



Bilateral Workshop on Nanostructured Materials for Magnetic and Spintronic Devices

Embassy of Italy
Canberra

31st October – 1st November 2012



*Office of the Scientific
Attaché
Embassy of Italy
CANBERRA*

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Sean Cadogan (University of New South Wales, Canberra); Stephen Collocott (Materials Science and Engineering, CSIRO, Sydney); Dino Fiorani (ISM, Consiglio Nazionale delle Ricerche, Roma, and President of the Italian Association of Magnetism); Michael Kostylev (University of Western Australia); Garry McIntyre (Australian Nuclear Science and Technology Organisation, Sydney); Oscar Moze (Embassy of Italy, Canberra); Annemieke Mulders (University of New South Wales, Canberra); Alessandro Soncini (University of Melbourne); Glen Stewart (University of New South Wales, Canberra); Kiyonori Suzuki (Monash University)

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PROGRAM

WEDNESDAY, 31st October

- 08.30 – 09.00 Registration
- 09.00 – 09.15 Opening and Welcome from the Ambassador of Italy and the Science Attaché

MOLECULAR MAGNETISM – Chair: Alessandro Soncini

- 09.15 – 09.45 **Inorganic molecules for molecular nanoscience** (W01)
Colette Boskovic, University of Melbourne
- 09.45 – 10.15 **Multifunctional nanomagnets: from hard to soft materials** (W02)
Marco Affronte, Università di Modena e Reggio Emilia
- 10.15 – 10.45 **Magnetic network materials: complexity and porosity** (W03)
John Stride, University of New South Wales
- 10.45 – 11.15 **Coffee break**

MOLECULAR MAGNETISM – Chair: Marco Affronte

- 11.15 – 11.45 **Magnetic memory and quantum tunneling effects in surface-wired single molecule magnets** (W04)
Andrea Cornia, Università di Modena e Reggio Emilia
- 11.45 – 12.15 **Multifunctionality in an antiferromagnetic, electrochemically-active soluble vanadium cluster** (W05)
Tony Keene, University of Adelaide
- 12.15 – 12.45 **Neutron studies of cobalt based molecular magnets** (W06)
Richard Mole, Bragg Institute, Australian Nuclear Science and Technology Organization, Kirrawee, NSW
- 12.45 – 14.00 **Lunch**

NANOSTRUCTURED MATERIALS – Chair: Paola Tiberto

- 14.00 – 14.30 **Multifunctional ferromagnetic shape memory alloys: from bulk to nano (W07)**
Franca Albertini, Istituto dei Materiali per l'Elettronica ed il Magnetismo, Consiglio Nazionale delle Ricerche, Parma
- 14.30 – 15.00 **Rare earth based bulk amorphous ferromagnets: structure and magnetic surprises (W08)**
Stephen Collocott, CSIRO Materials Science and Engineering, Lindfield, NSW
- 15.00 – 15.30 **Materials for high density magnetic recording media (W09)**
Dino Fiorani, Istituto di Struttura della Materia del Consiglio Nazionale delle Ricerche, Roma
- 15.30 – 16.00 **Nanoscale and long range magnetic order in layered magnetic materials (W10)**
Darren Goossens, Research School of Chemistry, Australian National University
- 16.00 – 16.30 **Coffee break**

NANOSTRUCTURED MATERIALS – Chair: Franca Albertini

- 16.30 – 17.00 **Effect of particle size on the magnetic ordering direction of nanocrystalline gadolinium (W11)**
Seán Cadogan, The University of New South Wales, Canberra
- 17.00 – 17.30 **Ordered arrays of nanostructures: fabrication and magnetic properties (W12)**
Paola Tiberto, Istituto Nazionale di Ricerca Metrologica, Torino
- 17.30 – 18.00 **Magnetic nanostructures: from charge-transfer ferromagnetism in capped nanoparticles to exchange softening in nanostructured melt-spun alloys (W13)**
Kiyonori Suzuki, Monash University
- 18.00 – 18.30 **Magnetic metal organic framework composites (W14)**
Raffaele Riccò, CSIRO Process Science and Engineering, Clayton, VIC

THURSDAY 1st November**SPINTRONICS** – Chair: Colette Boskovic

- 09.00 – 09.30 **Spintronics for photonics, information storage and biological applications (T01)**
Riccardo Bertacco, Politecnico di Milano
- 09.30 – 10.00 **Spin current switches based on mixed-valence metal complexes (T02)**
Alessandro Soncini, University of Melbourne
- 10.00 – 10.30 **Multifunctional effects in organic spintronic devices (T03)**
Valentin Alek Dediu, Institute of Nanostructured Materials, Consiglio Nazionale delle Ricerche, Bologna
- 10.30 – 11.00 **Coffee break**
- 11.00 – 11.30 **Wall binding and vertical current injection: how to push, pull and probe domain walls (T04)**
Peter Metaxas, University of Western Australia

SPIN WAVES AND MODELLING – Chair: Gianni Stefani

- 11.30 – 12.00 **Using quantum information theory ideas to study control and manipulation of magnons (T05)**
Jared Cole, Royal Melbourne Institute of Technology University
- 12.00 – 12.30 **Collective spin waves in nanostructured magnonic crystals (T06)**
Giovanni Carlotti, Università di Perugia
- 12.30 – 13.30 **Lunch**

