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Abstracts

Magnetic molecules for quantum information: the challenge of single spin addressing

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The intrinsic quantum nature of the spin in magnetic molecules has made them the ideal playground to investigate quantum effects in magnetization dynamics. Magnetic molecules are currently explored as an alternative platform for spin-based quantum technologies. The accurate chemical control of spin-spin interactions in molecular architectures has great potential for the realization of quantum gates. Optical interfaces to control and detect the spin states can also be engineered. The processability of molecules allows the realization of hybrid nanostructures. However, the molecular approach also poses critical challenges. Achieving the control of single spins and spin-spin interactions at the single molecule level is a significant challenge. It requires the engineering of an efficient coupling of the spin with the electric field, the latter being confinable at the molecular scale. Learning from nature, we are proposing to exploit chirality, and in particular spin selectivity in electron transfer processes through chiral structures, as an alternative way to spin-polarize molecular systems, and to achieve an innovative and efficient spin-to-charge conversion. An overview of our recent results will be provided.

Unconventional computing with spin-orbit effects

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Novel spintronic devices can play a role in the quest for GreenIT if they are stable and can transport and manipulate spin with low power. Devices have been proposed, where switching by energy-efficient approaches is used to manipulate topological spin structures that are stable in multilayers [1] but also in 2D van der Waals systems [2].

We combine ultimate stability of topological states due to chiral interactions [3,4] with ultra-efficient manipulation using novel spin torques [3-5]. In particular orbital torques [6] increase the switching efficiency by more than a factor 10. Going towards 2D van der Waals systems, we explore bulk spin – orbit torques resulting from the particular symmetry [7].

We use skyrmion dynamics for non-conventional stochastic computing applications, where we developed skyrmion reshuffler devices [8] based on skyrmion diffusion, which also reveals the origin of skyrmion pinning [8]. Such diffusion can furthermore be used for Token-based Brownian Computing and Reservoir Computing [9].

Beyond spatially multiplexed quasi-static Reservoir Computing [9], we have recently taken the next step and realized time multiplexed Reservoir Computing [10]. Given the huge tunability of thermal spin dynamics of skyrmions, the reservoir response can be tuned to the input timescales allowing for a drastic simplification of the device architecture and dynamic detection of time series with variable input timescales [10].

Finally, we go beyond simple ferromagnets and study multilayers with antiferromagnetic coupling termed synthetic antiferromagnets. We find that the diffusion dynamics is drastically enhanced due to the topology [11].

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Nonlinear photon-magnon coupling

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Coherent spin waves [1] are ideal candidates for wave-based computing [2] since they offer various nonlinear properties, wavelengths scalable to the nanometer range and GHz clock rates compatible with CMOS-based circuits. In the context of computing, mainly nonlinear magnon-magnon interactions [3,4] have been in the focus since they are the basis of an all-magnonic logic approach. In many applications, however, efficient magnon excitation with GHz microwaves is still a cornerstone of many devices and will remain so in the future. In micro- and nanostructures, this microwave photon-to magnon conversion process can easily reach a nonlinear regime, which means that the photon-magnon coupling coefficient depends on the photon and magnon intensities. This nonlinear photon-magnon coupling process is generally challenging to describe theoretically but offers a vast variety of functionalities for computing and signal processing.

In my presentation, I will discuss different scenarios of nonlinear photon-magnon coupling based on the magnonic foldover effect and magnonic bistabilities [4]. Using microfocussed Brillouin light scattering in different ultralow damping micro- and nanostructures, I will show how nonlinear photon-magnon coupling can be used to build magnonic repeaters [5], magnonic neurons and signal processors.

