MA 24: Focus Session: Exploiting spintronics for unconventional computing (joint session MA/TT)

Over the past century, the miniaturization of electronics has improved commensurately to the growth in computational power following an empirical relationship known as "Moore's law", an observation that microprocessor performance doubles every 18 months. It has now become clear that this trend will unlikely continue in the future due to limits both in the downscaling of transistors as well as the fundamental throughput of data between CPU and memory elements in traditional Von Neumann computer architectures. A completely new path forward has however been offered by bioinspired approaches to computation which attempt to capture the intrinsic parallelism and energy efficiency exhibited by the animal brain. The past two decades have in fact seen the flourishing of digital machine learning and deep neural network techniques to process data intensive tasks ranging from image recognition to AI development. The next frontier will consist of further optimizing these approaches by designing physical devices capable of implementing these functional principles analogically. Advances in nanomagnetism and spintronics have assembled a versatile toolbox of electrically controllable materials and phenomena whose applications not only integrate seamlessly within current CMOS architectures but also present a radical new horizon for the evolution of device construction and development. The goal of this focus session is to construct a comprehensive picture of the state-of-the-art of spintronic applications to unconventional computing paradigms such as Boltzmann Machines, Neural Network, Probabilistic and Reservoir Computing. The talks will bring together leading scientist in the rapidly evolving field of spintronic computing to highlight the roles that thermally susceptible magnetization dynamics, exotic magnetic textures, frustrated systems and spin waves can play in shaping the computing devices of tomorrow.

Organized by: Daniele Pinna, Karin Everschor-Sitte (U. Mainz)

Time: Wednesday 9:30–12:15 Location: H 1012

Invited Talk MA 24.1 Wed 9:30 H 1012

Control of Mesoscopic Magnetism for Computation — •Laura Heyderman — Laboratory for Mesoscopic Systems, Department of Materials, ETH Zurich, 8093 Zurich, Switzerland — Laboratory for Multiscale Materials Experiments, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland

To exploit mesoscopic magnetism in computation, it is necessary to control the magnetic states with an external stimulus. In hybrid mesoscopic structures with two different ferromagnetic layers, the static and dynamic behaviour results from the mutual imprint of the magnetic domain configurations, which can be exploited to create a nanoscale switch for the magnetisation [1]. With multiferroic composites, an electric field can be used to induce uniform magnetization rotation in single domain submicron ferromagnetic islands grown on ferroelectric single crystal [2]. In artificial spin ice [3], which are arrays of coupled nanomagnets, emergent magnetic monopoles can be manipulated in a magnetic field [4]. For device applications, the additional control can be gained by modifying the anisotropy of the individual magnets. Such anisotropy engineering can also be used to control the chirality of vortex states in hexagonal rings of nanomagnets [5]. Finally, one can modify the geometry of an artificial spin ice to display dynamic chirality where the average magnetization rotates in unique sense during thermal relaxation [6]. [1] M. Buzzi et al. PRL (2013) [2] P. Wohlhüter et al. Nat. Commun. (2015) [3] L.J. Heyderman and R.L. Stamps, JPCM (2013) [4] E. Mengotti et al. Nature Phys. (2011) [5] R. Chopdekar et al. New J. Phys (2013) [6] S. Gliga et al. Nat. Mater. (2017)

MA 24.2 Wed 10:00 H 1012

Phase domain nucleation and growth investigated in nanofabricated FeRh — •Rowan Temple[1], Jamie Massey[1], Trevor Almeida[2], Kayla Fallon[2], Stephen McVitie[2], Thomas Moore[1], and Christopher Marrows[1] — [1]University of Leeds, Leeds, UK — [2]University of Glasgow, Glasgow, UK

The binary alloy FeRh with B2 (CsCl) chemical ordering displays a magnetostructural phase transition at an unusually high temperature of 350 K. Heating through this point the material undergoes an antiferromagnetic (AF) to ferromagnetic (FM) transition, this is accompanied by a 1% volume expansion in the crystal lattice. Being thermodynamically first order in nature, the transition is hysteretic with metastable states coexisting within the material close to the transition temperature. Using nanofabricated epitaxially grown films of FeRh we have examined the effects of rapid thermal heating of this material beyond its equilibrium state. We find decay into equilibrium state is exponential independent of temperature, commensurate with a purely nucleation rather than domain growth driven transition. We have further investigated size dependence of the transition through PEEM imaging and find edge nucleations are key to the transition in a patterned device and lower the expected transition temperature. This understanding will be used to enable the use of patterned FeRh for unconventional computing techniques.

