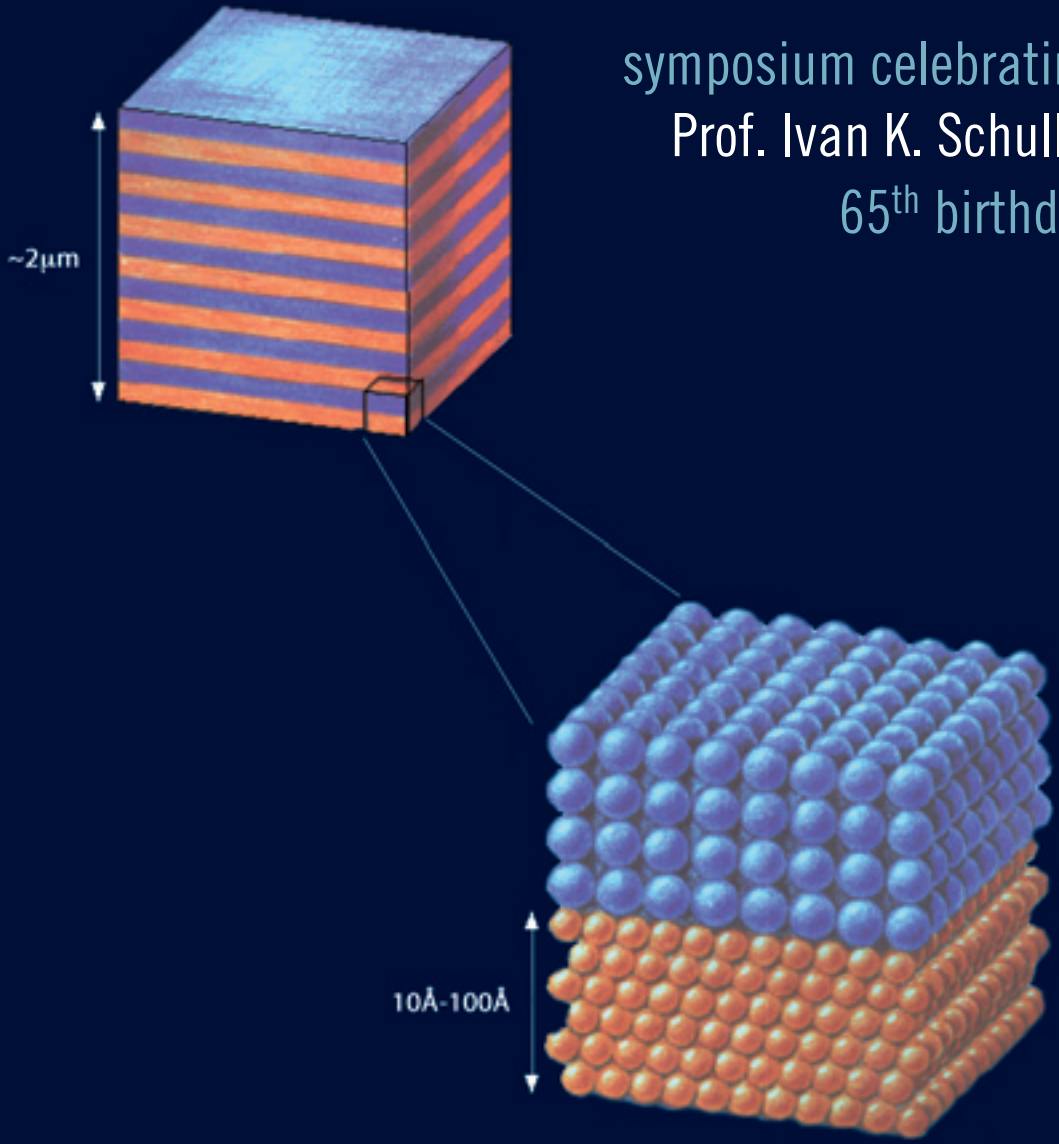


# physics at the nanoscale

18<sup>th</sup>-21<sup>st</sup> 2011  
october madrid.spain

symposium celebrating  
Prof. Ivan K. Schuller  
65<sup>th</sup> birthday



more information  
[www.nanociencia.imdea.org](http://www.nanociencia.imdea.org)

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# introduction

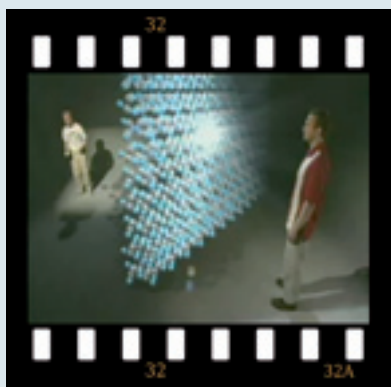


Ivan K. Schuller, a young and active researcher

Studies of Materials and Condensed Matter when their size is comparable to a characteristic physics length scales, in unusual geometric configurations has been central to Professor Schuller's research for more than 35 years and is crucial for his current activities. The focus on this field has been sharpened when it was renamed "Nanoscience" or "Nanotechnology", since most relevant and interesting length scales are at the nanoscale. This gave rise to so called "emergent properties", those which could not be predicted from a simple extrapolation from the properties of the individual constituents. Thus confinement into small structure, the incorporation into hybrid devices which are driven by external stimuli, and their behavior at short time scale is central to much of condensed matter physics and to important fore front technologies.

Prof. Ivan K. Schuller many contributions to the field have been recognized by a fellowship of the American Physical Society, appointments to the Chilean, Spanish, Colombian and Belgian Academies of Sciences, and many awards such as the American Physical Society's Wheatley (1999) and Adler Awards (2003), the German von Humboldt prize (2002), the Materials Research Society Medal (2004), the Lawrence Award from the US Department of Energy (2005), a Honoris Causa Doctorate (2005) from the Spanish Universidad Complutense, the Somiya Award from the International Union of Materials Research Societies (2008) and the UCSD Academic Senate Research Lectureship in Science, Engineering and Medicine (2008). He has published more than 480 technical papers and 20 patents, has given more than 350 invited lectures at international conferences and is one of the 100 most cited physicists (out of 500,000) in the last 15 years. Prof. Schuller's work was mentioned in the justification for the 2007 Nobel Prize ([http://nobelprize.org/nobel\\_prizes/physics/laureates/2007/sci.html](http://nobelprize.org/nobel_prizes/physics/laureates/2007/sci.html)) as a precursor to the discovery of Giant Magnetoresistance. Prof. Schuller's interest in maintaining high scientific standards and judging flawed and/or pathological science plays an important role in the development of fore front science.

Prof. Schuller has a very active program and extensive expertise in the high technology area. He is the head of a group of more than 10 researchers (technicians, students and postdocs), focusing their attention on the basic research



of Nanostructured, Organic, Magnetic and Superconducting materials (<http://ischuller.ucsd.edu>). As the Director of the AFOSR funded Multidisciplinary Research Initiative (MURI) on Integrated Nanosensors (<http://nanosensors.ucsd.edu/>) he lead a group of more than 40 physicists, chemists, biochemists and engineers focusing on the development of multiple nanosensors on a chip, with integrated power, limited computation and wireless communications. As one of the founders of the California Institute of Telecommunications and Information Technology (Calit2) he was the leader of the Materials and Devices layer (<http://matdev-calit2.ucsd.edu>). He has been a consultant to a variety of governmental commissions and national laboratories in the US, Latin America and Europe and to many commercial enterprises in the high technology area. He is presently the president of the IMDEA-Nanociencia Foundation which supports Nanoscience and Nanotechnology in Madrid, Spain and Director of the Center for Advanced Nanoscience (CAN) at UCSD.

In addition to his scientific activities, Prof. Schuller has extensive science related outreach and artistic activities. He has given numerous public lectures world wide in museums and TV about science to young and old, in several of the 7 languages he speaks. His movie “When Things Get Small” centered on Nanoscience has been translated to Spanish and Portuguese, has won 5 regional EMMYs, 2 TELLYS, a 1<sup>st</sup> Place Gold Camera Award and a 2<sup>nd</sup> place at the MRS professional film festival. His play “W=S” centered on the life of William Shockley is in the process of production. He is currently writing the script for his second full-length feature movie “When Things Get Big”. He believes that scientists have as an obligation to explain science to the public at large.

Perhaps the most important contribution in Prof. Schuller’s career has been developing his extensive, international net of collaborators; young and old. Prof. Schuller’s laboratory has been a meeting place for researchers from all over the world. His younger collaborators (students and postdocs) are doing first class research in their own right and his many more senior collaborators come from some of the best known research institution in the world. These activities have a multiplicative effect beyond the specific research or science outreach which have a direct link to Schuller’s name. Prof. Schuller’s interest and enthusiasm for science and life has been a motivator for many of us. We hope to have him around for many years as a colleague, collaborator, competitor, critic and friend.

