidal shaped samples with $\Phi_{\text{out}} = 7.00$ mm, $\Phi_{\text{in}} = 3.04$ mm and 3 mm thickness.

The experimental results indicate that the mechanical grinding process induces a nanocrystalline structure in the BM particles. The XRD investigation point out the presence of CoFe, Fe$_3$B and $\alpha$-Fe phases, respectively, with average nanocrystallites of 7 to 10 nm for 20 h BM particles. The SEM images indicate a decreasing of the initial average diameters of AGA particles from about 60 µm to 5 µm for 20 h BM particles. The VSM measurements indicate a decrease of the saturation magnetization from 79 emu/g for the AGA particles to 72 emu/g for the 20 h BM particles, due to the anisotropies induced by stress, demagnetization effect, defects and surface oxides. The BM particles present broadband microwave shielding properties between 4 GHz and 11 GHz, with large reflexion signal values of about -30 dBm.

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MICROSTRUCTURAL INVESTIGATION OF Fe$_{79.7-x}$Ti$_x$B$_{20}$Nb$_{0.3}$ MAGNETIC RIBBONS

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The microstructure of Fe$_{79.7-x}$Ti$_x$B$_{20}$Nb$_{0.3}$ magnetic ribbons has been investigated using transmission electron microscopy (TEM) and energy dispersive X-ray spectroscopy (EDX), for a range of titanium compositions, $x=12$, 16, 18 and 20 at%. With $x=12$ at%, the ribbon specimens were found to be amorphous, with no sign of crystallisation. However, using EDX mapping, iron and titanium were found to have separated out into iron-rich cells and titanium-rich cell-boundaries. From $x=16$ at%, all specimens contained nanocrystals embedded within an amorphous matrix (see Figure 1a). Using EDX mapping, the nanocrystals were shown to be titanium-rich; and using electron diffraction and JEMS simulation, the nanocrystalline diffraction rings were shown to correspond to titanium diboride (TiB$_2$) (see Figure 1b). High resolution TEM investigation, in conjunction with Crystal Maker simulation software, confirmed this. Using electron energy-loss spectroscopy (EELS) to measure foil thickness, by counting the number of precipitates within a known area, and by approximating the crystal shape to spherical, the phase fraction of precipitates was found to increase with titanium concentration.

![Fig. 1. a) STEM image showing nanocrystalline precipitates in an amorphous matrix, and b) electron diffraction and overlaid JEMS simulation indicating the precipitate phase to be titanium diboride.](image)

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