MATERIALS AND DEVICES – Chair: Stephen Collocott

- 13.30 – 14.00 **Magnetism of the valleys in a silicon single atom transistor (T07)**
Giuseppe Tettamanzi, University of New South Wales, Sydney
- 14.00 – 14.30 **Magnetic properties of 3d metal nanoparticles formed in SiO₂ by ion beam synthesis (T08)**
Wayne Hutchison, The University of New South Wales, Canberra
- 14.30 – 15.00 **Field-cooling dependence of magnetism of neutron-irradiated CuMn alloy (T09)**
Lester Barnsley, Griffith University, Brisbane
- 15.00 – 15.30 **Magnetism in Co-doped ZnO single crystalline thin films (T10)**
Rongkun Zheng, School of Physics, The University of Sydney, Sydney
- 15.30 – 16.00 **Coffee break**

ADVANCED TECHNIQUES FOR STUDYING NANOSTRUCTURED MATERIALS – Chair: Annemieke Mulders

- 16.00 – 16.30 **Spin-dependent electronic properties in thin magnetic films (T11)**
Gianni Stefani, Università Roma Tre, Roma
- 16.30 – 17.00 **Nanomagnetic structures investigated with polarized neutrons (T12)**
Frank Klose, Bragg Institute, Australian Nuclear Science and Technology Organisation, Kirrawee
- 17.00 – 17.30 **Ferromagnetic resonance investigations of magnetic nanostructures and multilayers (T13)**
Mikhail Kostylev, University of Western Australia
- 17.30 – 18.00 **Studying magnetism of metallic nanostructures by spin-polarized single- and two-electron spectroscopy (T14)**
Sergey Samarin, University of Western Australia
- 18.00 – 18.30 **Round Table and Conclusions**
- 19.30 – 22.00 **Reception hosted by the Ambassador of Italy**

ABSTRACTS

(in order of presentation)

W01

Inorganic molecules for molecular nanoscience

Colette Boskovic

School of Chemistry, University of Melbourne, Australia

Ongoing work in our group is directed towards the development of two very different classes of functional metal-based molecules for incorporation into new molecular nanomaterials. Stimulated intramolecular electron transfer in metal complexes with redox-active metals and ligands can provide a mechanism for switching between distinct valence tautomeric forms. We have recently synthesised a family of dinuclear Co complexes bridged by redox-active bis(dioxolene) ligands that show promise as molecular systems that can be interconverted between three different states, potentially paving the way to logic gates more complex than simple "on/off" switches on the molecular scale [1]. Single-molecule magnet (SMM) and luminescence properties of lanthanoid complexes with organic ligands are well-established. Polyoxometalates (POMs) approximate fragments of metal oxide and represent an important alternative as inorganic ligands for lanthanoid complexes with novel properties. We have developed new families of POM-supported lanthanoid complexes that are luminescent, photochromic or function as SMMs, which is promising for the development of bifunctional SMMs [2].

- [1] K.G. Alley, G. Poneti, J. B. Aitken, R.K. Hocking, B. Moubaraki, K.S. Murray, B.F. Abrahams, H.H. Harris, L. Sorace, C. Boskovic, *Inorg. Chem.* **51** (2012) 3944.
- [2] (a) C. Ritchie, M. Speldrich, R.W. Gable, L. Sorace, P. Kögerler, C. Boskovic, *Inorg. Chem.* **50** (2011) 7004 (b) C. Ritchie, E.G. Moore, M. Speldrich, P. Kögerler, C. Boskovic, *Angew. Chemie Int. Ed.* **49** (2010) 7702.

W02

Multifunctional nanomagnets: from hard to soft materials

Marco Affronte

University of Modena and Reggio Emilia and CNRNANO (Istituto Nanoscienze Consiglio Nazionale delle Ricerche) Institute, Italy

Examples of nano-fabrication of magnetic devices and sensors obtained by using Focussed Ion Beam and Electron beam lithography will be presented as well as some experiments performed in our low temperature laboratory. Functionalities of molecular nanoMagnets including magnetothermal properties and topical issues on the quantum magnetism

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related to these "soft" materials will be presented. The latest trend in our research is to combine molecular magnets with graphene in order to realize hybrid spintronic devices at the molecular scale and examples that illustrate this research line will be presented.

W03

Magnetic network materials: complexity and porosity

John Stride

School of Chemistry, University of New South Wales, Sydney, Australia 2052

Extended coordination complexes forming network structures of varying structural topologies have great potential to induce dimensionality on magnetic structures. We have undertaken a program to investigate coordination polymers focusing on their magnetic behavior, highlighting the emergence of complexity in the magnetism with factors such as hydration, guest uptake and hierarchical structures.

W04

Magnetic memory and quantum tunneling effects in surface-wired single molecule magnets

A. Cornia,^a M. Mannini,^b M. J. Rodriguez-Douton,^a Ph. Sainctavit,^c R. Sessoli,^b E. Tancina^a

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^c*IMPMC, Univ. Pierre et Marie Curie, Paris, France.*

In the emerging field of molecular spintronics, Single Molecule Magnets (SMMs) have been proposed as miniaturized magnetically-bistable units to be electrically written and read-out. The underlying idea is that of sensing and manipulating the molecular magnetic moment using spin-polarized electric currents produced, for instance, by a magnetic STM tip and injected through surface-supported molecules.¹ Alternative approaches entail the direct wiring of molecules to metal nanogaps^{2a-e} or their lateral coupling to nanoconductors (e.g. carbon nanotubes).^{2f} However, the complex nature, fragility and low operating temperature of most SMMs have represented a major blocking point for half a decade. We present here our recent observation of a magnetic memory effect on arrays of surface-wired SMMs.^{3a} By chemical tailoring of the surface binding groups, partially-oriented arrays have also been obtained which show anisotropic hysteresis loops and well-defined quantum tunneling steps.^{3b} SMMs are now expected to provide cutting-edge insight into the interplay between electron transport and the quantum spin dynamics of molecular systems.