### Professor Ivan K. Schuller's Honors

- University of Chicago Medal, 1981
- Outstanding New Citizen of Chicago in 1980-1981
- Technology 100 Award, 1981
- Fellow-American Physical Society, 1985
- Outstanding Scientific Accomplishments – US Department of Energy, 1987
- Foreign Member-Chilean Academy of Sciences, 1992
- Dozor Fellow, Israel, 1993
- Chilean Academy of Science, 1995
- Distinguished Speaker, Japan, 1998
- Centennial Speaker - American Physical Society, 1998-1999
- Wheatley Award - American Physical Society, 1999
- Corresponding Fellow-Belgian Academy of Sciences, 1998
- Alexander von Humboldt Prize – Germany, 2000
- 92nd most cited physicist (among 517,000) (<http://www.sst.nrel.gov/citations.pdf>)

- Highly Cited Researchers –Institute for Scientific Information, ISI-2000
- Adler Award - American Physical Society, 2003
- Medal- Materials Research Society, 2003
- E.O. Lawrence Award – U.S. Department of Energy, 2004
- Foreign Member-Spanish Academy of Sciences, 2005
- Doctor Honoris Causa – Universidad Complutense, Madrid, 2005  
(Only 6 physicists have been awarded with this honor: A. Einstein, P. Scherrer, L. Neel, A. Salam, I. Schuller and A. Leggett)
- Movie, *When Things Get Small* - 5 Regional EMMY awards, 2 TELLYs, First Place Gold Camera Award at the United States International Film and Video Festival, 2nd place Materials Research Society Professional Film Festival, 2006
- Sômiya Award for International Collaboration - International Union of Materials Research Societies (IUMRS), 2007



## Ivan Schuller Award Citations

Department of Energy-Outstanding Accomplishment in Solid State Physics, 1987  
*For research entitled "Structure of High Temperature Superconductors".*

American Physical Society-Wheatley-1999

*Dedication to the development of physics at the frontier level in Latin America, China and India; for his efforts in organizing international events and building strong bridges to connect people, ideas and resources from around the world; and for his results as an imaginative physicist and a close collaborator with young physicists in developing countries.*

German Government-von Humboldt, 2000

*Numerous research accomplishments in the field of metallic superlattices, which he initiated.*

American Physical Society-Adler, 2003

*For research in metallic heterostructures and superlattices, communicated with unusual enthusiasm and eloquence.*

Materials Research Society- Medal, 2003

*For innovative studies of exchange bias in magnetic heterostructures and nanostructures.*

Lawrence Award Department of Energy, 2004

*For creating the field of metallic superlattices and recognizing the impact of these materials on magnetism and superconductivity.*



# schedule & summary

## Tuesday 18<sup>th</sup> October

18:30 Welcome reception in Casa Sefarad-Israel

## Wednesday 19<sup>th</sup> October

09:00-09:30 Reception and Welcome

09:30-11:10 Talks

09.30 Y. Bruynseraede | p. 8 |

*Physics at all scales: 30 years of collaboration and friendship*

09.55 R.P. Huebener | p. 8 |

*Electronic nonequilibrium due to flux-flow in type-II superconductors*

10.20 J. M. Gallego | p. 9 |

*Charge transfer effects at the metal/organic interface*

10.45 K. Liu | p. 10 |

*Chirality control and vortex manipulation in nanomagnets*

11:10-11:30 Coffee Break

11:30-13:10 Talks

11.30 L. H. Greene | p. 10 |

*New superconducting materials research – International pursuits with Ivan*

11.55 R. Morales | p. 11 |

*Magneto-optical experiments to infer the spin configuration of FeF<sub>2</sub>-based exchange coupled systems*

12.20 D. N. Basov | p. 11 |

*Shedding infrared light on high-T<sub>c</sub> superconductivity*

12.45 A. Hoffmann | p. 12 |

*Discharging spintronics: pure spin currents*

13:10-14:30 Lunch

14:30-16:10 Talks

14.30 J. A. Schuller | p. 12 |

*Why I became a physicist*

14.55 E. M. González | p. 13 |

*Vortices on the move: playing with nanostructured hybrid systems*

15.20 J. Åkerman | p. 14 |

*Electrical and optical characterization of fundamental spin wave modes in nano-contact spin torque oscillators*

15.45 K. Temst | p. 15 |

*Exchange bias in Co/CoO bilayers and oxygen-implanted Co thin films: new surprises in an old system*

16:10-16:30 Coffee Break

16:30-18:10 Talks

16.30 J. B. Ketterson | p. 16 |

*Ferromagnetic resonance measurements and simulations on periodic dot and anti-dot arrays*

16.55 P. Prieto | p. 17 |

*Detailed magnetoresistance study in ferromagnetic antiferromagnetic bilayers based on the Ca-doped lanthanum manganite system*

17.20 R. Escudero | p. 17 |

*Coexistence of superconductivity and magnetism in intermetallic NiB<sub>3</sub>*

17.45 J. Nogués | p. 18 |

*Exchange bias, size and proximity effects in inverted, antiferromagnetic (AFM)/ferrimagnetic (FIM), core/shell nanoparticles*

## Thursday, 20<sup>th</sup> October

09:30-11:10 Talks

09.30 H. Weinstock | p. 18 |

*Nanotubes, nanosensors and superconductors*

09.55 C. M. Falco | p. 19 |

*Brillouin light scattering studies of buried magnetic nanostructures*

10.20 J. I. Martín | p. 19 |

*Magnetic nanostructures and superconducting vortices sign a collaboration agreement at UCSD*

10.45 D. Niarchos | p. 20 |

*Graded exchange spring media based on FePt*

11:10-11:30 Coffee Break

11:30-13:10 Talks

11.30 S. Sinha | p. 21 |

*Contributions towards Ivan's bias*

11.55 M-C. Cyrille | p. 22 |

*Magnetic tunnel junction based nano-oscillators*

12.20 M. A. García | p. 23 |

*Fabrication and properties of hybrid Au/Fe oxide nanostructures*

12.45 M. Varela | p. 24 |

*Magnetic oxide thin films under the electron microscope*

13:10-14:30 Lunch

# Summary

- 14:30-16:10 Talks**
- 14.30 S. Bader | p. 25 |**  
*Spintronics - Implications for energy, information and medical technologies*
- 14.55 J. Berger | p. 25 |**  
*Superconducting nanorings that operate as Brownian ratchets*
- 15.20 J. M. Colino | p. 26 |**  
*Uniaxial magnetic anisotropy in polycrystalline films nanopatterned with ion beam sputtering*
- 15.45 X. Batlle | p. 27 |**  
*Tuning exchange bias in Ni/FeF<sub>2</sub> heterostructures using antidot array*
- 16:10-16:30 Coffee Break**
- 16:30-18:10 Talks**
- 16.30 G. Güntherodt | p. 28 |**  
*From multilayers to bilayers of exchange bias and of graphene flatland: encounters with IKS*
- 16.55 V. Bekeris | p. 29 |**  
*The role of intrinsic random pinning in superconducting Nb films with periodic magnetic and non magnetic pinning sites*
- 17.20 D. Eger | p. 29 |**  
*Micro and nano-domain engineering in polar crystals*
- 17.45 E. Fullerton | p. 30 |**  
*Spin-transfer phenomena in high-anisotropy magnetic nanostructures*

## Friday, 21<sup>st</sup> October

- 09:30-11:10 Talks**
- 09.30 R. Miranda | p. 31 |**  
*Periodically rippled epitaxial graphene: an electronically and structurally nanostructured material*
- 09.55 M. Kiwi | p. 32 |**  
*Gold and rhodium nanocluster collisions: the relevance of d-shell polarization*
- 10.20 J. Santamaría | p. 33 |**  
*From metallic superlattices to complex oxides interfaces, a promenade with flavour to disorder*
- 10.45 D. Lederman | p. 33 |**  
*Using model systems to elucidate exchange bias mechanism*

- 11:10-11:30 Coffee Break**
- 11:30-13:10 Talks**
- 11.30 D. Dalhberg | p. 34 |**  
*A microscopic understanding of exchange anisotropy in Fe/MnF<sub>2</sub>*
- 11.55 J. E. Villegas | p. 35 |**  
*Nanoscale modulation of high-temperature superconductivity*
- 12.20 A. Gerber | p. 36 |**  
*Dynamics of successive minor hysteresis loops in thin multilayers*
- 12.45 J. d'Albuquerque Castro | p. 36 |**  
*Spatial dependence of the distribution of current in nanotubes and nanowires*
- 13:10-14:30 Lunch**
- 14:30-16:10 Talks**
- 14.30 M.R. Fitzsimmons | p. 37 |**  
*A whirlwind tour of neutron scattering at high altitude inspired by Ivan Schuller!*
- 14.55 R. K. Dumas | p. 37 |**  
*Graded anisotropy FePtCu films*
- 15.20 O. Petravic | p. 38 |**  
*Magnetic and electronic properties of nanoparticle super crystals*
- 15.45 E. Coronado | p. 39 |**  
*Molecular spintronics*
- 16:10-16:30 Coffee Break**
- 16:30-18:30 Talks**
- 16.30 J.-M. George | p. 40 |**  
*Spintronics with semiconductor materials*
- 16.55 W. A. A. Macedo | p. 40 |**  
*Depth-dependent spin structures in layered magnetic*
- 17.20 J. de la Venta | p. 41 |**  
*Methodology for the search for new superconducting materials*
- 17.45 M. B. Maple | p. 42 |**  
*Superconductivity, spin and charge order, and quantum critical behavior in correlated electron materials*
- 18.10 I. K. Schuller final remarks**

## Physics at all scales: 30 years of collaboration and friendship

Y. Bruynseraede<sup>1</sup>

<sup>1</sup> K.U.Leuven. Belgium.

**D**istinguished Professor Ivan K. Schuller is not only an internationally recognized Solid State Physicist and a recipient of many prestigious prizes and memberships, but also an artist and entertainment personality with activities centred on TV and theatre. My interactions and experiences with “the phenomenon” Schuller will be the main subject of my talk. Ivan’s

generous, conscientious and stimulating research and teaching during all those years provided a model to follow. Collaboration in the framework of research areas such as superconductivity, magnetism, metallic superlattices, x-ray diffraction, etc. will be briefly illustrated by personal reminiscences.

## Electronic nonequilibrium due to flux-flow in type-II superconductors

R. P. Huebener<sup>1</sup>

<sup>1</sup> Physikalisches Institut, Universität Tübingen. Auf der Morgenstelle 14, D-72076 Tübingen, Germany.