Invited Talk MA 24.3 Wed 10:15 H 1012

Spin waves for unconventional computing and data processing — •Philipp Pirro, Thomas Brächer, and Andrii Chumak — Fachbereich Physik and Landesforschungszentrum OPTIMAS, TU Kaiserslautern, Erwin-Schrödinger-Straße 56, 67663 Kaiserslautern

Spin waves, the collective excitations of the spin lattice of a magnetic material and their quanta, magnons, show a large variety of linear and nonlinear wave phenomena. They constitute a flow of spin angular momentum which opens a new sub-field of spintronics: magnon spintronics, where information is transferred and processed using magnons including a coupling to electron-based spintronic circuits.

In my presentation, I will first review different computing approaches based on spin waves and discuss the advantages and challenges of an interference-based logic. Next, I will present a selection of the experimentally realized macroscopic prototypes for spin-wave based logic like the majority gate and the magnon transistor. A downscaling of more than three orders of magnitude of these prototypes is required to compete with conventional CMOS technology. Therefore, I will discuss new features associated with the miniaturization like strong quantization effects as well as ways to interconnect to conventional spintronic circuits. Exemplarily, I will present different nanoscopic magnonic devices which use linear and nonlinear effects like magnonic wake-up receivers and nano-transistors.

15 minutes break

Invited Talk MA 24.4 Wed 11:00 H 1012

p-bits, p-transistors and p-circuits — •Kerem Camsari — Purdue University

Conventional logic/memory devices are built out of deterministic units such as MOS transistors, or nanomagnets with energy barriers in excess of 40 kT. We show that unstable, stochastic units which we call "p-bits" can be interconnected to create correlations that implement

Boolean functions with impressive accuracy, comparable to digital circuits. They are also "invertible", a unique property that is absent in digital circuits. In the direct mode, the input is clamped, and the network provides the correct output. In the inverted mode, the output is clamped, and the network fluctuates among all possible inputs that are consistent with that output. We present an implementation of such a p-bit using existing technology. The results for this hardware implementation agree with those from a universal model for p-bits, showing that p-bits need not be magnet based: any transistor-like tunable random bit generator should be suitable. We present an algorithm for designing a bi-directional p-bit network that implements a given truth table. We then show such bi-directional units, such as Full Adders, can be interconnected in a directed manner to implement 32-bit addition, that correlate hundreds of stochastic p-bits. We also show that despite the directed interconnections, invertibility is largely preserved. This combination of digital accuracy and logical invertibility is enabled by the hybrid design using bidirectional BM units to construct circuits with directed inter-unit connections.

MA 24.5 Wed 11:30 H 1012

Thermally excited skyrmion motion for probabilistic computing — •Jakub Zázvorka[1], Daniel Heinze[1], Kai Litzius[1,2,3], Samridh Jaiswal[1,4], Sascha Kromin[1], Niklas Keil[1], and Mathias Kläui[1,4] — [1]Johannes Gutenberg University Mainz, Institute of Physics, Mainz, Germany — [2]Max Plank Institute for Intelligent Systems, Stuttgart, Germany — [3]Graduate School of Excellence "Materials Science in Mainz", Mainz, Germany — [4]Singulus Technologies AG, Kahl am Main, Germany

A key problem for probabilistic computing is that cascading gates propagate undesired correlations. Therefore, one needs to reshuffle the signals to keep them uncorrelated. While for many non-conventional computing approaches non-magnetic implementations are most promising, for building a "reshuffler", skyrmions might be ideally suited due to the low footprint and low power compared to e.g. CMOS implementations [1]. We have studied a Ta-based material where we can stabilize skyrmions and controllably nucleate and displace them by current pulses due to spin-orbit torques. We find topologically non-trivial N=1 skyrmions that move with the application of current pulses. At zero applied current, we find thermally activated skyrmion motion. We track the trajectories of skyrmions and from the dependence of their mean-square-displacement (MSD) on time, we can identify motion by diffusion and obtain the diffusion constant. There is a strong dependence of the skyrmion diffusion parameter on temperature and the skyrmion size. Finally, we patterned the reshuffler geometry and ascertain its performance. [1] D. Pinna et al., arXiv:1701.07750, 2017.

Invited Talk MA 24.6 Wed 11:45 H 1012

Bits and Brains: New materials and brain-inspired concepts for low energy information processing — •Theo Rasing — Radboud University, Nijmegen, the Netherlands

Data is the fuel of the new digital economy that has stimulated a whole new class of innovative technologies and businesses. While data has become an indispensable part of modern society, the rate at which data is generated is exploding. This is not only pushing our current technologies to their limits, but also that of our energy production: our ICT and data centers already consume around 5% of the world electricity production and with an annual increase of 7%, this is rapidly becoming unsustainable. In stark contrast, the human brain, with its intricate architecture combining both processing and storing of information, only consumes about 10 Watt of energy while having a similar capacity as a supercomputer consuming around 10 Megawatt. We have created a consortium of condensed matter, material and neuro scientists with the aim to develop materials and concepts that mimic the efficiency of the brain by combining local processing and storage, using adaptable physical interactions that can implement learning algorithms.