- [1] (a) R. Wiesendanger, *Rev. Mod. Phys.* **81** (2009) 1495; (b) D. Serrate *et al.*, *Nat. Nanotechn.* **5** (2010) 350; (c) S. Loth *et al.*, *Science* **335** (2012) 196; (d) S. Loth *et al.*, *Nat. Phys.* **6** (2010) 340.

- [2] (a) F. Haque *et al.*, *J. Appl. Phys.* **109** (2011) 07B112; (b) A. S. Zyazin *et al.*, *Nano Lett.* **10** (2010) 3307; (c) E. A. Osorio *et al.*, *J. Phys.: Condens. Matter* **20** (2008) 374121; (d) E. A. Osorio *et al.*, *Nano Lett.* **10** (2010) 105; (e) J. J. Parks *et al.*, *Science* **328** (2010) 1370; (f) M. Urdampilleta *et al.*, *Nat. Mater.* **10** (2011) 502.
- [3] (a) M. Mannini *et al.*, *Nat. Mater.* **8** (2009) 194; (b) M. Mannini *et al.*, *Nature* **468** (2010) 417.

W05

Multifunctionality in an antiferromagnetic, electrochemically-active soluble vanadium cluster

Tony D. Keene,^{ab} D. M. D'Alessandro,^a K. W. Krämer,^c J. R. Price,^a
D. J. Price,^a S. Decurtins^c and C. J. Kepert^a

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Multifunctional magnetic materials represent a key area of magnetochemical research, allowing the interplay of multiple properties that can affect the magnetism of a material or allow the magnetic properties to act as an indicator of changes to the material.

$K_9[V_{16}O_{38}(CN)] \cdot 13H_2O$ is a new member of the $[V_{16}O_{38}(X)]^{n-}$ series where a polyoxovanadate cage encapsulates an anion or small neutral moiety. This particular compound displays the 8- state, previously unseen in this series and is soluble in water, readily combining with metal ions in solution. The cluster shows a dominant antiferromagnetic interaction with a transition at 2.25 K. Solution-phase and solid state electrochemistry allow us to access further oxidation states on the cluster, raising the possibility that the magnetic properties can be selectively controlled through manipulation of the electrochemical properties of the cluster.

- [1] T. D. Keene, D. M. D'Alessandro, K. W. Krämer, J. R. Price, D. J. Price, S. Decurtins and C. J. Kepert, *Inorg. Chem.*, ASAP article online 23/04/2012.

W06

Neutron studies of cobalt based molecular magnets

Richard A. Mole

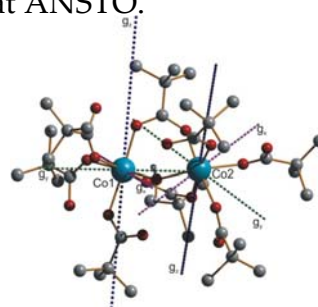
Bragg Institute, ANSTO, Locked Bag 2001, Kirrawee DC, 2232, Australia

Molecule based magnetic materials containing octahedral Co(II) are often not quantitatively studied due to the complexity of the behaviour often associated with orbitally degenerate ions. Recent work however has highlighted that there are many target materials based around this ion that show interesting properties, such as unusual

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types of single molecule magnetism, complex long range magnetic ordering and hydration dependent ferromagnetism. This highlights the need for further study, as many of these properties could possibly be utilized in functional materials. The underlying basis of all these effects are thought to be structure property relationships, however the nature of these relationships is often difficult to unravel when the ion involved has unquenched orbital angular momentum. Recent work has shown that both neutron diffraction and inelastic neutron scattering can be used to gain essential information about the nature of these structure property relationships. The work presented will include examples highlighting the complementarity and relative simplicity of inelastic neutron scattering in studying cobalt dimers, in comparison with techniques such as EPR [1]. A second example will show that porous, extended, cobalt networks can show unusual magnetic ordering that is strongly dependent on changes to the structure, which can be manipulated by varying the level of hydration of the structure [2]. I will also show the first results from the Pelican cold neutron time of flight spectrometer at ANSTO.

Fig 1: Structure of
 $[\text{Co}_2(\text{H}_2\text{O})(\text{O}_2\text{CtBu})_4(\text{HO}_2\text{CtBu})_4]$
 one of the dimers studied in ref 1.



- [1] A.B. Boer, A.-L. Barra, L.F. Chibotaru, D. Collison, E.J.L. McInnes, R.A. Mole, G.G. Simeoni, G.A. Timco, L. Ungur, T. Unruh and R.E.P. Winpenny, *Angewandte Chemie* **50** (2011) 4007.
- [2] R.A. Mole, J.A. Stride, P.F. Henry, M. Hoelzel, A. Senyshyn, A. Alberola, C.J. Gomez Garcia, P.R. Raithby and P.T. Wood, *Inorganic Chemistry* **50** (2011) 2246.

W07

Multifunctional ferromagnetic shape memory alloys: from bulk to nano

Franca Albertini

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Ferromagnetic shape memory alloys are multi-functional materials suitable for a variety of applications and exploitable in new-concept smart devices thanks to their extraordinary phenomenology (e.g giant magnetoelastic, magnetocaloric, barocaloric effects) arising from the interplay between magnetic and structural degrees of freedom. The most representative material is the Heusler alloy, Ni_2MnGa . It is ferromagnetic and shows a martensitic transformation in response to variations in temperature, stress and magnetic field. My talk will be focused on the possibility to contemporarily improve more than one effect by tuning the key physical properties, through suitable compositional changes in bulk materials. I will also report on some results of the size-scaling dependence of the main properties in epitaxial thin films.