**I**n a normal metal nonequilibrium transport effects are usually dominated by Joule heating because of the large concentration of charge carriers. This leads to high electric currents and large power dissipation already at small electric fields. The opposite case is found in semiconductors, where the small concentration of charge carriers allows the presence of relatively large electric fields without excessive Joule heating. In this case, the Gunn effect and avalanche breakdown are typical electronic non-

equilibrium phenomena. In the mixed state of a type-II superconductor, in the flux-flow electric field, the small concentration of the quasiparticles can lead again to distinct electronic nonequilibrium effects (whereas the large concentration of charge carriers in the superconducting phase is not involved directly). Experiments dealing with this last case are described. Here Joule heating was suppressed by a geometry of very thin films and by cooling within a bath of superfluid helium.



## Charge transfer effects at the metal/organic interface

J. M. Gallego<sup>1</sup>

<sup>1</sup> Instituto de Ciencia de Materiales, CSIC. Cantoblanco. 28049-Madrid. Spain. Instituto Madrileño de Estudios Avanzados en Nanociencia (IMDEA-Nanociencia). Cantoblanco. 28049-Madrid. Spain.

Organic/metal interfaces are integral components of many optoelectronic organic devices, including organic light-emitting diodes or field-effect transistors. And as the quality of molecular crystals increases, transport across these interfaces starts to determine the device performance. This observation has motivated a large effort aimed at understanding the electronic structure of organic/metal interfaces and, in particular, the alignment of the energy levels, which finally determines the hole and electron injection barrier, and is often related to the charge transfer between the organic donor or acceptor species and the metallic surface.

Charge transfer, however, not only leads to modifications in the align-

ment of energy levels; it also may give rise to structural, electronic and chemical transformations in both donating and accepting species. Here we show, using a variety of surface analysis techniques (STM, LEED, XPS, XAS) in combination with theoretical calculations (DFT), several examples where charge transfer is proven to produce additional effects, such as: i) structural rearrangements on both sides of the organic/metal interface which can mediate new intermolecular interaction and thus modify the film growth; ii) thermally-controlled isomerization of the organic molecules and consequently of their self-assembly properties; and iii) polymerization reactions on the surface by the weakening of intramolecular bonds.



## Chirality control and vortex manipulation in nanomagnets

R. K. Dumas<sup>1</sup>  
D. A. Gilbert<sup>1</sup>  
N. Eibagi<sup>1</sup>  
T. Gredig<sup>2</sup>  
Chang-Peng Li<sup>3</sup>  
I. K. Schuller<sup>3</sup>  
**Kai Liu<sup>1</sup>**

- 1 University of California – Davis, USA.
- 2 California State University – Long Beach, USA.
- 3 University of California – San Diego, USA.

**M**agnetic vortices in sub-micron sized dots have gained considerable interests in recent years due to their fascinating physics and potential applications in information storage, spin-torque oscillators, and magnetic memory and logic devices. Reproducible control of the vortex chirality is of critical importance for these studies. Here we report on two distinctly different chirality control mechanisms in e-beam patterned asymmetric Co dots. Below a critical diameter and/or thickness, chirality control is achieved by the nucleation of a single vortex within each dot. The vortex can be manipulated to annihilate at particular sites under different field orientations and cycle sequences. Interestingly, above these critical

dimensions a new chirality control mechanism is realized by the nucleation and subsequent coalescence of double vortices, resulting in a single vortex at remanence with the *opposite* chirality as found in smaller dots. Magneto-optical Kerr effect and magnetic force microscopy measurements confirm this new process. Micromagnetic simulations not only reproduce the experimentally observed behavior, but also elucidate the delicate interplay between exchange, demagnetization, and Zeeman energies and the role of fractional vortices bound to the dot edge.

Work supported by the NSF (ECCS-0725902, ECCS-0925626, DMR-1008791), AFOSR, and CITRIS.

## New superconducting materials research – international pursuits with Ivan

**L. H. Greene<sup>1</sup>**

- 1 Department of Physics and Frederick Seitz Materials Research Laboratory, Center for Emergent Superconductivity, University of Illinois at Urbana-Champaign, Urbana, IL 6180 USA.

Ivan's 65<sup>th</sup> birthday coincides with the centenary of the discovery of superconductivity. Yet, the design of new and more useful superconductors remains as enigmatic as ever. These materials play crucial roles both for basic science and applications, and hold great promise in addressing our global energy challenge. The recent discovery of a new class of high-temperature superconductors has made the community more enthusiastic than ever about finding new

superconductors. Historically, these discoveries were almost completely guided by serendipity, and now, researchers in the field have grown into an enthusiastic global network to find a way, together, to predictively design new superconductors. I will share our general guidelines, comparing and contrasting with other approaches, including Ivan's, and hope to convey the renewed passion we all share in this international pursuit.



## Magneto-optical experiments to infer the spin configuration of FeF<sub>2</sub>-based exchange coupled systems

R. Morales,<sup>1,2</sup>  
 X. Batlle,<sup>3</sup>  
 J. M. Alameda,<sup>4</sup>  
 Ivan K. Schuller<sup>5</sup>

- 1 Dpto. de Química-Física, Universidad del País Vasco, 48940 Leioa, Spain. e-mail: rafael\_morales@ehu.es
- 2 Ikerbasque, Basque Foundation for Science, 48011 Bilbao, Spain.
- 3 Departament de Física Fonamental and Institut de Nanociència i Nanotecnologia, Universitat de Barcelona, 08028 Barcelona, Catalonia, Spain.
- 4 Departamento de Física, Universidad de Oviedo-CINN, Oviedo, 33007 Spain.
- 5 Physics Department, University of California-San Diego, La Jolla, California 92093, USA.

The penetration depth of the light in metallic materials has been used to probe the magnetic configuration of exchange coupled FeF<sub>2</sub>/FM (FM = Ni, FeNi) thin films. Antiferromagnetic/ferromagnetic (AF/FM) heterostructures have been engineered to investigate the existence of incomplete domain walls in the FM and the role of bulk AF spins in the origin of exchange bias. Magneto-optical measurements demonstrate that the exchange interaction at the AF/FM interface induces a magnetic depth profile through the thickness of the FM, which reverses its magnetization by an incoherent rotation parallel to the interface. On the other hand, experiments with trilayers provide evidence of an internal magnetic structure in the bulk of the AF that determines the magnitude of the exchange bias field. This finding suggests that the exchange bias phenomenon is not

only a purely interfacial effect in FeF<sub>2</sub>-based systems. Other magneto-optical experiments supporting this conclusion will also be presented.

## Shedding infrared light on high-Tc superconductivity

D. N. Basov<sup>1</sup>

- 1 University of California San Diego, USA. <http://infrared.ucsd.edu/>

The mechanism of high-Tc superconductivity is one of the most challenging unresolved problems in contemporary physics. The recent discovery of high Tc superconductivity in the iron pnictides, while interesting in itself, offers a new perspective on several aspects of cuprate high-Tc superconductors. I will overview common patterns as well as contrasting trends between the two classes of high-Tc materials, focusing on the information generated through infrared/opti-

cal probes. Infrared methods enable experimental access to energy gaps in a superconductor, strong coupling effects responsible for pairing, the collective response of the superfluid and allow one to quantify the strength of electronic correlations [Nature-Physics 5, 647 (2009)]. With this panoramic view of effects central for our understanding of superconductivity I will attempt to identify factors favoring higher Tc in exotic superconductors [Nature-Physics 7, 271 (2011)].

## Discharging spintronics: pure spin currents

A. Hoffmann<sup>1</sup>

<sup>1</sup> Materials Science Division, Argonne National Lab., Argonne, IL 60439, USA.

The idea of spintronics, where charge currents are combined with spin-dependent physics, has rejuvenated magnetism research over the last 25 years. However, looking further into the future the question arises, whether eliminating charge currents altogether could provide additional benefits. Towards this end, non-local device geometries allow for separating spin and charge currents, which in turn enables the investigation and use of pure spin currents. This approach opens up new opportunities to study spin-dependent physics and gives rise to novel approaches for

generating and controlling angular momentum flow as has been recently demonstrated by many groups, including Ivan Schuller's group at UCSD. In this context I will discuss one of Ivan's favorite topics; namely, what is the role of imperfect interfaces? Luckily, it turns out that for the case of spin injection, imperfection (in our case the presence of an interfacial oxide) is beneficial for large spin signals.

This work was supported by DOE BES under Contract No. DE-AC02-06CH11357.

## Why I became a physicist

J. A. Schuller<sup>1</sup>

<sup>1</sup> Columbia University Energy Frontiers Research Center, USA.

Prof. Ivan Schuller's success in the field of physics can be attributed to a variety of qualities which characterize him as a scientist: a passion for communicating and teaching science, an enthusiasm for mentoring and assisting younger scientists, the ability to distill difficult scientific concepts into easily understood physical principles, and the confidence to pursue his own scientific interests regardless of conven-

tional wisdom or popularity. In this talk I will discuss examples from Ivan's career and personal life which exemplify these attributes and demonstrate how these qualities inspired me to become a physicist myself. Finally, I will describe examples of how I have endeavored to develop and nurture similar capabilities in my own career as a physicist working in the field of nanophotonics.

## Vortices on the move: playing with nanostructured hybrid systems

E. M. González<sup>1</sup>

<sup>1</sup> Dpto. Física de Materiales, Facultad de Ciencias Físicas, Universidad Complutense de Madrid, Spain.