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Light-Controlled Nanomagnetic Logic

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Single-domain nanoscale magnets interacting via magnetostatic interactions are potentially key metamaterials to develop novel paradigms for versatile, low-power computation [1]. Examples include in-memory computing to circumvent the so-called van Neumann gap between data storage and data processing units on conventional chips and neuromorphic inspired probabilistic computation paradigms. Their properties and functionality are determined by the capability to reverse the moment of each nanomagnet to minimize the mutual dipolar interactions, which happens more quickly at elevated temperatures. As of today, thermal excitation of nanomagnetic logic networks is achieved by thermal contact to a hot reservoir (global heating). This approach is energetically inefficient, spatially non-discriminative, and intrinsically slow, with time scales of seconds. Furthermore, for implementation in devices of magnetic metamaterials, e.g., magnonic crystals and nanomagnetic logic circuits, global heating lacks the control, spatial discrimination, and speed required for integrated operation with CMOS technology. We propose and demonstrate an approach in which the nanomagnetic arrays are made of hybrid nanostructures that combine a plasmonic nano-heater with a magnetic element. We achieve the reliable and contactless plasmon-assisted optical heating of nanomagnets with a flexible control of length (down to the micrometer) and time (down to sub-ns) scales of the thermal excitation [2]. Furthermore, the polarization-dependent absorption cross section of elongated plasmonic elements enables selective heating of a desired subset of nanomagnets within the illuminated area depending on their in-plane, which is not possible with conventional heating schemes [3]. This provides the spatial discrimination and speed required for their integration with CMOS technology. Furthermore, the here presented concept of plasmon-assisted optical heating offers powerful prospects for novel functionalities and applications in the fields of magneto-calorics, spintronics, magnonics.

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Neuromorphic computing on oxide platforms utilizing charge and spin

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Neuromorphic computing inspired by the brain is widely researched today as a promising avenue for low-power computing with efficient information processing, for applications in cognition to edge intelligent devices. However, at the hardware level, the present system lacks the rich non-linear phenomenon that occurs in biological systems and in this the rich phase space offered by correlated oxides provides an important platform. Intrinsic to these materials and their devices are emergent phenomena at their heterointerfaces which can be tailored by strain and doping and tuned by external stimuli such as temperature, electric field and magnetic field. This talk will discuss new examples of non-linear systems akin to synapses and neurons – components of any neuromorphic hardware made up of such materials viz manganites. These interfaces exploit the octahedral orbital coupling effects to design anisotropic transport that persists over long length scales in a network and bears functional resemblance to the biological brain. Electronic instabilities manifested as negative differential resistance (NDR), exploiting the intrinsic metal-to-insulator coupled transition in strained thin ferromagnetic films will be discussed. Multiple NDR regimes at different voltage bias have been exploited to demonstrate voltage control oscillators with tunable frequencies, driving them either synchronously or asynchronously. Further examples of tailoring magnetic anisotropy in ruthenate thin film gated devices, aimed to induce stochasticity for exploring them as p bits will also be discussed.

Reprogrammable Analogue Multi-functional Nanodevices: the building blocks of Neuromorphic Spintronics

Alex Jenkins

INL - Braga (Portugal)

Spintronics, and specifically magnetic tunnel junctions (MTJ), are an exciting candidate as the building block of future artificial neural networks due to their multi-functional, analogue and reprogrammable nature. In this presentation, an overview of recent work will be presented on the vortex-based MTJ, discussing a single magnetic stack which can be optimised for both neuronal and synaptic functionalities in the context of radio-frequency multiplexed artificial neural networks. Additionally, several mechanisms which allow for individual devices to be statically and dynamically reprogrammed in a non-volatile manner will be discussed. This reprogrammability allows for individual devices which are already integrated as part of a larger network to be reconfigured even after integration with CMOS technologies.

Electrical manipulation and detection of skyrmions for memory and logic applications