W08

Rare earth based bulk amorphous ferromagnets: structure and magnetic surprisesStephen Collocott*CSIRO Materials Science and Engineering, Lindfield, NSW, Australia 2070*

Bulk amorphous alloys with hard magnetic properties (intrinsic coercivity ~300 kA/m and remanence ~100 mT at room temperature) are known to form in the Nd-Fe-Al alloy system. These alloys are not truly amorphous, having an amorphous matrix in which nanocrystalline clusters, typically of size 1 to 50 nm, are embedded. In the context of this structure the temperature dependence of the coercivity, and time dependent magnetic properties, in these materials will be discussed. A striking feature in these alloys is the non-monotonic behavior of the magnetic viscosity (or anomalous magnetic viscosity) on the recoil line that leads to the dc demagnetized state.

W09

Materials for high density magnetic recording mediaDino Fiorani*ISM (Istituto di Struttura della Materia), Consiglio Nazionale delle Ricerche, Roma, Italy*

The main results of the activity of the Institute of the Structure of Matter on nanostructured materials for high density recording media, carried out within European projects, will be presented. Materials with different sources and type of anisotropy were investigated: (Co/Pd)_n multilayers, CoCrPt-SiO₂ and FePt/Fe with perpendicular anisotropy and CoPt films with tilted easy axes. The magnetization processes and the reversal mechanisms will be discussed.

W10

Nanoscale and long range magnetic order in layered magnetic materialsDarren Goossens*Research School of Chemistry, Australian National University, Canberra*

The layered magnetic materials in the MPX₃ family ($M = \text{Fe}^{2+}$, Mn^{2+} , etc and $X = \text{S}$, Se) show a wide range of magnetic orderings and anisotropies [1-3]. This has made them interesting from the point of view of fundamental physics of magnetism. The layered structure allows intercalation of lithium for battery applications [4], and functional guest molecules for other potential technological uses (for example non-linear optics). Some members of the family can be grown as large but thin single crystals, although as yet their use as a substrate material has not been heavily explored.

The materials can show antiferromagnetic and ferromagnetic ordering, as well as a range of different spin glass phases, including a classic spin glass and a possible magnetic cluster glass. This presentation will outline some of the structures, both long-range

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ordered and nanoscale, physical properties and potential uses of the family of materials.

- [1] D.J. Goossens, “Dipolar anisotropy in quasi-2D honeycomb antiferromagnet MnPS₃”, *European Physical Journal B* **78** (2010) 305-309.
- [2] K.C. Rule, T.J. Hicks, S.J. Kennedy, D.J. Goossens and A.M. Mulders, “Contrasting antiferromagnetic order between FePS₃ and MnPS₃”, *Applied Physics A* **74**[Suppl.] (2002) S811813.
- [3] E. Ressouche, M. Loire, V. Simonet, R. Ballou, A. Stunault, and A. Wildes, “Magnetoelectric MnPS₃ as a candidate for ferrotoroidicity” *Phys. Rev. B* **82**, 100408(R) (2010).
- [4] G. Giunta, V. Grasso, F. Neri and L. Silipigni, “Electrical conductivity of lithium-intercalated thiophosphate NiPS₃ single crystals” *Phys. Rev. B* **50** (1994) 8189-8194.

W11

Effect of particle size on the magnetic ordering direction of nanocrystalline gadolinium

Seán Cadogan

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Despite being the “simplest” of the magnetic rare earths (due its 4f⁷ S-state electronic configuration), gadolinium and its many inorganic and intermetallic compounds present a rich variety of magnetic ordering behaviour. The extreme absorption cross section of natural gadolinium has, for the most part, led to neutron diffraction studies of magnetic ordering in Gd-based systems being avoided, greatly limiting the available data. Pure metallic gadolinium is a ferromagnet with a T_c of 293K and a saturation moment of 7μ_B/atom, ordered initially along the hexagonal c-axis. However, on cooling below 232K, the moments tilt away from the c-axis, reaching a maximum deviation of 65° at about 180K, before rotating back towards the c-axis on further cooling. By 10K the deviation is about 32° [1]. More recent calculations have shown that the anisotropy that leads to this canting arises from a combination of dipole-dipole interactions between the Gd moments, and a spin-orbit interaction of the conduction electrons [2].

Increasing the effects of the free surface by reducing the crystallite size has been shown to affect several aspects of the magnetic ordering of gadolinium. SANS experiments on nanocrystalline samples of ¹⁶⁰Gd (used to reduce the absorption by avoiding the presence of the highly absorbing odd isotopes ¹⁵⁵Gd and ¹⁵⁷Gd) have shown that in small fields (~0.6T) 33nm crystallites of Gd exhibit a significant sinθcosθ anisotropy due to non-uniformities in the magnitude of the magnetization [3,4]. This is somewhat surprising for a single-phase material and was attributed to spin disorder *within* individual grains. This is supported by the observations that the saturation magnetization is 25% lower and T_c is reduced by about 6K. Earlier ¹⁵⁵Gd Mössbauer measurements also showed evidence for significant spin disorder in nanocrystalline gadolinium at 4.2K [5].