**N**anostructured hybrid systems, based on a superconducting film grown on top of an array of ordered magnetic nanostructures, allow studying the behavior of the superconducting vortex lattice moving in the presence of well defined potential landscapes. In this talk, I show a variety of experimental results found in the dynamical response of the superconducting vortex lattice induced by the potential landscape. Among them, reduced dissipation can be observed for certain values of the external applied magnetic field, ratchet effects (unidirectional vortex movement under zero-time average exter-

nal forces) can appear when the potential landscape provides a source of asymmetry. Electron beam lithography has been used for patterning the nanostructured array. The superconducting and magnetic materials were deposited by sputtering technique. Finally, etching and conventional lithography define a bridge for magnetotransport measurements.

Work supported by Spanish Ministerio de Ciencia e Innovación under grants No. FIS2008-06249 and Consolider No. CSD2007-00010, CAM grant S2009/MAT-1726 and Santander-UCM grant GR35/10-A-910571



# Electrical and optical characterization of fundamental spin wave modes in nano-contact spin torque oscillators

J. Åkerman<sup>1</sup>

S. Bonetti

Y. Pogoryelov

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M. Madami

G. Carlotti

G. Gubbiotti

G. Consolo

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Nano-contact based spin torque oscillators (NC-STOs) operate through the generation of spin waves in a region of the free layer underneath the nano-contact. The frequency and amplitude of these spin waves can be tuned by the drive current and the applied field strength and the type of spin wave mode can be controlled from propagating to localized as a function of the out-of-plane angle  $\theta_e$  of the applied magnetic field as shown both theoretically and using micromagnetic simulations [1-4]. By studying the NC-STO signal as a function of  $\theta_e$ , we find that at angles  $\theta_e$  below a certain critical angle  $\theta_{cr}$ , two distinct spin wave modes can be excited: a propagating mode, and a localized mode. The experimental frequency, current threshold and frequency tunability with current of the two modes can be described qualitatively by analytical models and quantitatively by numerical simulations. We also show that the Oersted field strongly affects the current tunability of the propagating mode at subcritical angles, and it is also the fundamen-

tal cause of the mode hopping observed in the time-domain [5]. We also argue that the NC-STO is the ideal spin wave generator in magnonic circuits and we will describe our efforts in using scanning micro-BLS to directly observe the propagation of such spin waves and the spatial profile of this propagation outside of the nano-contact region.

## References

- [1] A. Slavin and V. Tiberkevich, *Phys. Rev. Lett.* **95**, 237201 (2005).
- [2] G. Consolo, B. Azzerboni, G. Gerhart, G. A. Melkov, V. Tiberkevich, and A. N. Slavin, *Phys. Rev. B* **76**, 144410 (2007).
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- [4] G. Consolo, B. Azzerboni, L. Lopez-Diaz, G. Gerhart, E. Bankowski, V. Tiberkevich, and A. N. Slavin, *Phys. Rev. B* **78**, 014420 (2008).
- [5] S. Bonetti, V. Tiberkevich, G. Consolo, G. Finocchio, P. Muduli, F. Mancoff, A. Slavin, and Johan Åkerman, *Phys. Rev. Lett.* **105**, 217204 (2010)





## Exchange bias in Co/CoO bilayers and oxygen-implanted Co thin films: new surprises in an old system

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Exchange bias (EB), the interfacial coupling between a ferromagnet (FM) and an antiferromagnet (AFM) has been a widely studied phenomenon since its discovery. It has been studied in bilayers, core-shell clusters, and nano-structured materials. In the first part of the lecture we will review the properties of exchange bias in surface-oxidized Co thin films, with the emphasis on the asymmetry of the magnetization reversal mechanism and the training effect. We will also discuss how the training effect can be (partially) restored by applying a magnetic field perpendicular to the initial cooling field direction.

In the second part we will discuss the use of ion implantation and irradiation, which has been limited so far to the modification of pre-existing exchange bias systems. We present the application of ion implantation to *generate* an EB system [1], rather than to modify it. We implanted O ions in thin Co films (100 nm) in order to form CoO, embedded in the film. The coupling between the formed CoO and the Co matrix gives rise to EB. We show the feasibility of this approach

and prove that the observed EB is a consequence of the formation of CoO and not of implantation related damage, by comparison to Ne implanted Co films. Furthermore, this system exhibits a clear training effect, i.e. the EB effect depends on the number of times the hysteresis loop is measured. In the more conventional EB bilayers, this effect is understood by a change in magnetization reversal mechanism. Due to the clear morphological differences of the FM-AFM interface between this implanted system and bilayers, a strong influence on the reversal mechanism is anticipated. Therefore it was studied with *anisotropic magnetoresistance* and *polarized neutron reflectometry*. Both measurements reveal a different behavior from bilayers: all reversals are governed by domain wall nucleation and motion, where in bilayers a change from domain wall nucleation and motion to coherent rotation is observed.

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# Ferromagnetic resonance measurements and simulations on periodic dot and anti-dot arrays

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Using a broad band meander-line based technique, that allows the study of mode structures continuously as a function of applied microwave frequency, we have carried out extensive ferromagnetic resonance (FMR) measurements on arrays of square-, circular- and diamond-shaped holes, as well as circular discs, both of which form a square Bravais lattice. The structures were e-beam patterned starting from thin permalloy films. Such samples generally show multiple resonances. At higher fields, where the hole arrays are uniformly magnetized, the behavior is non hysteretic and the overall structure of the FMR spectrum displays the symmetry of the underlying lattice. At low fields, resonances that are positioned asymmetrically with respect to positive and negative fields (and sometimes absent all together for one field direction) are observed when sweeping from positive fields through zero to negative fields; a corresponding behavior is observed when sweeping in the opposite direction. Such hysteretic effects, typically limited to studies of static characteristics, represent a relatively novel development in FMR studies, particularly with respect to their possible connection with symmetry-breaking (e.g. domain formation) transitions in the underlying lattice. Hysteretic effects involving the discs allow a determination of the phase boundaries of vortex phases

Simulations of the static magnetization distribution and FMR mode

spectrum were carried at low and high fields using both the discrete dipole approximation (DDA) and Fourier transform methods. The DDA is adapted to incorporate the periodicity of the underlying lattice as well as the Bloch-like structure of the excitations. On the other hand the Fourier transform approach, applied to a large but finite array of holes, also allows calculations at low fields where domain formation is found to break the underlying translational symmetry of the hole lattice. Such calculations are generally in good agreement with the experiments with respect to field, field-angle and microwave frequency. Simulations of disc arrays reveal vortex phase boundaries.

As a simple model of the high field FMR spectrum one can view an underlying hole lattice as a two dimensional diffraction grating that couples the essentially uniform microwave field (on the scale of the patterned array) into modes with wave vectors corresponding to the first and higher Brillouin zones associated with the lattice. Magneto-static contributions, originally described by Damon and Eshbach, result in differing dispersion for wave vector components parallel and perpendicular to the in-plane field direction resulting in the presence of multiple resonances (in addition to the uniform mode) along with a nontrivial dependence on the angle between the magnetic field and the symmetry axes of the lattice.

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- [1] The work to be reported involved a collaboration between: J. Sklenar (Northwestern University), V. Bhatt and L. D. DeLong (University of Kentucky), K. Rivkin (Seagate Technologies), V. Metlushko (University of Illinois -Chicago), C. C. Tsai (Chinese Christian University -Taiwan), O. Heinonen (Argonne National Laboratory); it was supported by the U. S. National Science Foundation, the Air Force Office of Scientific Research, and the U. S. Department of Energy.



## Detailed magnetoresistance study in ferromagnetic antiferromagnetic bilayers based on the Ca-doped lanthanum manganite system

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We studied the isothermal magnetic field dependence of the resistance behavior in ferromagnetic/antiferromagnetic bilayers based on the Ca-doped lanthanum manganite system at temperatures below Neel temperature of the antiferromagnetic layer. We studied the influence of the thickness of the AF-layer,  $t_{AF}$ , and F-layer,  $t_F$ , on the ZFC and FC magnetoresistance (MR) in  $La_{2/3}Ca_{1/3}MnO_3(t_F)/La_{1/3}Ca_{2/3}MnO_3(t_{AF})$  bilayers.  $H_{FC}$  was varied from 400 Oe to 100 Oe. We systematically varied the  $t_F$  and  $t_{AF}$  thickness, maintaining constant the total bilayer thickness ( $d = t_F + t_{AF}$ ). We found that MR has hysteretic behavior as observed in  $[La_{2/3}Ca_{1/3}MnO_3(t_F)/La_{1/3}Ca_{2/3}MnO_3(t_{AF})]_N$  superlattices, but; MR increases with the increasing field from  $H=0$  to a maximum and then decreases continuously. This behavior also appears for

negative fields in both ZFC and FC loops. The position and magnitude of the maximum is not symmetric with respect to the axis  $H=0$  for ZFC loops. We found that some magnetic behavior of the bilayers is interfacing dependent for both ZFC and FC loops.

Work supported by “*El Patrimonio Autónomo Fondo Nacional de Financiamiento para la Ciencia, la Tecnología y la Innovación Francisco José de Caldas*” contract RC- No. 275-2011.

## Coexistence of superconductivity and magnetism in intermetallic $NiBi_3$

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$NiBi_3$  polycrystals were synthesized via a solid state method. X-ray diffraction analysis shows that the main phase present in the sample corresponds to  $NiBi_3$  in a weight fraction of 96.82% according to the refinement of the crystalline structure. SEM - EDS and XPS analysis reveal a homogeneous composition of  $NiBi_3$ , without Ni traces. The powder superconducting samples were studied by performing magnetic measurements. The superconducting transition temperature and critical mag-

netic fields were determined as  $T_c = 4.05$  K,  $H_{C1} = 110$  Oe and  $H_{C2} = 3,620$  Oe. The superconducting parameters were  $\xi_{GL} = 301.5$  Å,  $\lambda_{GL} = 1549$  Å, and  $\kappa = 5.136$ . Isothermal measurements below the transition temperature show an anomalous behavior. Above the superconducting transition the compound presents ferromagnetic characteristics up to 750 K, well above the Ni Curie temperature.