Olivier Boulle

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Skyrmions are topological spin textures which hold great promise as nanoscale bits of information in memory and logic devices [1]. The recent demonstration of room temperature skyrmions [2,3] as well as their current induced motion in industry compatible sputtered thin films have lifted important roadblocks toward the realization of skyrmion-based devices. However, their development is impeded by a too low current-induced velocity (about 100 m/s) [4] as well as the skyrmion Hall effect, namely a motion transverse to the current direction due to their topological charge which can lead to their annihilation in tracks. Antiferromagnetic (AF) skyrmions allow these limitations to be lifted owing to their vanishing magnetization and net zero topological charge, promising fast dynamics without skyrmion Hall effect. In this presentation, I will address the stabilization and current induced manipulation of skyrmion in compensated synthetic antiferromagnetic (SAF). I will first show that skyrmions can be stabilized at room temperature in Pt/Co/Ru based compensated SAFs and nucleated using local current injection or ultrafast laser pulses [5]. I will then show that SAF skyrmions can be moved by current at velocities over 900 m/s without skyrmion Hall effect. Micromagnetic simulations and analytical models using experimental parameters show that this enhanced skyrmion velocity can be explained by the compensation of the topological charges as well as an enhanced spin orbit torque in the synthetic antiferromagnet. I will conclude the talk with recent results on the electrical nucleation and detection of a skyrmion in magnetic tunnel junctions, which is another important milestone for skyrmion based devices [6]. Our results open important paths toward the realization of logic and memory devices based on the fast manipulation of skyrmions.

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Electrically Programmable Nanomagnetic Ising Network

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Two-dimensional arrays of magnetically coupled nanomagnets provide a mesoscopic platform for exploring collective phenomena as well as realizing a broad range of spintronic devices. In particular, the magnetic coupling plays a critical role in determining the nature of the cooperative behaviour and providing new functionalities in nanomagnet-based devices. Here, we create coupled Ising-like nanomagnets in which the coupling between adjacent nanomagnetic regions can be reversibly converted between parallel and antiparallel through solid-state ionic gating (Fig. 1)[1]. This is achieved with the voltage-control of magnetic anisotropies in a nanosized region where the symmetric exchange interaction favours parallel alignment and the antisymmetric exchange interaction, namely the Dzyaloshinskii-Moriya interaction, favours antiparallel alignment[2]. Applying this concept to a two- dimensional lattice, we demonstrate a voltage-controlled phase transition in artificial spin ices. Furthermore, we achieve an addressable control of the individual couplings and realize an electrically programmable Ising network, which opens up new avenues to design nanomagnet-based logic devices [3] and neuromorphic computers.

Keywords: Nanomagnet, Magnetic coupling, Voltage-controlled magnetic anisotropy, DMI, Ising network

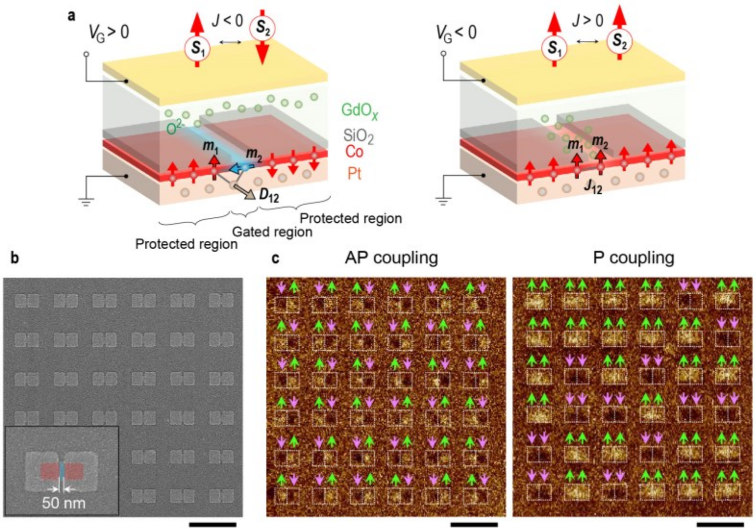

Figure 1. Basic concept of voltage-controlled magnetic coupling.

Neuromorphic and probabilistic computing with spintronic devices

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The development of more efficient and high performance spintronic devices and the efforts to have co-integration of spintronics with CMOS technology is driving the development of hybrid CMOS-spintronic solutions for applications where one can take the advantages of both technologies while minimizing their disadvantages. In this talk, I will present our recent developments on new potential applications of magnetic tunnel junctions (MTJs) in neuromorphic and probabilistic computing. For neuromorphic computing, I will discuss how to implement spiking neurons and on-chip training taking advantage of MTJ properties.