We have studied the magnetic order of nanocrystalline ^{160}Gd samples with volume-weighted average particle sizes of 21nm, 38nm and >100nm (essentially 'bulk'), prepared by means of the inert-gas condensation technique. Our 'bulk' sample confirms the magnetic reorientation behaviour measured on a Gd single-crystal by Cable and Wollan [1]. The magnetic behaviour of our nano-Gd materials, however, is quite different from that of the 'bulk' sample. In particular, the initial magnetic ordering is canted away from the c-axis and the lower-temperature rolling back of the magnetization towards the c-axis is suppressed. These findings will be discussed in terms of the spin-disorder associated with the particles' nanostructure, as seen by SANS [3,4].

This work is a collaborative project with colleagues in Luxembourg (A. Michels, F. Döbrich), Germany (R. Birringer) and Canada (D.H. Ryan, Z. Yamani).

- [1] J.W. Cable and E.O. Woollan, *Phys. Rev.* **165** (1968) 733.
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W12

Ordered arrays of nanostructures: fabrication and magnetic properties

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Progress in nanomagnetism has been achieved by the simultaneous advances in nanotechnology that allows the fabrication of novel magnetic nanostructures, such as arrays in magnetic thin films. This is primarily motivated by applications such as spintronics, magnetic sensing, and ultrahigh-density magnetic recording. In this context, fabrication processes based either on high-resolution planar lithography (i.e. sequential optical, electron-beam and focused ion beam lithography) or large area self-assembly approaches (polystyrene nanospheres or nanotemplates) have played a major role and has been intensively worldwide investigated in the last decade. The accurate control of the dimensions, distance and ordering of the nanostructured arrays, together with thin film composition has led to a variety of new classes of magnetic nanomaterials with a unique combination of remarkable properties: DC magnetotransport, exchange bias, magnetization switching and spin dynamics. In this talk, fabrication lithography processes to pattern magnetic thin films, either sequential, large area self-assembling or a combination of the two techniques will be presented (available in the INRIM laboratory) highlighting advantages and disadvantages with respect to magnetic properties interesting for applications.

W13

Magnetic nanostructures: from charge-transfer ferromagnetism in capped nanoparticles to exchange softening in nanostructured melt-spun alloys

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Two main research problems in magnetic nanostructures tackled by our group at Monash University are (i) the effect of chemical capping or doping on inducing spontaneous magnetization in intrinsically nonmagnetic materials and (ii) the influence of macroscopic induced anisotropies on the local random magnetocrystalline anisotropies in Fe based alloys. The former effect is potentially relevant to the development of magnetic semiconductors, an essential ingredient in spintronics. The latter problem is directly linked to the efficiency of soft magnetic cores used in electric motors, a vital component in realization of low-emission automotive technology. A brief overview of our recent progress in these research areas including the synthesis of nanoparticles and nanostructured alloys, the results of element specific synchrotron experiments and modeling of the exchange softening process will be given.

This progress has been made in collaboration with researchers from Australia (N. Ito, S.J. Chen, K. Saito, J.D. Cashion), Germany (G. Herzer), Japan (M. Suzuki) and Spain (J.S. Garitaonandia, E. Goikolea, M. Insausti).

W14

Magnetic metal organic framework composites

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Metal Organic Frameworks (MOFs) are a novel class of hybrid materials, where metal centres are assembled into one-, two-, or three-dimensional networks with multifunctional organic linkers. The high surface area in the thousands of square meters per gram, and the controlled pore size, pore distribution and pore architecture of MOFs are all relevant features for the fabrication of devices that rely on highly controlled transport properties. The ability to embed magnetic nano-particles and nano-fibers within MOFs is an emerging strategy for the spatial manipulation of the porous crystals that can be used for sensing [1], drug delivery[2] or pollutant sequestration[3].

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T01

Spintronics for photonics, information storage and biological applicationsRiccardo Bertacco*L-NESS (Laboratory for Epitaxial Nanostructures on Silicon and Spintronics) - Dipartimento di Fisica del Politecnico di Milano, Como, Italy*

The basic idea of spin-optoelectronics is exploiting the coupling between the angular momentum of photons and the spin angular momentum of electrons. Here we describe the room temperature integrated detection of the helicity of photons with 1300-1500 nm wavelength, via spin-photodiodes based on fully epitaxial Fe/MgO/Ge(001) heterostructures [1].

In the field of information storage and non volatile magnetic RAMs one of the major problems is implementing efficient systems for writing the information without use of current pulses. In this contribution we discuss interfacial magnetoelectric coupling at the BaTiO₃/Fe interface [2]. First examples of application of these effects in magnetic tunneling junction will be presented. Regarding applications to biology, the basic idea of spintronic biosensors is replacing the fluorescent tags employed in standard microarrays for biomolecular recognition with magnetic nanoparticles, whose presence can be sensed by spintronic transducers. We present here some results on the application of magnetic sensors based on CoFeB/MgO/CoFe tunneling junctions in experiments of DNA recognition [3].

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T02

Spin current switches based on mixed-valence metal complexesAlessandro Soncini*School of Chemistry, University of Melbourne, Australia*

Theoretical and computational models of spin quantum transport in devices based on single-molecule nanomagnets are presented. The crucial role played by molecular mixed-valence states in single-molecule charge and spin tunneling processes is discussed, also by means of exactly soluble Hubbard models. In lanthanide-based nanomagnets the interplay between weak spin-delocalisation, strong electron correlation, and strong magnetic anisotropy, can be harnessed to design single-molecule spin-switching devices.

Multifunctional effects in inorganic spintronic devices

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Information and communication technology (ICT) is calling for solutions enabling lower power consumption, further miniaturization and multifunctionality requiring the development of new device concepts and new materials. A fertile approach to meet such demands is the introduction of the spin degree of freedom into electronics devices, an approach commonly known as spintronics. This already led to a revolution in the information storage (GMR readheads) in the last decades. Nowadays, the challenge is to bring spintronics also into devices dedicated to logics, communications and storage within the same material technology [1].