## Exchange bias, size and proximity effects in inverted, antiferromagnetic (AFM)/ferrimagnetic (FiM), core/shell nanoparticles

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Although passivated ferromagnetic (FM) nanoparticles coated with antiferromagnetic (AFM) oxide shells have been extensively investigated, studies of core/shell nanoparticles with AFM cores are rather scarce. Here we present the study of inverted AFM-core/ferromagnetic (FiM)-shell systems. MnO/Mn<sub>3</sub>O<sub>4</sub> nanoparticles with different core sizes (2-20 nm) and fixed shell thickness (~3 nm) were synthesized. Interestingly, the phase of the passivation shell ( $\gamma$ -Mn<sub>2</sub>O<sub>3</sub> or Mn<sub>3</sub>O<sub>4</sub>) depends on the nanoparticle size. This system may be considered as *double inverted* since  $T_C(\text{Mn}_3\text{O}_4) < T_N(\text{MnO})$ , as opposed to conventional systems. Monodispersed 11 nm FeO/Fe<sub>3</sub>O<sub>4</sub> particles, with eas-

ily tuneable core/shell ratio, were prepared by controlling the passivation conditions. In this case  $T_C(\text{Fe}_3\text{O}_4) > T_N(\text{FeO})$ , thus the system can be considered *single inverted*. In both systems the coupling at the AFM/FiM interface leads to strong exchange bias effects (e.g., large loop shift and coercivities) at low temperatures. The magnetic properties depend in a complex way on the core and shell sizes. In both systems the temperature dependence of the exchange bias properties is controlled by the counterpart with lowest critical temperature. Remarkably, in the case of MnO the magnetic order of the FiM shell is stable far above its  $T_C$  up to  $T_N$  of the core (magnetic proximity effect).

## Nanotubes, nanosensors and superconductors

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I've known Ivan Schuller for over 30 years when we both were employed in the Chicago area. I reconnected with Ivan about 12 years ago when I came to UCSD to visit another faculty member. Not unexpectedly, Ivan described some research for which he was seeking funding. At that time I had no funds available. Shortly thereafter, I discovered a new source of funds that might apply to Ivan's research on close-packed alumina nanotubes. A deadline for proposal submission was fast approaching while Ivan was in Chile, but he managed to beat the deadline. Thus began an uninterrupted period in which I've had the privilege of helping provide Air

Force basic research funds that supported some of his creative scientific endeavors. I still fund his alumina nanotube work, but additionally he has received funding for a 5-year Multidisciplinary University Research Initiative (MURI) on multifunctional nanosensors in 2002, and for another MURI in 2009 on a search for new classes of superconductors. I shall review some of Ivan's achievements under these AFOSR grants, and under subsequent subcontracts with small businesses working with Ivan and 2 chemistry colleagues to market nanosensors to detect trace amounts of explosives.



## Brillouin light scattering studies of buried magnetic nanostructures

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Because of the very short-range nature of the magnetic interaction, the anisotropy is particularly sensitive to the perfection of the interfaces, and thus is strongly dependent upon the quality of the deposition process. Recently we have been applying *in situ* spinwave BLS techniques at pressures  $\sim 10^{-10}$  torr to ultrathin films and sandwich structures we are growing by Molecular Beam Epitaxy (MBE). The sensitivity of the BLS

technique is illustrated by our results on MBE-grown Co films with thicknesses in the range 1-7 atomic monolayers (ML). We are able to clearly observe spinwave excitations for samples as thin as 1 ML of Co buried by as much as 20 nm of Au. Research supported by U.S. DOE DE-FG02-93ER45488.

## Magnetic nanostructures and superconducting vortices sign a collaboration agreement at UCSD

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In this presentation, I will first review how the optimization of the fabrication process of ordered magnetic nanostructures by electron beam lithography, together with the possibility to measure magnetotransport properties in superconducting films, resulted in the observation of synchronized pinning of the vortex lattice by arrays of magnetic dots at Ivan Schuller's lab, opening the opportunity to tailor and tune several physi-

cal properties of the superconducting mixed state during the following years up to now. I will also present some recent results on Magnetism, partially inspired in the previous ones, showing how it is possible to pin, control and modify the magnetic domain wall motion in uniaxial magnetic films with nanostructured arrays of holes.

## Graded exchange spring media based on FePt

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Since their invention in 1957, magnetic hard disk drives (HDDs) have remained in the forefront of data-storage technology providing a robust and versatile way to quickly record, store and retrieve data at a better cost compared to other type of storage media. The longitudinal technology has been overtaken by the perpendicular recording technology in the last decade, promising densities of close to 1 Tbit/in<sup>2</sup>. For a Tbit/in<sup>2</sup> we do need bit cells in the range of 10-15 nm and materials with high magnetic anisotropy ( $K_u$ ) so that  $K_u V > 60 K_B T$  in order that written data must retained for more than 10 years. Perpendicular high magnetic anisotropy materials, like fct-FePt have been proposed as the best candidates for supporting densities 1Tbit/in<sup>2</sup> and beyond. The high coercivity ( $H_c > 3T$ ) of these materials makes difficult the writing process using the available magnetic write heads. For a solution to this problem a novel type of Exchange Spring Media (ESM) has been proposed. In such media a magnetically hard layer (high anisotropy  $K_u$ ) and a magnetically softer layer (lower anisotropy  $K_s$ ) are strongly exchange coupled leading to structures with lower  $H_c$  thus lowering the write field requirements. A better approach for reducing more the writing field but keeping the thermal stability very high is the class of Graded Exchange Spring Media (GESM), which have been proposed as a new class of nanocomposite material appropriate for ultra high density

recording media. Graded ESM with a spatially varying anisotropy  $K_u(z)$  offer improved characteristics in comparison to homogeneous, constant  $K$  Hard / Soft bilayer media. Our efforts have been focused on the growth of graded exchange spring media based only on FePt using sputtering. Changing the deposition temperature affects the fcc to fct transformation and thus changes the fct order parameter and the anisotropy  $K_u(z)$ . To achieve this we have worked with (200) textured MgO substrates where the FePt can be grown with (001) orientation on MgO, i.e. with the  $c$ -axis, the easy anisotropy axis of the tetragonal phase, perpendicular to the film plane. At first a single phase fct FePt layer with high coercive field  $H_c$  and perpendicular to the film plane magnetic anisotropy has been deposited on MgO substrate using sputtering at 700 °C. The next step was the growth of the graded layer on the top of the magnetically hard fct FePt layer, which produces a monotonic gradient of the anisotropy constant through the thickness of the layer (~ 20 nm). Here we will report an overview of the state-of-the-art of the structural and magnetic properties of graded media using XRD, GID, TEM, AFM, MFM and SQUID measurements. The first results showed that the switching field is significantly reduced compared to single phase media, verifying the theoretical calculations.

Work supported by the ICT-224001 TERAMAGSTOR Project of the EU.

## Contributions towards Ivan's Bias

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Exchange Bias in ferromagnetic-antiferromagnetic bilayers is a phenomenon that has been known for fifty years, and has already been put to wide commercial use in devices such as magnetic read-heads and other devices. Nevertheless a detailed and complete microscopic understanding of the effect has proved to be fairly difficult, notwithstanding many beautiful studies on this problem over the years by Ivan and other researchers, and the development of several alternative theoretical models. This is partly due to the necessity of understanding the details of the interactions and the magnetic structure across and in the vicinity of the interface between the ferromagnet and the

antiferromagnet. The details of how interface roughness and other defects affect exchange bias and the details of how magnetic domains are established on both sides of the interface are still not well understood. Non-destructive probing of such buried interfaces is conveniently accomplished with neutron scattering or synchrotron X-ray techniques, and these types of experiments have been increasingly employed over the last decade. We shall discuss what has been learned from a few such recent experiments and what crucial issues remain unresolved, with particular emphasis on recent studies of the Co/FeF<sub>2</sub> exchange bias bilayer system.



# Magnetic tunnel junction based nano-oscillators

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Mobile phones and wireless telecommunication devices are mostly based on single-frequency RF oscillators (one per band). Current technology state of art is a combination of stand-alone high quality, low frequency mechanical resonators (e.g. quartz crystals) and integrated high frequency, low-quality LC tank-based phase locked loops (PLL). This technology has been mature and low cost for several decades, but it now faces severe limitations in terms of integration (large chip area), power consumption, and multiple frequency standard compatibility. Part of the more-than-Moore mutation of micro-electronics, emerging disciplines such as Spintronics offer new nanotechnologies for RF oscillators based on the spin torque exerted by a spin-polarized current in a magnetoresistive device:

Spin transfer driven magnetization oscillations in CoFeB based magnetic tunnel junctions (MTJs) containing crystalline MgO barriers, with high tun-

ing magnetoresistance (TMR) and low resistance-area products (RA) are reported. Frequency and time domain characterisation of those MTJ based Spin Torque Oscillator (STO) will be presented. It will be shown that although output power is significantly increased compared to conventional spin valve based STOs [1], their output power and spectral purity are not yet fully compatible with telecom applications requirements [2]. Possible solutions to overcome those issues and a path to improvement at device and system level will be presented [3], [4].