I will also focus on probabilistic computing with probabilistic-bits (p-bits) which is emerging as a computational paradigm able to be competitive in solving NP-hard combinatorial problems. I will show how to map hard combinatorial optimization problems (Max-Sat, Max-Cut, Traveling Salesman problem) into probabilistic Ising machine. We will discuss the potential of advanced annealing schemes comparing simulated annealing, parallel-tempering, and simulated-quantum-annealing and how it will be possible to implement an efficient probabilistic co-processor.

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Time-Multiplexed Spinwave Ising Machines

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The spinwave Ising Machines (SWIMs) are a new class of time-multiplexed Ising machines which are implemented with spinwave radio frequency (RF) pulses propagating in YIG delay lines. The interconnection between SWIM Ising spins can be implemented with delay cables or an electronic measurement and feedback system using FPGA. Spinwaves can propagate 5 to 7 orders of magnitude slower than the speed of light allowing for miniaturization of time-multiplexed Ising machines and using just mm-long YIG delay lines. Moreover, a combination of GHz carrier frequency and small physical length of YIG delay lines leads to 2-3 orders of magnitude better frequency stability than in Coherent Ising machines. The presentation focuses on design, development, and potential of the SWIM concept.

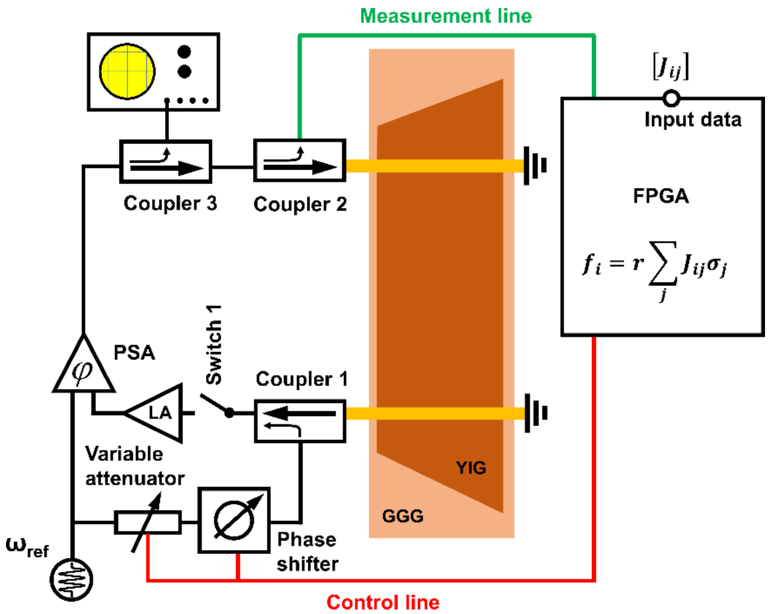

Figure 1. Spinwave Time-multiplexed Ising machine.

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Brain-Inspired Computing Using Magnetic Domain Wall Devices

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Neuromorphic computing or brain-inspired computing is considered as a potential solution to overcome the energy inefficiency of the von Neumann architecture for artificial intelligence applications [1-4]. To realize spin-based neuromorphic computing practically, it is essential to design and fabricate electronic analogues of neurons and synapses. An electronic analogue of a synaptic device should provide multiple resistance states. A neuron device should receive multiple inputs and should provide a pulse output when the summation of the multiple inputs exceeds a threshold.

Our group has been carrying out investigations on the design and development of various synaptic and neuron devices in our laboratory. Domain wall (DW) devices based on magnetic tunnel junctions (MTJs), where the DW can be moved by spin-orbit torque, are suitable candidates for the fabrication of synaptic and neuron devices [2]. Spin-orbit torque helps in achieving DW motion at low energies whereas the use of MTJs helps in translating DW position information into resistance levels (or voltage pulses) [3]. This talk will summarize various designs of synthetic neurons synaptic elements and materials [4]. The first half of the talk will be at an introductory level, aimed at first-year graduate students. The second half will provide details of the latest research.

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