In this context the electric control of the magnetoresistance represents one of the most promising issues enabling both further miniaturization and multifunctional operation of spintronic devices. Likewise, also the electronics community is committed to follow the Moore's law, and one of the promising approaches is the use of arrays of crossbar memristors capable of information processing and storing ('stateful' logic) [2].

We show that an electrically controlled magnetoresistance can be achieved in organic devices [3] combining magnetic bistability (spin-valve) and resistance switching effects. In such devices the GMR effect can be turned ON and OFF by a programming bias that sets the device in low or high resistance state respectively. The magnitude of the GMR depends on the bias history and can be recovered up to the pristine value [4].

We show in detail how these effects can be operated in memory and logic gate applications merging together spintronics and electronics approaches towards new future device concepts.

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T04

Wall binding and vertical current injection: how to push, pull and probe domain walls

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The ability to efficiently control and drive domain wall (DW) dynamics will pave the way for exciting new spintronic devices ranging from DW-MRAMs to memristors. Here we show that moving away from the traditional single-layer, lateral-injection systems can be interesting both with respect to device-focused and fundamental physics. We firstly look at domain walls moving in physically separate (but magnetically coupled) layers. In certain field ranges, which can be related to the strength of the coupling, the walls are observed to move in a bound state described by unique velocity-field characteristics¹. Beyond furthering our understanding of the influence of interlayer coupling on domain wall dynamics, our multilayer film is shown to be attractive as a model system for studying the general problem of bound interface dynamics. Secondly, we look at the use of vertical current injection² to displace domain walls in a nano-scale MTJ structure. This vertical current geometry allows for a drastic reduction of the critical current density for domain wall motion as compared to lateral current injection². Furthermore, the large resistance variations provided by the MTJ enables us to make time resolved measurements of the domain wall motion which reveal high domain wall speeds (~ 500 m/s) and, at current densities below ~ 6 MA/cm², clear stochastic effects.

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T05

Using quantum information theory ideas to study control and manipulation of magnons

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Many important concepts in quantum physics such as decoherence and quantum control have gained new relevance in the quest to build a quantum computer. In this process many new models and ideas have been developed. We are looking at how these ideas can be applied back to the venerable field of spin-wave physics. Questions of interest include, "how can we use wave-guide analogies to design magnon control schemes?" or "how does a magnon decohere due to a spatially correlated bath?".

T06

Collective spin waves in nanostructured magnonic crystals

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Similar to photons in photonic crystals, the spectrum of spin excitations in materials with periodically modulated properties at the submicrometric scale shows bands of allowed magnonic states, alternated with forbidden band gaps. This constitutes a new class of artificial crystals, known as magnonic crystals (MC), in which collective spin excitations rather than light are used to transmit and process information. Here we present an overview of both conventional and micro-focused Brillouin light Scattering (BLS) study of collective spin waves in 1D and 2D planar magnonic crystals, consisting of either ordered arrays of interacting magnetic elements with separation below 100 nm or antidot arrays. Thanks to the wave vector conservation in the magnon-photon interaction, one has the possibility to measure the dispersion relation (frequency vs. wave vector) of the collective spin excitations.

This work was supported by the European Community's Seventh Framework Programme (FP7/2007-2013) under Grant Agreement n°228673 (MAGNONICS). Fruitful collaboration with Prof. M. Kostylev from University of Western Australia, under ARC project DP110103980 "Complex magnetic structures for microwave, logic and memory applications", is kindly acknowledged.

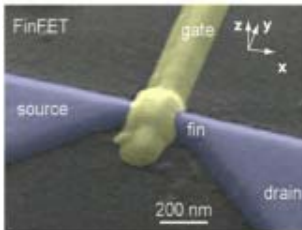
Magnetism of the valleys in a silicon single atom transistor

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Quantum mechanics is a well-established theory playing a major role in the correct description of many physical phenomena's in magnetism. Exotic phenomena's such as the Kondo effect [1] make no exception to this rule, as their modelling requires truly quantum theories. In particular, the Kondo is an effect that has been first observed in bulk metallic systems with magnetic impurities [1]. More recently, however, it was demonstrated that also quantum dots (QD's) could behave as Kondo impurities [2].

Our system of choice is a recently introduced Si Field Effect Transistor (FET) geometry [3]; the FinFET. A technique allowing the observation single electron transport through a single atom has been established for these fully CMOS compatibles devices [4], i.e.: they can be used in a Single Atom Transistor (SAT) [4,5] configuration. SAT's have some



Typical SEM image of a FinFET device [7].

interesting properties compare to more traditional QD's, the most notable of these is the possibility to address the Si valley degree of freedom. In 2011 it was shown that this new degree of freedom act as a pseudo spin which leads to unusual spin and valley selection rules for relaxations of electrons in silicon [6]. From another side, it has been later theoretically and experimentally demonstrated that, in these devices, it is possible to access in transport to higher order effects and that valley degeneracy leads to SU(4) Kondo-correlations, which entangle

spin and pseudo spin of the exchanged electrons [7]. The possibility to address spin and pseudo spin independently leads to the observation of a universal SU(4) to SU(2) symmetry crossover [7]. This Kondo effect provides also new opportunities for spin control in silicon such as, for example, the coherent exchange of electrons between two donors in a two donors system in silicon [8].