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# Fabrication and properties of hybrid Au/Fe oxide nanostructures

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Metallc nanoparticles supported onto a substrate can be obtained by thin film deposition and subsequent annealing. The stress relief after the thermal annealing, due to the difference of thermal expansion coefficient between the metal and the substrate, promotes hillock formation and subsequent hole nucleation, growth and percolation, leading to the formation of layers of nanoparticles. The nanoparticle size and inter-particle distance can be tuned by controlling the initial film thickness and the annealing time, temperature and atmosphere, providing a simple and low cost method to prepare NPs layers over large areas.

This method has been successfully applied in the past to obtain nanoparticles from a single metallic layer in the past.

We report here the formation of complex nanoparticles ensembles by deposition and annealing of Au-Fe multilayers. The large differences in thermal properties between Au and Fe allow tuning the features of the NPs separately and promoting the formation of hybrid nanostructures. The optical and magnetic properties of the ensembles as well as cross-over effects are studied as a function of the structure of the multilayers and the annealing conditions.



## Magnetic oxide thin films under the electron microscope

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The properties of magnetic films are intimately related to their atomic structure and the presence of defects, interfaces etc. Electron energy loss spectroscopy (EELS) in the aberration corrected scanning transmission electron microscope (STEM) allows simultaneous exploration of structure, chemistry and electronic properties in real space with atomic resolution. Techniques such as electron magnetic chiral dichroism allow studies of magnetization in real space [1]. These techniques combine to provide a unique tool to understand systems such as the  $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3/\text{SrTiO}_3$  (LSMO/ STO) ferromagnetic/insulating superlattices where a magnetic moment on Ti atoms has been measured [2]. EELS images show that charge transfer takes place due to the presence of an extra interfacial  $\text{La}_{0.7}\text{Sr}_{0.3}\text{-O}$  plane. Other examples to be described include the sensitivity of the EELS fine structure to the spin

state of Co atoms in perovskites [3]. The ordering of O vacancies along with the presence of epitaxial strain in these compounds can stabilize a superlattice in the Co spin state which can be measured by EELS [4]. Research supported by the U.S. DoE, Office of Basic Energy Sciences, Materials Sciences and Engineering Division and the European Research Council Starting Investigator Award.

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## Spintronics – implications for energy, information and medical technologies\*

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Spintronics encompasses the ever-evolving field of magnetic electronics [1]. Fields such as spintronics hold the potential to extend the information technology revolution as the semiconductor roadmap reaches its end. A major issue with present day electronics is in its demand for increased power. Spintronics offers the possibility to communicate via pure spin currents as opposed to electric charge currents. The talk provides a brief perspective of recent developments to switch magnetic moments by spin-polarized currents, electric fields and photonic fields. Developments in the field of spintronics continue to be strongly dependent on the exploration and discovery of novel nanostructured materials and configurations. An array of exotic transport effects dependent on the interplay between spin and charge currents have been explored theoretically and experimentally in recent

years. The talk highlights select promising areas for future investigation, and, features recent work at Argonne [2-4], including, most strikingly, in the realm of medical applications [5].

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## Superconducting nanorings that operate as Brownian ratchets

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Experiments at Chernogolovka have found a flux-dependent dc voltage in nonuniform superconducting loops. Under assumptions that appear reasonable, simulations also predict a dc voltage in loops with two weak links, each with a different current-phase relation.

# Uniaxial magnetic anisotropy in polycrystalline films nanopatterned with ion beam sputtering

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In this work we review advances in ion beam sputtering (IBS) nanostructuring of magnetic films in order to induce uniaxial magnetic anisotropy as well as present our recent contributions in this topic. Pioneering studies of magnetic effects induced by IBS date in 2003 and focused in nanometer thin epitaxial cobalt films; later some groups have pursued application to “real” thick polycrystalline ferromagnetic films, e.g. permalloy, iron and cobalt. We have investigated the formation, magnetization reversal, and magnetotransport of nanoscale ripples on sculpted polycrystalline Co films. After growth, films are eroded *in situ* with Ar<sup>+</sup> beam (1 keV) in grazing incidence. Atomic and magnetic microscopy show a periodic array of quasi unidimensional surface ripples running parallel to the ion beam direction. The amplitude and periodicity of the ripples can be tuned in several ways.

Very-well defined uniaxial magnetic anisotropy, with the magnetization easy axis (e.a.) along the ripple direction, has been found for samples with a long erosion time. The relevant mechanism of magnetization reversal changes from nucleation and further domain propagation around the e.a. to rotation processes around the hard axis direction. The precise origin is discussed in terms of magnetostatic stray fields and magnetic-dipole effects.



## Tuning exchange bias in Ni/FeF<sub>2</sub> heterostructures using antidot arrays

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The transition from positive to negative exchange bias can be systematically tuned with antidot arrays artificially introduced into Ni/FeF<sub>2</sub> ferromagnetic (FM)/antiferromagnetic (AF) heterostructures [1, 2]. This is a consequence of the energy balance between the Zeeman coupling of the spins in the AF and the AF coupling at the FM/AF interface. The nanostructure plays a key role in the formation of pinned uncompensated spins in the AF [2, 3]: the antidot carving produces regions of locally pinned uncompensated spins throughout the antidot faces of the FeF<sub>2</sub> and these *non* interfacial magnetic moments favor the onset of positive exchange bias at lower cooling fields, by increasing the Zeeman energy of AF domains and favoring the alignment with the latter. Those *non* interfacial AF spins, and the pinned uncompensated interfacial AF spins responsible for the exchange bias (loop shift), align simultaneously with the cooling field since they belong to the same domain and become pinned below the Néel temperature. As a result, the cooling field required for positive exchange bias decreases by one order of magnitude for the antidot arrays, as compared

to the unpatterned heterostructures. This is relevant concerning the applicability of FM/AF bilayers as multi-state storage media [4], since the minimum cooling field necessary to obtain positive exchange bias establishes the magnetic field required for multi-state storage writing [5].

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# From multilayers to bilayers of exchange bias and of graphene flatland: encounters with IKS

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Inspirations and cooperations owed to Ivan K. Schuller (IKS) in the context of magnetism in layered- and nano-structures are being reviewed from a more personal point of view. I take this opportunity to express my admiration and gratitude to a long-time friend and “hombre de acción”.

The Schuller-Falco “dream team” initiated in 1979 a new class of materials due to artificial layering: the metallic superlattices, challenging the well established semiconductor variant. It caught my attention, having carried out light scattering in metals. With the “Falco branch” my group investigated collective spin wave excitations in magnetic multilayers using Brillouin light scattering. During a sabbatical in 1996 Ivan Schuller awakened my interest in the “exchange bias” (EB) phenomenon, the exchange interaction between a ferromagnet and an antiferromagnet. Besides a number of joint papers, the “EB Manifesto” resulted in 2002 ([http://ischuller.ucsd.edu/exchange\\_manifesto.php](http://ischuller.ucsd.edu/exchange_manifesto.php)) during Schuller’s visit to RWTH Aachen as Humboldt Research Prize Awardee. In the course of this stay he initiated magneto-optic studies of the magnetization reversal asymmetry in EB. In parallel, my group together with Uli Nowak happened to develop the “domain state” (DS) model. Random defects in the magnetic sub-

lattices throughout the volume of the antiferromagnet give rise to domain wall pinning and the creation of uncompensated spins, which are also responsible for the pinning of the uncompensated interfacial spins, thus yielding EB. This DS model was further supported in a seminal paper by Schuller’s group in 2009 (PRL **102**, 097201).

However, despite all sputtering or molecular epitaxy (MBE) machinery for layer deposition, the most perfect epitaxial layer is obtained by simply mechanically exfoliating graphene from graphite single crystals. I would like to convey as a birthday gift the fascinating physics of pure spin currents in graphene. We found for the first time spin relaxation times of 2 ns at room temperature in exfoliated bilayer graphene [1] as well as in Cu-based CVD synthesized wafer scale samples [2]. Besides  $\mu\text{m}$ -long spin relaxation lengths, these data hold the promise of potential spintronics applications.

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## The role of intrinsic random pinning in superconducting Nb films with periodic magnetic and non magnetic pinning sites

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**W**e study vortex lattice (VL) dynamics in patterned Nb films containing dense periodic arrays of sub 50 nm magnetic nanodots or holes, by means of ac susceptibility measurements. For temperatures near the critical temperature  $T_c$ , reversible matching effects are observed that are related to the periodicity of the strong artificial pinning potentials. As the temperature is reduced below a characteristic cross over temperature  $T^* \sim 0.75 T_c$  in both samples, an anomalous hysteretical behavior is observed, with a history dependent apparent matching field value. We find that this behavior is consistent with the competition below  $T^*$  between periodic pinning, independent of its origin, and intrinsic random pinning.

## Micro and nano-domain engineering in polar crystals

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**I**nverted domain structures in optical polar crystals are used for a variety of applications such as second harmonic generation, parametric frequency down-conversion, electro-optical deflection and all-optical switching.

In this talk I'll describe different methods for the fabrication of inverted domain micro structures: chemical patterning, electric field poling and oriented epitaxial growth. Some attempts in creating nano-scale domains by

direct E-beam writing or by using high voltage atomic force microscopy will also be mentioned.

Next I shall describe the basics of optical interactions that are taking place in the inverted domain structure and show some results for different applications. In particular, I'll point out some gaps in our fundamental understanding of parametric process that may require more theoretical and experimental work.

# Spin-transfer phenomena in high-anisotropy magnetic nanostructures

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In most magnetic applications the orientations of the magnetic elements are controlled by external magnetic fields. However, it has recently been appreciated that the relative orientations of nano-magnets can be controlled directly by the injection of spin polarized currents known as spin transfer effects. The ability of a spin-polarized current to reverse the magnetization orientation of a nano-magnets should enable a range of devices such as high performance random-access magnetic memories and spin-oscillators [1]. In this presentation I will review the basic properties of spin-transfer and highlight recent research on spin-transfer effects in nano-elements having strong perpendicular magnetic anisotropy [2,3]. This perpendicular geometry has a number of advantages including efficient coupling of the spin-current to magnetic

excitations, narrow (<10 nm) domain walls that interact more strongly with the electron spin, and higher magnetic resonance frequencies. I'll describe recent experimental and theoretical studies of the influence of spin currents on the field and angular dependence of the free layer switching fields, scaling of critical currents with energy barrier heights and the efficiency of spin currents on domain wall depinning.

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## Periodically rippled epitaxial graphene: a playground for 2D self-organization and organic magnetism

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Graphene is an extraordinary material that sustains a low energy manifestation of Quantum ElectroDynamics at surfaces. Its charge carriers behave as massless Dirac fermions with a group velocity  $\approx 1/300$  of the speed of light, ballistic transport of charge and spin and a half-integer Quantum Hall Effect at 300 K.

Ultra perfect graphene monolayers can be epitaxially grown on many single crystal metal surfaces under Ultra High Vacuum conditions. These graphene layers are spontaneously nanostructured forming a periodic array of nanoripples caused by the difference in lattice parameter between graphene and the different substrates. The periodicity of the ripples is 2-3 nm depending on the metal substrate.

Local tunneling spectroscopy at 4 K shows that the rippled graphene layer consists of a periodic array of quantum dots containing electron and hole pockets [1]. Electronic structure around the Fermi level, Image Potential States, Field Emission Resonances

[2], doping and work function differences between “high” and “low” regions will be compared for epitaxial graphene on Ru(0001) and Ir(111). Examples will be shown of how these corrugated potential landscapes of epitaxial graphene provide with a periodic pattern that directs the self-assembly of different functional molecules [3]. The charge transfer from graphene to certain organic molecules, like TCNQ, results in the appearance of magnetic moments on the molecules, electron delocalization in pseudo-metallic bands and long range magnetic order in the molecular adlayer. Implications of these findings towards all-carbon electronic and plasmonic devices will be briefly discussed.

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## Gold and rhodium nanocluster collisions: the relevance of d-shell polarization

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The interplay between the large elastic energies and the much smaller magnetic interaction determines the configuration of many crystals, clusters and molecules. We use collision processes between single gold and rhodium atoms and gold and rhodium nanoclusters, respectively, to investigate, by means of ab initio techniques, the subtle balance between these two forces. The targets we consider are minimum energy 13 (12) atom gold (rhodium) clusters. The kinetic energy of the projectile and its impact parameter are chosen within a range such that the three regimes we are mainly interested in studying (fusion, scattering and fragmentation) are realized. The collision is treated by means of density functional theory molecular dynamics (DFT-MD). Both spin unpolarized and polarized treatments are implemented. Results for

gold and rhodium are compared emphasizing the relevance of d-shell polarization, since the gold magnetic configuration does not make a difference, but for rhodium it is important. The different results obtained with classical MD and DFT-MD will also be discussed, since they are quite significant. The use of these collision processes to generate putative cluster energy minimum configurations will be presented and illustrated with successful examples.

Work in collaboration with Francisco Muñoz, Griselda García, Ricardo Ramírez, José Rogan and Juan Alejandro Valdivia. Supported by FONDECYT 1090225 and CEDENNA “Financiamiento Basal para Centros Científicos y Tecnológicos de Excelencia”.





## From metallic superlattices to complex oxides interfaces, a promenade with flavour to disorder

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Metallc superlattices have paved the way to the discovery of new physics in the last decades thanks to the possibility of playing with individual thickness or superlattice periods to match important length scales governing physical laws. This is the case of Giant Magnetoresistance which apart from its fundamental interest, has triggered a revolution in magnetic storage. Interfacial disorder has shown to be determinant in broad variety of these phenomena. Recently, there has been a surge of the interest in superlattices combining transition metal correlated oxides. They can display almost every possible electronic ground state including ferromagnetism, ferroelectricity, multiferroicity, superconductivity, and since many share a perovskite structure with similar lattice parameters, it is possible combining

them in heterostructures with high quality interfaces. Interesting behaviours and functionalities can result from the competition and interplay between groundstates at the interfaces. At interfaces, the important quantities controlling correlated oxides phase nucleation (charge density, electrostatic repulsion and band width) change and novel phases with emergent properties may be stabilized. An interesting consequence of the bonding reconstruction at the interface is the possibility of manipulating its spin structure which is largely determined by the orbital structure in these materials. In this talk I will discuss several examples of phase manipulation at interfaces to tailor novel behaviour and functionalities with special emphasis on the possibility of nucleating novel spin states.

## Using model systems to elucidate exchange bias mechanism

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Exchange bias is a phenomenon dominated by interface magnetic interactions between antiferromagnets (or ferrimagnets) and thin ferromagnetic layers. Recent work in this field performed using transition metal fluoride (MF<sub>2</sub>) model antiferromagnetic systems has helped elucidate some of the important fundamental mechanisms of exchange bias.

These systems have relatively simple magnetic structures and allow controlled variation of key parameters, including crystallinity, magnetic anisotropy, and magnetic dilution. I will review important contributions in this field made by Schuller's group at the University of California – San Diego and others, including my group at West Virginia University.

# A microscopic understanding of exchange anisotropy in Fe/MnF<sub>2</sub> bilayers

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A microscopic understanding of the Ferromagnetic/Antiferromagnetic (F/AF) direct exchange coupling or exchange biasing has been elusive for the over 45 years since it was discovered. In part, the almost exclusive use of hysteresis loops to study the phenomenon has limited our understanding. A new experimental technique was developed to study the exchange coupling between a ferromagnet and antiferromagnet [Appl. Phys. Lett. 69,3932-3931 (1996)]. This new technique has enjoyed considerable success in explaining many general exchange bias features using Co/CoO as a model system [J. Appl. Phys. 87, 6418-20 (2000), J. Appl. Phys. 89, 7543-5, (2001), and Phys. Rev. B 65(RC) 180406-10(2002)]. We will review the models of exchange bias and then apply them to our work on Fe/MnF<sub>2</sub> bilayers. In this work we used variations of the AMR technique to study the angular dependence of the exchange anisotropy in Fe/MnF<sub>2</sub> bilayers. We were able to phenomenologically describe the anisotropy energy as a combination of unidirectional, uniaxial, threefold and fourfold

components [Phys. Rev. B 65(RC), 100402, (2002)] and thus explain the anomalous magnetization reversal asymmetry discovered in this system [Phys. Rev. Lett. 84, 3986 (2000)]. Since our initial effort, we have been able to explain the phenomenological energy terms using a microscopic model which sums over all lattice sites in both the ferromagnet and antiferromagnet [Phys. Rev. B 68, 054430 (2003)]. The microscopic model includes terms for the interfacial exchange coupling, uncompensated spin density in the AF, the AF spin-canting energy, and domain walls in both the F and AF. Application of the model to the Fe/MnF<sub>2</sub> bilayer experimental data allows one to separately determine the fraction of uncompensated interfacial spins in the AF layer and the interfacial exchange coupling energy for the first time. An understanding of the spatial distribution of the microscopic energies allows for a simplification of the energy in which the physics is transparent.

This work supported by the University of Minnesota MRSEC.



## Nanoscale modulation of high-temperature superconductivity

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Modulating the superconducting order parameter at the nanoscale allows one to manipulate macroscopic properties in superconductors. Besides being interesting from a fundamental point of view, that enables a number of technological applications. Examples of these are the artificial control of vortex dynamics and the fabrication of planar Josephson junctions. Nanolithography, etching and lift-off techniques are usually combined to fabricate *ordered* nanostructures in low-superconductors, in which the film thickness modulation, proximity effects or the presence of a magnetic-field templates produce a nanoscale modulation of superconductivity. However, these techniques are more difficult to implement and seldom used in oxide high- superconductors - typically, lithographic features obtained in these materials have sizes above several hundreds of nanometres, longer than the superconducting characteristic lengths -. Here we show two novel approaches to produce a nanoscale ordered modulation of the superconducting condensate in thin

films of oxide superconductors. The first one combines electron-beam lithography – to fabricate PMMA masks with arrays of nanoholes - and oxygen ion irradiation. The mask pattern is imprinted into the superconductor via the *local* depression of the critical temperature ( $T_c$ ) caused by ion implantation. The advantage of this approach is that we can accurately control both the geometry (at the sub-10 nm scale) and strength (amplitude of the local  $T_c$  variation) of the superconductivity modulation. The second approach exploits electrostatic doping via ferroelectric field effects. We use heterostructures that combine a large-polarization ferroelectric and a high-temperature superconductor. The ability to design the ferroelectric domain structure at will enables us to create nanoscale “patterns” of normal regions within the superconductor. The advantage of this approach is that the nanoscale modulation is *reversible* and *reconfigurable*.

Work supported by French ANR via “SUPERHYBRIDS-II” grant.

## Dynamics of successive minor hysteresis loops in thin multilayers

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We study the cumulative growth of successive minor hysteresis loops in multilayers with perpendicular magnetic anisotropy, the effect recently reported by Berger et al [1]. Extraordinary Hall effect was used as a sensitive experimental tool to perform high resolution measurements of field and time dependent relaxation and minor loops dynamics in thin Co/Pd multilayers with perpendicular anisotropy. Major growth of the successive minor

hysteresis loops and a range of associated phenomena is consistently explained by a difference between the generation rate of small nucleation domains and their annihilation in the reversed field.