In conclusion, by studying this novel magnetic effect, we have unveiled its possible use in new directions of both classical and quantum electronics. This is of great interest also because these phenomena's are observed not in exotic and difficult to reproduce geometries but in devices very similar to the one used in commercial machines.

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T08

Magnetic properties of 3d metal nanoparticles formed in SiO₂ by ion beam synthesis

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Metallic nanoparticles are of both fundamental and technological interest since their properties can differ significantly from those of bulk material. Of particular interest is the fact that nanoparticles exhibit size-dependent magnetic properties. Below a certain size (<20 nm) some nanoparticles exhibit a unique form of magnetisation known as superparamagnetism [1], while for others the magnetic coercivity has been shown to increase with the size up to a critical point and then decrease with further increase in size [2]. Ion implantation offers a relatively simple and flexible means of fabricating metallic nanoparticles in different host materials and is therefore a useful tool for exploring such systems. In this approach, the size distribution of the nanoparticles is controlled by the implantation and annealing parameters.

In our studies, nanoparticles containing 3d metals such as Fe, Ni, and Co, plus alloys of these together with Pt, have been synthesized within a 100 nm silica film by ion implantation and thermal annealing. Rutherford back scattering (RBS), transmission electron microscopy (TEM) and X-ray diffraction (XRD) are used to study the composition, structure, size and spatial distribution of the nanoparticles, while magnetic properties are determined with a SQUID magnetometer (see for example [3]).

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T09

Field-cooling dependence of magnetism of neutron-irradiated CuMn alloy

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Atomic short range order (SRO) in CuMn alloys can be drastically modified through aging [1–5], leading to the growth of magnetic clusters when the temperature is less than the characteristic glass temperature (T_g), which play a significant role in the low temperature magnetism. Gray [6] demonstrated in a CuMn alloy sample with 16.4 at.% Mn concentration that the SRO process may be driven to equilibrium through neutron irradiation of the alloy, leading to an observed magnetic susceptibility over 20 times greater than the as-quenched value at the glass temperature. He attributed this to the neutron irradiation acting as a continuous supply of vacancies, which drives the ordering

process through vacancy migration. Subsequent studies by Cussen and coworkers [7,8] showed that neutron irradiation induces the onset of long range order in $CuMn$ at a slightly higher concentration.

In this paper, a study of the low temperature magnetic properties of a sample of $Cu_{83.6}Mn_{16.4}$ alloy exposed to the neutron irradiation process described in reference [6] is reported, with a particular focus on the cooling field dependence of minor hysteresis loops at 5 K. The sample showed a greater susceptibility in its temperature dependent magnetization, and a greater step magnetization, a greater training effect and suppressed exchange bias in minor hysteresis loops measured at low temperature compared with similar samples exposed only to thermal treatment. This was consistent with previous investigations that have shown that aging of concentrated $CuMn$ enhances ferromagnetic interactions.

Three models of increasing complexity are applied to the data, the first two involving semi-empirical expressions with a Langevin component, and the third based on a modified Stoner-Wohlfarth expression. Each model results in a set of scenarios for the dependencies of the effective cluster moment, cluster concentration, uniaxial (shape) anisotropy and unidirectional (exchange) anisotropy on cooling field. These scenarios are then considered in terms of their physical plausibility. The most plausible of these scenarios suggests that magnetic clusters behave as multi-domain particles when the system is cooled in particularly high fields.

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T10

Magnetism in Co-doped ZnO single crystalline thin films

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In order to unravel the magnetism of Co doped ZnO films, we have performed rigorous experiments on Co doped ZnO grown on α - Al_2O_3 and O-polar ZnO (000 $\bar{1}$) substrates by molecular beam epitaxy. Room-temperature ferromagnetism was found in single crystalline $Zn_{0.9}Co_{0.1}O$ thin films on α - Al_2O_3 substrate, but ferromagnetism was not

(continues on next page)

observed in ZnO:Co on ZnO substrate until Co concentration reaches as high as 20%. In the ZnO:Co on α -Al₂O₃ substrate, atom probe tomography confirms a random distribution of Co ion even at the interface region. High resolution transmission electron microscopy discloses a high density of threading dislocation close to the interface, with some penetrating through the buffer layer and into the Co doped layers. Density functional calculations are then performed to illustrate the spatial distribution and the interaction between dopants, point defects (mainly Zn and O vacancies) and dislocation for both neutral and charged states. Co incorporation is predicted to considerably lower the formation energy of Zn vacancy (by ~ 2.4 eV for neutral VZn⁰) and, more importantly, to broaden the range of magnetic states (VZn⁰ and VZn¹⁻) in the Fermi level. Highly mobile VZn prefer to accumulate at the dislocation sites, in which the repulsive VZn couple strongly favouring an extended ferromagnetism. The interplay between point and extended defects could hold the key to understand the hitherto puzzling ferromagnetism observed in wide variety of doped and undoped semiconductors. In the ZnO:Co on ZnO substrate, Although an additional n-type doping with Ga increases the magnitude of magnetization, the origin of the observed ferromagnetism is not carrier induced as confirmed by electric-field effect measurements. Three dimensional atom probe tomography shows that Co ions are randomly distributed, indicating that Co clustering or spinodal decomposition is not the origin of the ferromagnetism either. One possible mechanism for the ferromagnetism is hydrogen facilitated interaction, which is supported experimentally by magnetic measurements on hydrogen-treated ZnO:Co as well as theoretically by first-principles calculation.

T11

Spin-dependent electronic properties in thin magnetic films

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Itinerant electron systems are often characterized by a Coulomb interaction energy (U) that is small compared to the valence band width (W), and are well described within the independent electron approximation using approaches such as density functional theory. On the other hand, for systems where U is large compared to W , the mutual repulsion among the electrons cannot be neglected when describing material's electronic properties. It has to be noted that the Coulomb repulsion among electrons is typically characterized

by a single average interaction energy U when its value is important with respect to W . In ferromagnetic systems where the magnetic exchange interaction energy is of a similar magnitude as U and W , this may no longer be the case. In such circumstances, majority and minority spin electrons may exhibit dramatically different degrees of localization. In order to investigate this issue we used a combined experimental and theoretical angle-resolved Auger-photoelectron coincidence spectroscopy (AR-APECS)^{1,2}. We report on a case study on the Fe $M_{2,3}VV$ Auger transition from 3-monolayers of Fe grown epitaxially on the Cu(100) surface. The final state in this core-valence-valence Auger transition consists of two holes in the Fe valence band. By appropriate choice of experimental parameters, sensitivity of the AR-APECS spectra to triplet (primarily parallel spin) configurations of the two-hole final state can be enhanced or suppressed with respect to that of the singlet (antiparallel spin). We find that, while contributions to the spectrum from decay channels that involve minority spin electrons are well described within an independent electron approximation, significant correlation effects must be included to account for the final state with two majority-spin holes. This dramatically different interaction between majority and minority spin holes arises because a hole in the completely filled majority-spin band is significantly more localized than a hole in the half-filled minority-spin band. This different degree of localization should manifest itself in a wide variety of physical properties, such as spin-dependent transport, relevant for spintronic applications.

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T12

Nanomagnetic structures investigated with polarised neutrons

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The new OPAL research reactor near Sydney and the state-of-the-art neutron scattering instruments operated by the Bragg Institute provide tremendous scientific opportunities for the nanomagnetic and spintronic research community. A very active thin film magnetism research program was established over the past few years since the start-up of OPAL. In this presentation, we will review our current activities in nanomagnetism research, which includes exchange bias, doped magnetic semiconductors, Rare Earth nitrides and multiferroic thin film systems [1,2,3]. Key instruments for our research are the Platypus polarised neutron reflectometer which is able to detect in-plane magnetic moments on nanometer scale with depth-resolution and the Taipan triple-axis diffractometer which is capable of detecting atomic scale ferro- and antiferromagnetic structures.

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T13

FMR investigations of magnetic nanostructures and multilayers

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Currently, thin magnetic multi-layered films and nanostructures attract a lot of attention due to possible applications in microwave signal processing, spintronic devices, magnetic memory, and magnetic logic. Ferromagnetic resonance (FMR) and magnetostatic spin waves (MSW) are magnetic excitations in these materials. Typical frequencies for FMR and MSW lie in the microwave range and are magnetic-field tuneable. In my talk I will introduce the modification of the broadband ferromagnetic resonance method we developed in our laboratory at the University of Western Australia which we call “sample flipping FMR”. This method allows extraction of information on magnetic properties and their spatial uniformity for plane magnetic conducting materials. It is based on the unexpectedly strong microwave shielding effect of eddy currents in these materials we found for the excitation geometry of microstrip-based broadband FMR. Results of investigation of microwave magnetic dynamics in single and multi-layered films and periodic nanostructures using this novel method will be presented.

T14

Studying magnetism of metallic nanostructures by spin-polarized single- and two-electron spectroscopy

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We applied spin-polarized two-electron spectroscopy [1] for studying ultrathin layers of Ni, Co, Fe, Au, Ag and bi-layer structures on W(110). The essence of the two-electron spectroscopy is the detection of two electrons excited by a single incident electron in coincidence. In the case of symmetric detection of electron pairs with equal energies the spin-asymmetry of the binding energy spectrum represents the spin-asymmetry of the

Spectral Density Function (SDF) in the centre of the Brillouin zone [1]. A non-zero value of the spin asymmetry of SDF is characteristic for a ferromagnetic sample. If the asymmetries for non-reversed and reversed target magnetization are denoted A^{M1} and A^{M2} , the spin-orbit (A_{SO}) and exchange (A_{ex}) contributions are given to leading order by: $A_{ex} = \frac{1}{2} (A^{M1} - A^{M2})$ and $A_{SO} = \frac{1}{2} (A^{M1} + A^{M2})$. In such a way the exchange and the spin-orbit interaction in 3ML Co film on W(110) were identified [2].

In contrast to the Co film a 5 ML Fe film does not show any spin-orbit component in the asymmetry spectrum although a substantial exchange component is observed in binding energy spectrum and in the energy sharing distribution.

The deposition of 1ML of Au on 5 ML of Fe decreases the spin-asymmetry of SDF from 10% to 7% still showing a ferromagnetic feature of the spectrum. In the asymmetry of energy sharing distribution a spin-orbit component of about 2% appeared together with an exchange component of about 7%. The ferromagnetic state of the Au/Fe structure is very stable and did not change during at least two months. Since the (e,2e) spectroscopy is very surface sensitive this result may indicate a ferromagnetism of the ultrathin Au film on the Fe layer.

A thin Ni buffer layer (1 – 3 ML) between 3 ML of Co and W(110) substrate substantially improve the crystallinity of the Co film and enhances the spin asymmetry of the spectral density function.

Plasmons in thin Ag film on magnetic and nonmagnetic substrates excited by spin-polarized electrons have been studied.

[1] A. Morozov *et al.* Phys. Rev. B **65** (2002)104425.

[2] S. Samarin *et al.* Phys. Rev. Lett. **97** (2006) 096402.

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