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## Spatial dependence of the distribution of current in nanotubes and nanowires

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Electric transport in nanostructures has become an issue in the field of Nanoscience and Nanotechnology since the discovery of the giant magnetoresistance effect (GMR) in the late 1980s. In the last decade, attention has been focused on quasi-one-dimensional structures such as nanowires and nanotubes, which find applications in several areas. The occurrence of magnetoresistance ratios as high as 14% in Co/Cu/Co multilayered nanowires, as observed by Blondel *et al.* [1], has raised the interest in the study of the transport process in such structures. We have found that the distribution of current

along the nanotube and nanowire axis exhibits oscillations along the radial direction. The source of the effect and its characteristic parameters are discussed.

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## A whirlwind tour of neutron scattering at high altitude inspired by Ivan Schuller!

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Situated at the steps of the Jemez Mountains in New Mexico lies the Lujan Neutron Scattering Center. Being a cutting-edge kind of guy, Ivan Schuller immediately recognized unique opportunities afforded by the high elevation (nearly 2300 meters) location. For example, being further away from Earth's center, the influence of gravity on the neutron beam is noticeably less compared to low altitude neutron scattering facilities. The much reduced atmospher-

ic pressure of a high altitude facility is responsible for greatly reducing the absorption of the neutron beam, liquid helium boiling at much lower temperatures and the seemingly light-headed and pleasant demeanor of his high altitude collaborators. Thus, nearly 20 years ago began Ivan's quest to understand explain exchange bias, magnetic vortices, alcohol-induced swelling, superconductivity and emergent phenomena with neutron scattering.

## Graded anisotropy FePtCu films

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Graded anisotropy materials are currently being aggressively researched in order to address the magnetic recording trilemma. By continuously varying the Cu content during co-sputtering, a compositionally graded  $(\text{Fe}_{53}\text{Pt}_{47})_{100-x}\text{Cu}_x$  ( $x=0-30$ ) film is realized. The anisotropy gradient is then achieved after post-annealing and the strong dependence of the  $A1 \rightarrow L1_0$  ordering temperature on the Cu content. The critical role annealing temperature ( $T_A$ ) has on the anisotropy gradient, and the resulting reversal mechanisms, is studied using a combination of standard major hysteresis loop, polarized neutron reflectivity (PNR), and first-order reversal curve (FORC) analyses. For low  $T_A$ , the major loop remains relatively soft, exhibiting a single switching process. However, the PNR and FORC results reveal a significant hard phase component towards the bottom, Cu-rich region, of the film.

For intermediate  $T_A$ , a fundamentally different anisotropy profile is generated. Here, the  $L1_0$  anisotropy gradient has become better established where the bottom, Cu-rich region, is now relatively soft. Finally, at elevated  $T_A$ , the magnetic behavior becomes consistent with a single uniform hard phase, due to significant interdiffusion of the Cu.

Work supported by SSF, VR, Göran Gustafsson Foundation, and the Knut and Alice Wallenberg Foundation.

## Magnetic and electronic properties of nanoparticle super crystals

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First I will review several selected results from my post-doc time in Ivan's lab, where I have investigated exchange biased nanostructures and films. E.g. we have observed a peculiar bi-domain state of alternating signs of exchange bias in Ni/FeF<sub>2</sub> film systems. Second, I will report on my current research at Bochum (Germany). In Bochum we investigate the magnetic and electronic transport properties of self-assembled nanoparticles systems. Two types are of interest: (a) self-assembled films of nanoparticles and (b) templated self-assembled nanoparticles. For the first case we fabricate regular 2- or 3-dimensional colloidal "super crystals" of iron oxide nanoparticles. The particles have a diameter of 20 nm and a size distribution of 7 %. Regular closed-packed self-assembly in a hexagonal lattice can be observed. Depending of the self-assembly technique we can fabricate various colloidal "super crystals" showing all three film growth modes, i.e. Stranski-Krastanov, Volmer-Weber and Frank-

van der Merwe growth. Depending on the thermal pre-treatment we can tune the internal structure and composition of the particles, i.e. magnetite/wüstite, maghemite, or maghemite/wüstite particles. Mixed phase particles show an exchange bias effect.

The second type involves the combination of self-assembly and templating. For templating we either use alumina pore membranes or nanostructured trenches.



## Molecular spintronics

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Spin-based electronics is one of the emerging branches in today's nanotechnology and the most active area within nanomagnetism. So far spintronics has been based on conventional materials like inorganic metals and semiconductors. Still, molecular electronics emerged several decades ago as a promising possibility to complement or even to replace conventional inorganic electronics when it goes nano. In this context, a natural evolution of molecular electronics is that of using magnetic molecules, as well as molecule-based materials, as components of new spintronic systems [1].

In this talk I will show with three examples the important role that chemistry can play in molecular spintronics and, in general, in molecular nanomagnetism. The first example will concern the design of nanostructured magnetic materials exhibiting multifunctional properties, in particular magnetism and electric conductivity [2]. The second example will concern the electrical addressing of spin-crossover nanopar-

ticles (i.e., the electric control over the spin-state in a single magnetic nano-object) [3]. The third example will be the design of single-molecule magnets using polyoxometalate molecules and their use as qubits in quantum computing [4].

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## Spintronics with semiconductor materials

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The controlled creation of a non-equilibrium spin polarization in non-magnetic materials is a central aspect of spintronics and plays a role in virtually all spin-based electronic nanostructures. In the spin valve, the most well-known example of a metallic spintronic device consisting of two ferromagnetic layers separated by a thin non-magnetic metal, spin information can be transmitted between the two ferromagnets via the spin accumulation in the spacer. This gives rise to giant magnetoresistance, exchange coupling, and allows one ferromagnet to exert a torque on the other. In a spin transistor, an example of a spin-based semiconductor device, spin information between ferromagnetic source and drain is transmitted via a semiconductor channel, making

it possible to manipulate the spins during transit by a gate electric field. Understanding the physics of spins in non-magnetic materials is thus crucial as it controls the overall behavior and performance of spin-based nanostructures.

In this framework, I will discuss the conditions for efficient spin injection and detection from a ferromagnet into a semiconductor. It will be illustrated with our recent experimental results involving MgO tunnel barriers in spin LED experiment as well as electrical measurement in a 3 points geometry. In the latest case new effect of spin accumulation enhancement have been observed at the Co /Al<sub>2</sub>O<sub>3</sub>/ GaAs interface that I will comment.

## Depth-dependent spin structures in layered magnetic systems

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The magnetism of nanostructured materials in the form of ultrathin films and multilayers is an important current topic in material science and technology. Studies of buried magnetic interfaces and also depth-dependent determinations of spin orientations in layered magnetic nanostructures are particularly challenging, and the combination of conversion electron Mössbauer spectroscopy and/or nuclear resonant scattering of synchrotron radiation with isotope-enriched probe layers can be a powerful tool in this field. In this talk, the

study of magnetic nanostructures with isotope-selective measurements is illustrated with recent results on the investigation of depth-dependent spin structures in exchange-biased ferromagnetic / antiferromagnetic bilayers and in epitaxial magnetic system with perpendicular magnetic anisotropy, obtained from samples containing <sup>57</sup>Fe probe layers.

Financial support from the Brazilian agencies CNPq and FAPEMIG is gratefully acknowledged.

## Methodology for the search for new superconducting materials

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Here we describe a methodology for the search for new superconducting materials. The search for materials with novel properties, new superconductors in particular, is a difficult and sometimes tedious task. It is difficult because a deliberate search for new superconducting materials in a particular system is rarely successful. As a consequence, the discovery of these new materials has been mostly accidental since the discovery of the phenomenon. Based on the past history of discoveries in superconductivity clearly some novel unconventional ideas are needed. Our method consists of a fast process for discarding most of the (“uninteresting”) non-superconducting part of a multinary phase diagram. This is done by combining a parallel

method for the preparation of highly inhomogeneous samples (“phase spread alloy”) together with a fast, sensitive screening using Magnetic Field Modulated Microwave Spectroscopy (MFMMS). Once a sample containing a minority superconducting phase is identified, comprehensive and quantitative structural, transport and magnetic methods are applied to identify the phase responsible for the superconductivity. These ideas are applied to different systems which exhibit promising normal state properties which are sometimes correlated with superconductivity. We show how a systematic structural study helps in avoiding misidentification of new superconducting materials when there are indications from other methods of new discoveries.



## Superconductivity, spin and charge order, and quantum critical behavior in correlated electron materials

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Multinary d- and f-electron compounds have proven to be a rich reservoir of strongly correlated electron phenomena that arise from a delicate interplay between competing interactions. These interactions can be “tuned” by the variation of an external control parameter such as chemical composition  $x$ , pressure  $P$  and magnetic field  $H$ , resulting in complex electronic phase diagrams of temperature  $T$  vs.  $x$ ,  $P$  and  $H$ . The suppression of the spin or charge ordered phase as a function of  $\delta$  towards 0 K at a critical value  $\delta_c$  is often accompanied by the emergence of superconductivity or an exotic magnetic phase, as well as anomalous normal state

electronic properties that violate the Fermi liquid paradigm (so-called “non-Fermi liquid” behavior). For a 2<sup>nd</sup> order phase transition, order parameter fluctuations in the vicinity of  $\delta_c$  (quantum critical point) are widely believed to be responsible for electron pairing in the superconducting phase, which often occurs in a “dome-shaped” region that envelops  $\delta_c$ , and the non-Fermi liquid behavior in the normal state properties. Recent experiments in our laboratory that address the interrelation between superconductivity, various types of spin and charge order, and non-Fermi liquid behavior in novel d- and f-electron materials are discussed.





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